Investigation and Assessment of Colored Concrete Pavement

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August 2014

Research Project
Final Report 2014-26

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The incorporation of full-depth colored concrete into street and roadway projects has been rapidly increasing in Minnesota. Some of these projects have exhibited significant early distresses, particularly near contraction joints. The first objective of this project was to identify any materials, design, or construction methods unique to colored concrete that may contribute to the early deterioration observed in colored concrete pavements, sidewalks and medians in Minnesota. The second objective included developing recommendations for improved specifications for materials, mix designs, and construction practices for colored concrete in cold climates. Finally, recommendations were made for suitable repair and rehabilitation techniques or alternative construction systems that might provide more durable, longer-lasting colored concrete features in Minnesota. Many projects exhibited panel cracking, either a result of possible thermal expansion restraint or potentially some expansive materials related issues. A number of the projects demonstrated significant joint distress. Smooth surface textures were also reported for many colored concrete crosswalks and sidewalks. Based on this investigation, it was determined that typical placement and finishing practices during construction were not a principal cause for the observed deterioration. Recommendations included producing mixes with a lower water-to-cementitious ratio (≤ 0.43), and increasing consolidation of the mix during placement. Designers were instructed to consider the differences in thermal expansion rates of various colored concretes placed side by side. The report concludes with discussions on suitable repair options, as well as alternative streetscaping techniques.</td></tr>
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Investigation and Assessment of Colored Concrete Pavement

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Final Report

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EXECUTIVE SUMMARY

The decoration or delineation of certain features in a street or roadway can provide a means toward improving user satisfaction and safety. One method that can be used to improve the perceived environment of a street or roadway is “streetscaping.” In many cases, colored concrete sidewalks, medians and intersections play a predominant role in creating the desired architectural effects. Colored concrete is also used to delineate paths for both traffic and pedestrians.

The incorporation of full-depth colored concrete into street and roadway projects has been rapidly increasing in Minnesota. Unfortunately, a number of these projects have exhibited significant early distresses, particularly near contraction joints. Owing to the increased cost and visibility of such project features, it is important to understand the causes and remedies for such early distresses.

Determining the cause for such deterioration is difficult, as very little knowledge has been published related to the performance of colored concrete pavements, especially in relation to its durability in cold climates. Early joint deterioration is coincidently being observed in standard (non-colored) jointed concrete pavements in cold climate regions of the U.S. Findings from a national pooled-fund study (TPF5-224) running concurrently with this study proved helpful.

The first objective of this project was to identify any materials, design, or construction methods unique to colored concrete that may contribute to the early deterioration observed in colored concrete pavements, sidewalks and medians in Minnesota. The second objective included developing recommendations for improved specifications for materials, mix designs and construction practices for colored concrete in cold climates. Finally, this study was charged with recommending suitable repair and rehabilitation techniques or alternative construction systems that might provide more durable, longer-lasting colored concrete features in Minnesota.

The investigation began with a review of the production of colored concrete mixes. The next step was to identify existing street and roadway projects in Minnesota that include colored concrete in at least part of their pavement, sidewalk or median. For each of those projects, the overall performance was documented, with special care to determine the extent of early distress. Several new construction projects were visited to document typical processes used to produce and place colored concrete in Minnesota street and roadway projects. A detailed investigation of core samples taken from projects with distress was then carried out. Finally, recommendations for improved specifications, placement techniques and repairs were developed.

During the study, a database of colored concrete pavements in Minnesota was created. With the recent surge in construction of colored concrete in Minnesota roadways, many projects examined were too new to comment on anything other than potential construction errors. Many projects however, exhibited panel cracking, either a result of possible thermal expansion restraint, or potentially some expansive materials related issues. A number of the projects demonstrated significant joint distress. Smooth surface textures were also reported for many colored concrete crosswalks and sidewalks.

Construction site visits revealed that the current practices for placement likely result in poor consolidation through the depth of the pavement. While excessive surface leveling and finishing was observed, surface scaling has not commonly resulted. Due to the infill locations of colored concrete crosswalks, most are constructed using high-early strength gain mixes.

A forensic examination of four projects exhibiting distress revealed that most mixes were produced with a high water-to-cementitious ratio ($\geq$0.45), exceeding the maximum value recommended for concretes placed in freeze-thaw climates like Minnesota. Secondary ettringite and magnesium were detected in many locations throughout a majority of the core samples. Presence of these minerals was deemed to be caused by the high porosity of the mixes. Infilling of a substantial amount of entrained air voids with secondary ettringite was determined to be reducing the freeze/thaw resistance of the pavements.

Based on this investigation, it was determined that typical placement and finishing practices during construction were not a principal cause for the observed deterioration. The lack of observed surface scaling also supports this conclusion. Of greater concern was the observation of chemical attack within the colored concrete. Due to the small number of samples examined, the research team was not comfortable identifying the exact cause for the alkali-silica reaction (ASR) and chemical attack observed. The prevalence of magnesium throughout the core samples is certainly one possibility, however other impurities in modern deicing materials may also be potential sources for the chemical reactions.

Joint distress was the most commonly observed issue. Microcracking within the joint regions typically extended from the top to the bottom of the pavement. Because of this, simple partial-depth concrete repairs are not likely suitable. The other common distress type was panel cracking, which was identified as being associated with thermal expansion forces. Instrumented test slabs were constructed to characterize the thermal behavior of both colored and non-colored concrete.

Based on the findings of this study, recommendations were made for improving the construction methods and mix design specifications for full-depth colored concrete placed in future roadway projects. These recommendations include producing mixes with a lower water-to-cementitious ratio ($\leq$ 0.43), and increasing consolidation of the mix during placement. Improved curing methods and establishment of adequate surface texture were also recommended. Designers were instructed to consider the differences in thermal expansion rates of various colored concretes placed side by side.

The report concludes with discussions on suitable repair options, as well as alternative streetscaping techniques.

CHAPTER 1: INTRODUCTION

Colored Concrete in Streets and Roadways

Streets and roadways serve many purposes, the primary one being the movement of vehicles and pedestrians. Due to their prevalence, streets often tend to look the same, and therefore could be considered rather boring in appearance. That sameness can also create an atmosphere where people and drivers often tune out the surrounding when going about their daily activities.

The decoration or delineation of certain features in a street or roadway can provide a means toward improving user satisfaction, as well as safety. One method that can be used to improve the perceived environment of a street or roadway is through the use of "streetscaping." Figures 1.1-1.4 show some examples of streetscaping in Minnesota. In these cases, colored concrete sidewalks, medians and intersections play a predominant role in creating the desired architectural effects. Another method that can be used to increase safety for both traffic and pedestrians is through the use of delineation. Figures 1.5-1.7 show several crosswalks that have been built specifically to help guide pedestrians and alert vehicular traffic. Again, colored concrete has been used to provide the means of delineation.

While the use of colored concrete in streetscaping provides architectural appeal to a street or roadway environment, it also comes with additional costs. The materials, like color pigments and special curing waxes, as well as construction methods, like hand placement and finishing, often command higher prices than more traditional street or roadway construction. With the extra costs involved in this process, it is the expectation of the owner that the quality and longevity of the finished product meet or exceed that of more standard construction methods and materials.

Figure 1.1 Sculpted and colored concrete sidewalks in Park Rapids, MN

Figure 1.2 Colored concrete sidewalks in Apple Valley, MN

Figure 1.3 Colored concrete median in Apple Valley, MN

Figure 1.4 Colored concrete intersection in Centerville, MN

Figure 1.5 Colored concrete crosswalk in Columbia Heights, MN

Figure 1.6 Colored concrete crosswalk in Sauk Rapids, MN

Figure 1.7 Colored concrete crosswalk in Roseville, MN

Research Need and Objectives

As described above, colored concrete can provide many aesthetic and safety benefits to pavements, sidewalks, and medians. For these reasons, the incorporation of full-depth colored concrete in street and roadway projects has been rapidly increasing in Minnesota. Unfortunately, a number of these projects have exhibited significant early distresses, particularly near contraction joints. Owing to the increased cost and visibility of such project features, it is of great interest to understand the causes and remedies for such early distresses.

Determining the cause for such deterioration can be difficult, as there is very little knowledge in the literature specifically on the performance of colored concrete, especially in relation to its durability in cold climates. Similar early joint deterioration is also being observed in standard (non-colored) jointed concrete pavements in the cold climate regions of the U.S. As a result, a national pooled-fund study (TPF5-224) was initiated to investigate the cause of the deterioration. That study recently produced several reports and guidelines [1, 2] that were of at least some benefit toward this investigation.

The first objective of this project was to identify any materials, design, or construction methods unique to colored concrete that may contribute to the early deterioration observed in colored concrete pavements, sidewalks and medians in Minnesota. The second objective included developing recommendations for improved specifications for materials, mix designs, and construction practices for colored concrete in cold climates. Finally, this study was charged with recommending suitable repair and rehabilitation techniques or alternative construction systems that might provide more durable, longer lasting colored concrete features in Minnesota.

Colored Concrete Production

Before the causes of distress in colored concrete can be investigated, it is important to understand its basic components. There are three common methods of producing colored concrete: integral color, dry-shake color, and stains or dyes.

Integral colored concrete is produced by adding color pigments (powders), pigment granules, or liquid colorant to normal concrete. Powdered pigments are typically a blend of synthetic or natural iron-oxide pigments. Other less common pigments consist of manganese oxide, titanium oxide, and chromium oxide. Powders are finer than cement by a factor of 10 to 100 [3]. Pigment granules are formed from a pigment and a binder to eliminate dust. The binder can be water soluble (e.g. organic binder or aqueous solutions of inorganic salts) or insoluble (e.g. pozzolanic clay agglomerator) [4]. These granules can be formed by pressure extruding wetted pigments to compact the mixture, and then drying the resulting granules. Liquid colorant is achieved through the use of several admixtures, allowing pigments to be suspended in water.

Color hardeners (dry-shake color) are a blend of pigments, finely graded silica sand, wetting agents, and Portland cement. These hardeners are hand broadcast onto fresh concrete and "worked" into the surface with a float or trowel. It is claimed that these hardeners "densify the surface," because they contain hard mineral aggregates and Portland cement. The result is a surface that's stronger, more wear resistant, and less permeable to moisture and deicing chemicals than standard concrete" [5].

There are three categories of stains and dyes used to color a concrete surface. Acid based stains are mix of water, hydrochloric acid, and acid soluble metallic salts. These stains penetrate the surface and react chemically with the hydrated lime (acid etches the surface to allow metallic salts to penetrate and react with concrete). With water-based penetrating stains, no reaction occurs, as this material is low in volatile organic compounds. Dyes are non-reactive (unlike acid stains). They have a much smaller particle size than stains, are available in water or solvent-based formulas, and are not UV Stable, which requires them for use in indoor concrete only. All stains and dyes can be applied with a low pressure sprayer, roller, brush or sponge.

There is an ASTM standard for using pigments in integrally colored concrete: ASTM C979 -10 [6]. This standard places limits on the pigments effect on concrete. The 28-Day compressive strength cannot be less than 90% and a water-cement ratio not greater than 110% of that of a control mixture. The pigment cannot accelerate the initial or final set by more than 1 hour, and not retard the set by more than 1.45 hours. Using the same amount of air entraining agent, the air content of the mix cannot change by more than 1%. This standard also tests water wettability, alkali resistance, percentage of SO_3, water solubility, atmospheric curing stability, and light resistance of the colored concrete.

There is a lack of research and published information on the behavior of coloring additives in concrete pavements. Studies have found the compressive strength and workability of structural concrete can be affected by the inclusion of colored pigments[7]. The University of Iowa conducted an evaluation of colored polymer concrete with a synthetic resin binder after early distresses, such as shoving and potholes were observed in a concrete overlay of similar material. The study found however, that the material was actually stronger and more resistant to moisture related damage[8]. In general, previous research has identified select situations where undesirable effects from using coloring additives in concrete have occurred, but little has been written about the means to mitigate problems, improve production or placement practices, or provide guidelines for the repair of deterioration once it has occurred.

Road Maintenance Treatments

Modern roadway deicing chemicals are continuing to be developed in an effort to increase the safety of pavements in cold climates. These chemicals offer improved deicing capabilities at lower temperatures than traditional materials like sodium chloride (salt). Unfortunately, the temperature conditions when these chemicals are applied to the roadway coincide with times when concrete joints are at their widest, thus expediting the entry of the chemicals into poorly sealed joints. Previous research has indicated the potential for increased concrete deterioration when using some of these chemicals[9]. The early deterioration found in the colored concrete projects identified in this study may be simply a result of the increased concentration of these chemicals into the concrete, or possible some chemical reactions between the pigments and the deicing chemicals.

Research Methodology

This study was structured primarily to investigate the causes for early distress in colored concrete used in street and roadway projects in Minnesota. This study was also focused on developing improved specifications for the production of colored concrete in cold climates, as well as identifying suitable repair and rehabilitation techniques for projects exhibiting early distress.

This study consisted of five major tasks. The first task was to identify existing street and roadway projects in Minnesota that include colored concrete in at least part of their pavement, sidewalk, or median. For each of those projects, the overall performance was documented, with special care to determine the extent of early distress. The second task involved observation of typical construction practices used to produce and place colored concrete in Minnesota street and roadway projects. The third task involved detailed laboratory and field investigations to determine the cause of the distresses observed in the field. The fourth task consisted of developing improved specifications for the production and placement of colored concrete in Minnesota. The final task was to identify suitable repair and rehabilitation technique for projects that have developed distresses early in their life.

This final report was designed to provide comprehensive guidelines and recommendations for producing more durable colored concrete pavements, sidewalks and medians in Minnesota.

CHAPTER 2: PROJECT DATABASE

Colored Concrete in Minnesota Roadways

Due to the increasing popularity of streetscaping in urban environments, the amount of street and roadway projects incorporating colored concrete grows tremendously each year. The goal for this study was to locate and document the performance of a substantial amount of those projects constructed prior to the March 2013. Due to budget and time constraints, not all of the projects, nor all of the construction details about each of the projects that were located, could be documented in this report. Nevertheless, a broad range of projects that include colored concrete in street and roadway projects were found, and they were sufficient enough to allow this study to investigate some of the early problems that are being observed.

To help quantify and document projects with colored concrete in Minnesota, a database was constructed. Table 2.1 lists the projects considered in this study. Recall again that these were projects discovered prior to March 2013. It should be noted that due to the prevalence of joint deterioration observed in colored concrete crosswalks and intersections, this study was initially focused mainly on those types of structures. However as projects were visited, it was observed that additional items like medians and sidewalks were also constructed with colored concrete, and since the materials and placement techniques are similar to the crosswalks and intersections, it was decided to include all colored concrete street and roadway features into the study.

From Table 2.1, one can see that obtaining the complete information for each project was found to be difficult. Project records were either lost or discarded, or key personnel involved in their design and construction have moved on. Regarding the observed performance of the colored concrete in these projects, many of the older sections exhibited noticeable distress in their joints, as well as various types of cracking. Overall surface distresses, like scaling or pop-outs, did not frequently appear near the middle of the slabs.

As projects with colored concrete were discovered, a visit was made to a select number of them to observe and document their overall condition. The following section highlights several projects that were visited during this study. Note that some of the projects were recently constructed, and as such, little could be noted about their condition other than construction flaws.

Projects Visited

Apple Valley - Cedar Avenue

Stamped colored concrete was used in the medians at the intersection of Cedar Avenue and 162nd Street West. Figure 2.1 shows the newer colored concrete in excellent condition. Colored concrete was also used in the sidewalks along Cedar Avenue near 153rd Street West, as well as along 153rd Street West. Figures 2.2 and 2.3 show these locations. These projects were newly constructed in 2012.

Table 2.1 Projects with colored concrete in Minnesota

City	County	Project Name	Type of structure	Year constructed	Site visit date	Observed distress	Construction Notes	Color/type	Mix Design
Apple Valley	Dakota	Metro Transit I35 Park and Ride	Bus lane	2009	8/20/2012	Cracking			
Apple Valley	Dakota	Apple Valley Transit center	Sidewalks	2009	8/20/2012	Cracking	Formed	Liquid	3A32
Apple Valley	Dakota	Cedar Avenue	Sidewalks	2011-2012	8/20/2012		Formed, stamped & brushed	Powder and liquid	3A32, 3Y46WG
Apple Valley	Dakota	Founders Lane/Galaxy/153rd	Crosswalks, sidewalks	2009	8/20/2012	Cracking	Formed, stamped		3Y32C
Arden Hills	Ramsey	Lake Johanna Blvd.	Crosswalk	1999	8/20/2012	Joint Deterioration			
Barnesville	Clay	Front Street	Sidewalks	2011			MnDOT Specs		
Baxter	Crow Wing	Timberwood Drive and RR Crossing	Median	2010	8/15/2012				
Blaine	Anoka	TH14 bridge over TH65	Sidewalks, medians	2008	8/9/2012	Cracking			
Blaine	Anoka	TH14 and University Avenue	Median	2012	8/15/2012		Vibrating screed used	Quarry red	
Brainerd	Crow Wing	College Drive	Crosswalks, Roundabouts	2012	8/15/2012		Hand pour	Prism Pigments	3A32, 3A41, 3A41HE
Brooklyn Center	Hennepin	Brooklyn Blvd and TH694	Median	?	8/13/2012	isolation material			
Brooklyn Center	Hennepin	Bass Lake Rd.	Sidewalks, Median	2010	8/13/2012		Formed, stamped & brushed		
Burnsville	Dakota	Nicollet Avenue	Intersections,sidewalks, medians	8/21/2012	4/4/2014			Santa Barbara Brown	3Y32 AC
Centerville	Anoka	County Rd 14 Main Street and Centerville Rd	Intersections	2008	6/11/2012	Joint Deterioration		Chicory, Spice, Etruscan Tile	
Columbia Heights	Hennepin	40th and Central	Crosswalks, sidewalks	2012	8/13/2012				
Detroit lakes	Becker	Washington Ave.	Intersections, sidewalks	2010	8/15/2012				3A22, 3A32
Forest Lake	Washington	Broadway	Crosswalks	2011-2012	7/26/2012		Hand pour, reinforced	Bridgeport Beige and Brusset	
Forest Lake	Washington	Broadway	Crosswalks	2012	7/26/2012		Hand pour, reinforced	(CPC120L)/ Liquid Color	3A24, 3A41

Table 2.1 Projects with colored concrete in Minnesota (con't.)

City	County	Project Name	Type of structure	Year constructed	Site visit date	Observed distress	Construction Notes	Color/type	Mix Design
Grand Rapids	Itasca	Hwy 2	Intersections, sidewalks	?			Stamped in intersections		
Lakefield	Jackson	CSAH50 Downtown Lakefield	Sidewalk (no crosswalks)	2012			Contractors first time		
Lakeville	Dakota	Lakeville Park and Ride	Medians	2009			Formed, stamped		
Maplewood	Ramsey	White Bear Avenue and Beam	Crosswalks	2010-2012					3A41 AW-BC
Minneapolis	Hennepin	I35 and 46th Street Bus Lane	Bus lane	2010	8/13/2012	Joint spalling			
Park Rapids	Hubbard	Main Avenue 5th St. and Hwy 34	Intersections, crosswalks, sidewalks	2010	8/15/2012	Cracking, Joint Damage		Prism Pigments	
Princeton	Sherburne	TH95 and CSAH 29	Roundabout	2010	8/6/2012	Cracking			
Rochester	Olmsted	6th Street SW from 1st Ave to 4th Ave SW	Crosswalks	2012					
Roseville	Ramsey	Cty Rd C from Long Lake Rd to Snelling Ave	Crosswalks, gutterline	2005/2006	12/7/2011			CR. Mix C-32	3A3ZH-68
Roseville	Ramsey	Josephine Road from Hamline to Lexington Ave	Crosswalk	2001					
Roseville	Ramsey	Twin Lake Parkway (Cleveland to Prior Ave)	Crosswalks, Roundabouts	2009-2010					
Roseville	Ramsey	Larpenteur Ave from Oxford to Hamline	Crosswalks	2001	8/17/2012				
Roseville	Ramsey	Larpenteur Ave from Dale St to Oxford	Crosswalks	2003					
Roseville	Ramsey	County Rd C2 from Hamline to Lexington Ave	Crosswalk	2012					
Sauk Rapids	Benton	Benton Drive and 2nd Street N	Crosswalks	2007	8/6/2012	Cracking			
Shoreview	Ramsey	Cty Rd 96, Lexington Ave to Rice Street	Crosswalks	1997-1998, 2000		Joint Deterioration		Quarry Red	3A41-H
St Anthony	Hennepin	Silver Lake Road and 33rd Ave	Crosswalks	2007					

Table 2.1 Projects with colored concrete in Minnesota (con't.)

City	County	Project Name	Type of structure	Year constructed	Site visit date	Observed distress	Construction Notes	Color/type	Mix Design
St Paul	Ramsey	Shepard Road & Ontario St.	Intersection	1998	8/1/2012	Joint Deterioration			
St Paul	Ramsey	Shepard Road & Old Chestnut St.	Intersection	1998	8/1/2012	Joint Deterioration			
St Paul	Ramsey	Shepard Road & Washington St.	Crosswalks	1998	8/1/2012	Joint Deterioration			
St Paul	Ramsey	7th ST W and W 5th St.	Intersection	1987	8/1/2012	Joint Deterioration			
St Paul	Ramsey	Phalen Blvd and Payne Avenue	Crosswalks	2003	8/1/2012	Joint Deterioration			
Staples	Todd	TH10	Sidewalks	September <2008	8/15/2012				
Stillwater	Washington	Main Street N	Crosswalks, sidewalks	2012					
Thief River Falls	Pennington	Thief River Falls	Roundabouts, Underpass	2012-2013					
Vadnais Heights	Ramsey	County Rd 96, Rice St to Centerville Rd	Crosswalks	1997-2000	6/11/2012	Joint Deterioration			3A41-H

Figure 2.1 Apple Valley – Median on Cedar Avenue near 162nd Street W

Figure 2.2 Apple Valley – Sidewalk along Cedar Avenue near 153nd Street W

Figure 2.3 Apple Valley – Sidewalk along 153rd Street W. near Cedar Avenue

Apple Valley - Founders Lane near Galaxie Avenue

Colored concrete was used in the medians, sidewalks and crosswalks on Founders Lane near Galaxie Avenue in Apple Valley. See Figures 2.4 and 2.5. Constructed in 2009, the overall condition of most structures was very good. There was some cracking in several sidewalk panels, possibly due to thermal restraint from nearby structures (light posts?).

Apple Valley – Transit Center

Colored concrete was used in the sidewalks and medians around the Apple Valley Transit Center. These sidewalks were constructed in 2009. Figures 2.6 and 2.7 show that most joints are still intact and free of deterioration, however some mid-panel cracks are present.

Arden Hills - Lake Johanna Blvd & trail crossing in Tony Schmidt Park

A colored concrete crosswalk was constructed across Lake Johanna Blvd (on the north side of Lake Johanna) in 1999. As of 2012, significant joint deterioration is occurring near both wheel paths of the eastbound lane, as well as one wheel path of the westbound lane. Figures 2.8 and 2.9 show the distress.

For further investigation of the potential causes of the deterioration, core samples were taken near the distressed joints. Due to traffic flow considerations, only two core samples were obtained at longitudinal joints adjacent and parallel to the distressed joints. Results from the analysis of the core samples will be discussed in Chapter 4.

Figure 2.4 Apple Valley – Crosswalk on Founders Lane

Figure 2.5 Apple Valley – Sidewalk near Founders Lane

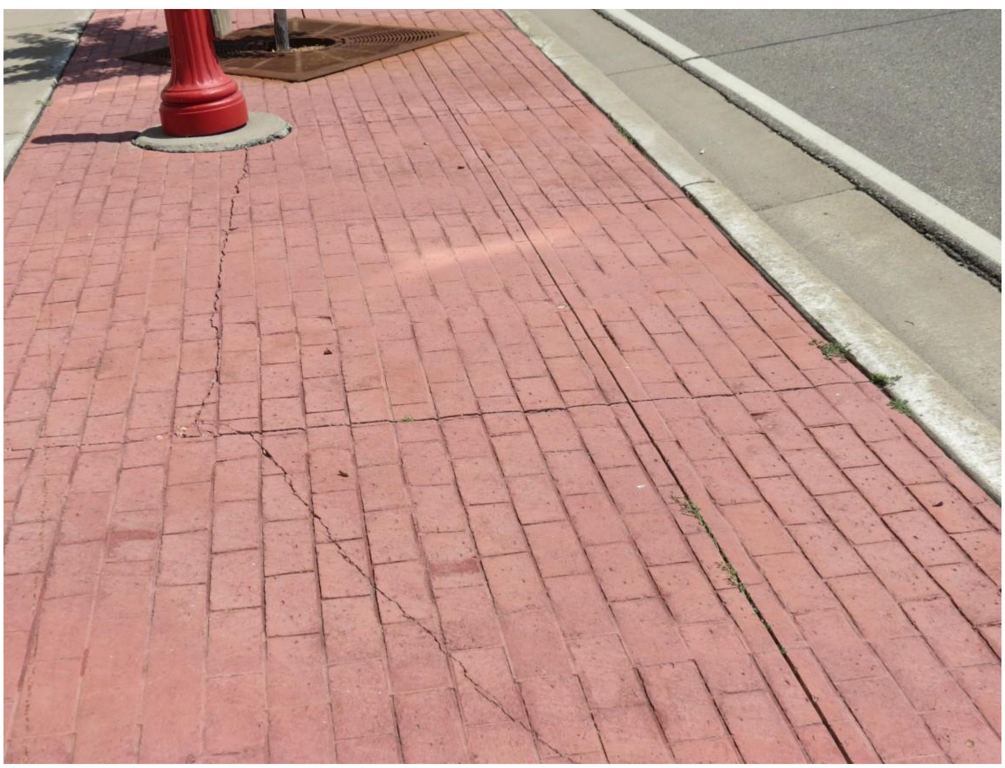


Figure 2.6 Sidewalk/median around Apple Valley Transit Center

Figure 2.7 Sidewalk around Apple Valley Transit Center

Figure 2.8 Arden Hills – Eastbound Lake Johanna Blvd in Tony Schmidt Park

Figure 2.9 Arden Hills – Westbound Lake Johanna Blvd in Tony Schmidt Park

Baxter – Timberwood Drive & TH210

Colored concrete was used in a large median straddling a railroad crossing near the intersection of Timberwood Drive and TH210. Constructed in 2010, Figures 2.10 and 2.11 show that its overall condition was still very good in 2012.

Blaine - Radisson Road south of County Road 14

Colored concrete resides in the median along Radisson Road, south of the intersection with County Rd 14 in Blaine. Constructed in 2011, the joints in the median are in excellent condition, except one location where a joint in the surrounding plain PCC likely caused distress in the colored concrete. See Figures 2.12 and 2.13.

Blaine – County Rd 14 west of TH65

Colored sidewalks, boulevards, and medians were constructed along County Road 14, west of TH65, in 2008-2009. The overall condition of the joints in 2012 was good; however panel cracking was prevalent throughout the project. See Figures 2.14 and 2.15. In one of the large medians, a sizeable area buckled. This is shown in Figures 2.16 and 2.17. It appeared that significant thermal stresses had been causing cracking throughout the area. Figure 2.18 shows that there was also spalling at the edge of the sidewalk, adjacent to a curb. Overall it appears there is a lot of expansion pressure throughout the median. Some cracks radiated from structures like light poles and manholes.

Of special note on this project, was that there was a good broom texture constructed into the surface of the colored concrete. Many colored concrete structures on other projects typically have a very smooth surface texture. Given the location and function of these structures, it seems advisable that an adequate texture be established. Such recommendations will be made in Chapter 7 of this report.

Brooklyn Center – Brooklyn Boulevard south of TH694

Colored sidewalks, boulevards, and medians were constructed along Brooklyn Boulevard, south of TH694. The year of construction could not be determined, but it did appear to be at least several years old. Figures 2.19 and 2.20 show that the joints are in good condition, however there was evidence of high compressive forces pushing joint isolation material upward during periods of high temperatures.

Brooklyn Center – Bass Lake Rd near TH100

Colored concrete was used in the medians and sidewalks along Bass Lake Road near TH100. The concrete was stamped in large rectangular patterns. Other than some poor consolidation in some locations, overall conditions appear to be very good on this project. Figures 2.21 and 2.22 show examples of the colored concrete located within this project.

Figure 2.10 Baxter - Median near railroad crossing on Timberwood Drive and TH210

Figure 2.11 Baxter – Joints in median on Timberwood Drive

Figure 2.12 Blaine – Joints in median on Radisson Road

Figure 2.13 Blaine – Distress in median on Radisson Road

Figure 2.14 Blaine – Median within County Rd 14, west of TH65

Figure 2.15 Blaine – Cracking of median within County Rd 14

Figure 2.16 Blaine – Buckling in median within County Rd 14

Figure 2.17 Blaine – Buckling in median within County Rd 14

Figure 2.18 Blaine – Edge spalling of median within County Rd 14

Figure 2.19 Brooklyn Center – Median within Brooklyn Boulevard, south of TH694

Figure 2.20 Brooklyn Center – Joint isolation material being squeezed from the joints in median during periods of high temperatures

Figure 2.21 Brooklyn Center – Island and boulevards on Bass Lake Road near TH100

Figure 2.22 Brooklyn Center – Poor consolidation of boulevard along Bass Lake Road

Centerville – County Road 14 and Centerville Road/Progress Road

In 2008, two multi-colored concrete intersections were constructed on County Road 14 (Main Street) in downtown Centerville, MN. Significant joint distress began to appear in 2011, particularly in the westbound lanes. Figures 2.23 and 2.24 clearly show the early and significant joint deterioration. Owing to its severity, it was decided that these intersections would be one of the four main focus areas in this study. A number of core samples were extracted for a detailed examination and determination of the potential causes of the distress. Findings from the detailed investigation of this location will be discussed in Chapter 4.

Columbia Heights – Central Avenue and 40th Avenue NE

Colored concrete was used in crosswalks, sidewalks, and boulevards near the intersection of Central Avenue and 40th Avenue NE. See Figures 2.25 and 2.26. Construction took place in 2012. Limited joint spalling from sawing was the only distress observed.

Detroit Lakes – Washington Avenue

Colored concrete was used in an intersection and between the sidewalk and curb along Washington Avenue. The intersection was constructed in 2010 and shows no noticeable deterioration along the joints. See Figures 2.27 and 2.28. Several areas showed evidence of surface scraping, likely due to snow plow damage.

Figure 2.23 Centerville – Joint deterioration on County Road 14 at intersection with Centerville Road

Figure 2.24 Centerville – Joint deterioration on County Road 14 at intersection with Progress Road

Figure 2.25 Columbia Heights – Crosswalk in intersection of Central Avenue and 40th St NE

Figure 2.26 Columbia Heights – Sidewalk and boulevard along Central Avenue

Figure 2.27 Detroit Lakes – Intersection of Washington Avenue and Central St E

Figure 2.28 Detroit Lakes – Scraped surface, likely due to snow plow damage

Minneapolis – 46th Street Metro Transit Station on I35W

Colored concrete was used in the bus lanes running through the 46th Street Metro Transit Stationon I35W. Constructed in 2010, this project only exhibits some minor joint surface spalling near the Jersey barriers. Thermal expansion/restraint may be the cause for this cracking. See Figures 2.29 and 2.30.

Park Rapids – Main Avenue

Constructed in 2010, many different colored concretes were used in the crosswalks, parking areas, and sidewalks along Main Avenue. The concrete was stamped with a textured pattern. Noticeable damage to the joints and surface texture was noted in the central parking areas running down the center of the street. See Figure 2.31. This damage was likely caused by snow removal equipment. Multiple large cracks were observed in the sidewalks, likely due to differences in thermal expansion rates between neighboring materials of different color. See Figure 2.32.

Princeton – TH95 and N Rum River Drive Roundabout

Colored concrete was used in a truck apron of a roundabout and boulevard strips behind the curb near the TH95 roundabout. Constructed in 2010, no deterioration was noticeable at the joints in the roundabout apron, however several cracks have formed across the full width of the panels. See Figure 2.33. Figure 2.34 show that cracking at the end of the boulevard strips in the sidewalk may indicate differing thermal expansive rates between the darker and lighter colored concretes.

Roseville – County Road C and Cleveland

Colored concrete crosswalks, medians, and gutter lines were installed in 2005 along County Road C, including the intersection with Cleveland Avenue North. Two large areas of distress were noted on one crosswalk panel, however, overall joint conditions in both the crosswalks and gutter lines were observed to be good. See Figure 2.35.

Roseville – Larpenteur Avenue W from Hamline Avenue to Oxford Street N

Colored concrete crosswalks, sidewalks and gutter lines were installed in 2001 along Larpenteur Avenue West, including the intersection with Fernwood Street. At this location, moderate to severe deterioration was observed in several areas of the colored concrete crosswalks. Joint deterioration was also occurring. Figures 2.36 and 2.37 show these distresses. Some minor joint deterioration was also occurring in some of the gutter-line joints. See Figure 2.38.

Owing to its variety of distress types, it was decided that the intersection of Larpenteur Avenue West and Fernwood Street would be one of the four main focus areas in this study. A number of core samples were extracted for a detailed examination and determination of the potential causes of the distress. Findings from the detailed investigation of this location will be discussed in Chapter 4.

Figure 2.29 Minneapolis – Bus lanes through 46th Street Metro Transit Station

Figure 2.30 Minneapolis – Cracking, likely due to thermal expansion/restraint

Figure 2.31 Park Rapids – Sculpted colored concrete joint damage, likely due to snow removal equipment

Figure 2.32 Park Rapids – Crack in sidewalk, likely due to different thermal expansion/contraction rates

Figure 2.33 Princeton – Crack in apron of TH95 roundabout

Figure 2.34 Princeton – Crack at end of colored concrete boulevard strip

Figure 2.35 Roseville – Two distressed areas in crosswalk at intersection of County Road C and Cleveland Avenue N

Figure 2.36 Roseville – Distressed areas in crosswalk panels at intersection of Larpenteur Avenue W and Fernwood Street

Figure 2.37 Roseville – Distressed joints in crosswalk panels at intersection of Larpenteur Avenue W and Fernwood Street

Figure 2.38 Roseville – Minor joint distress in colored concrete gutterline along Larpenteur Avenue W

Roseville – Josephine Road between Hamline Avenue N and Lexington Avenue N

Colored concrete crosswalks were installed in 2001 in four locations along Josephine Road. A stamped brick pattern was used. Overall condition of the panels and joints was verygood. See Figures 2.39 and 2.40. Gray colored sidewalks were also installed at the intersection with Lexington Avenue. Some joint deterioration was observed in these areas. See Figure 2.41.

Roseville – County Road C2 between Hamline Avenue N and Lexington Avenue N

Colored concrete crosswalks were installed in 2012 at the intersections of County Road C2 and Dunlap Street, as well as Lexington Avenue North. See Figures 2.42 and 2.43.

Sauk Rapids – 2nd Street North at 2nd Avenue South and Benton Drive

In 2007, colored concrete crosswalks were constructed in two major intersections in Sauk Rapids. See Figure 2.44 and 2.45. Only one small hairline crack was observed. The surface appeared mottled in many areas, with a smooth texture. Most joints appeared to be in very good condition, but some snow plow damage was evident.

Shoreview and Vadnais Heights – County Highway 96 West from Lexington Avenue North to Centerville Road

Colored concrete crosswalks were installed from 1997 to 2000 at the intersections along County Highway 96 West. Significant panel and joint deterioration was observed in several intersections, including Hodgson Road, Village Center Drive, McMenemy Street, Greenhaven Drive, and Centerville Road. Figures 2.46 to 2.49 show some of the distresses observed. Due to the variety and severity of the joint distress in the intersection with Greenhaven Drive, this became the fourth focus area in this study. Several cores were taken over and near the distressed joints in the crosswalks. Results from the analysis of the core samples will be discussed in Chapter 4.

St. Paul – Phalen Blvd and Payne Avenue

Colored concrete was used in the crosswalks of the intersection of Phalen Blvd and Payne Avenue. Constructed in 2003, the concrete was stamped in a brick pattern. Overall condition was fair, with some joint distress observed, but more prevalent was the noticeable wearing of the surface of the pavement. Figures 2.50 and 2.51 show the general conditions.

St. Paul – Shepard Road at Washington Street, Old Chestnut Street, Ontario Street

Colored concrete was used in 1998 to construct three different intersections along Shepard Road in St Paul: at Washington Street, at Old Chestnut Street, and at Ontario Street. The overall condition of the crosswalks at the intersection with Washington Street was good, with only some limited joint deterioration starting to appear. See Figures 2.52 and 2.53.

The entire intersection, including sidewalks of Shepard Road and Old Chestnut Street was constructed using colored concrete. Severe joint deterioration was found in multiple locations at this site. One large crack across multiple panels was also identified. See Figures 2.54 and 2.55. The colored concrete at the intersection of Ontario Street was in good condition, with some signs of joint deterioration starting to appear. See Figures 2.56 and 2.57.

Figure 2.39 Roseville – Colored concrete crosswalk in good condition at intersection of Josephine Road and Lexington Avenue

Figure 2.40 Roseville – Colored concrete crosswalk in good condition across Josephine Road near Fernwood Street N

Figure 2.41 Roseville – Minor joint distress in colored concrete sidewalk near intersection of Josephine Road and Lexington Avenue

Figure 2.42 Roseville – New colored concrete crosswalk across County Road C2 at intersection with Dunlop Street

Figure 2.43 Roseville – New colored concrete crosswalk across County Road C2 at intersection with Lexington Avenue North

Figure 2.44 Sauk Rapids – Colored concrete crosswalks at intersection of 2nd Street North and North Benton Drive

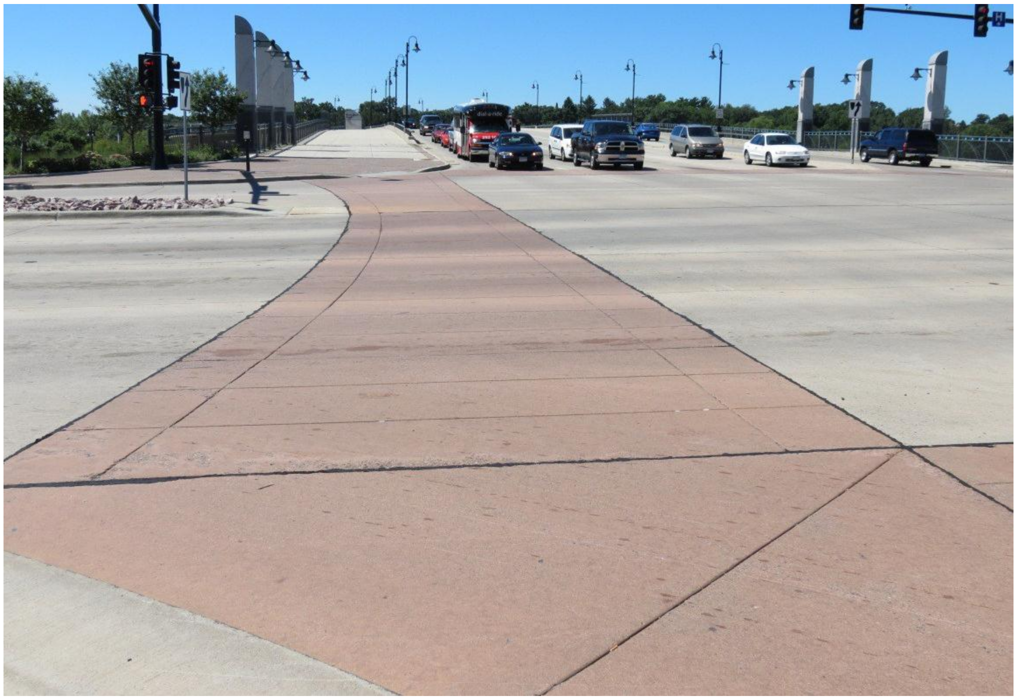


Figure 2.45 Sauk Rapids – Colored concrete crosswalks at intersection of 2nd Street North and 2nd Avenue South

Figure 2.46 Shoreview – Severe panel distress in crosswalk at intersection of County Highway 96 West and Hodgson Road

Figure 2.47 Vadnais Heights – Severe panel distress in crosswalk at intersection of County Highway 96 West and Village Center Drive

Figure 2.48 Vadnais Heights – Extensive joint distress in crosswalk at intersection of County Highway 96 West and McMenemy Street

Figure 2.49 Vadnais Heights – Extensive joint distress in crosswalk at intersection of County Highway 96 West and Greenhaven Drive

Figure 2.50 St. Paul – Joint distress in crosswalk at intersection of Phalen Boulevard and Payne Avenue

Figure 2.51 St. Paul – Noticeable wear on surface of colored concrete crosswalk at intersection of Phalen Boulevard and Payne Avenue

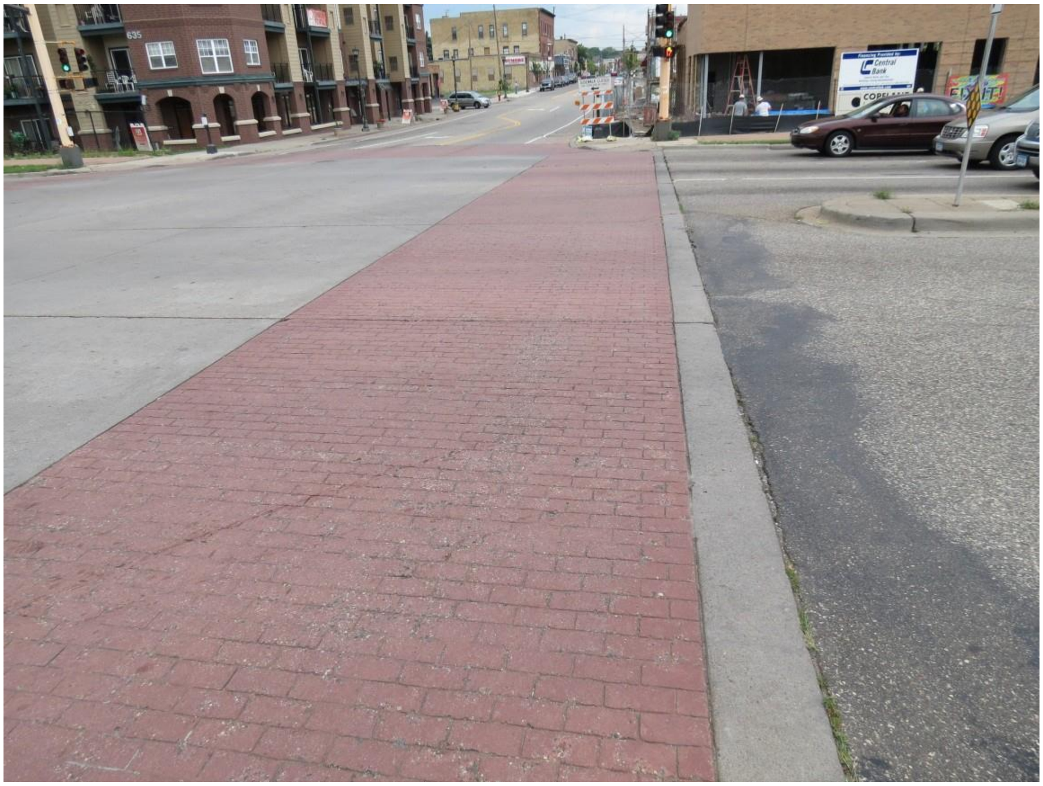


Figure 2.52 St. Paul – View of crosswalk at intersection of Shepard Road and Washington Street

Figure 2.53 St. Paul – Joint distress in crosswalk at intersection of Shepard Road and Washington Street

Figure 2.54 St. Paul – Joint distress in crosswalk at intersection of Shepard Road and Old Chestnut Street

Figure 2.55 St. Paul – Joint distress in crosswalk at intersection of Shepard Road and Old Chestnut Street

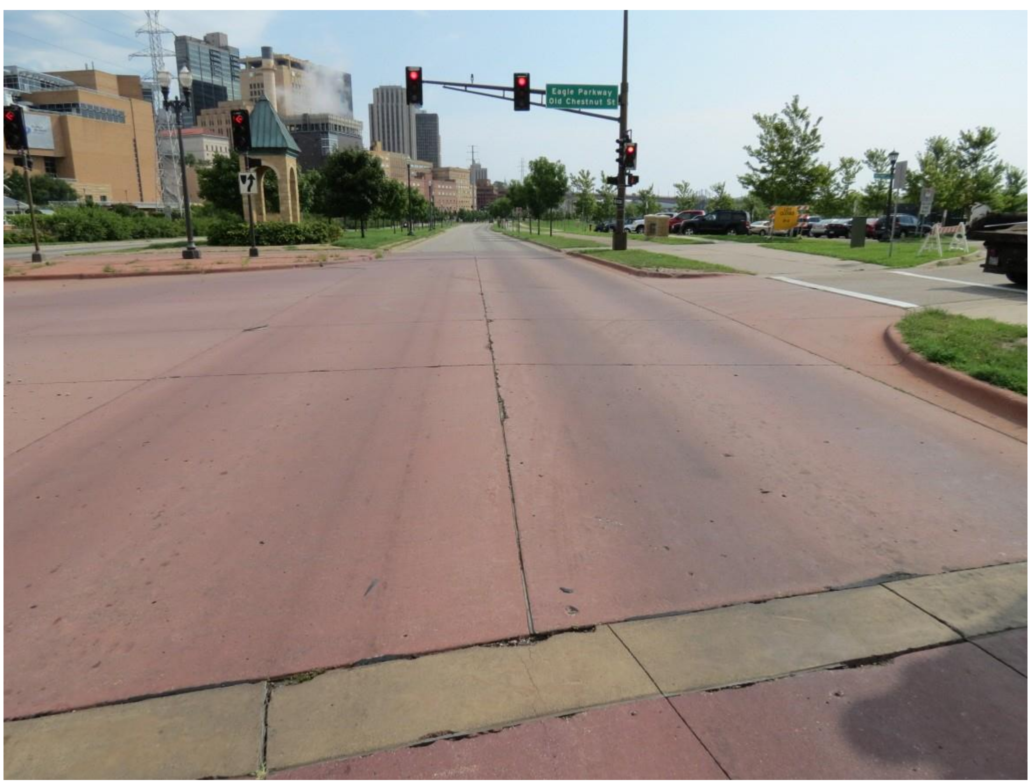


Figure 2.56 St. Paul – Minor joint distress in crosswalk at intersection of Shepard Road and Ontario Street

Figure 2.57 St. Paul – Overall view of intersection of Shepard Road and Ontario Street

St. Paul – 7th Street West and West 5th Street

Colored concrete was used across the entire intersection of 7th Street West and West 5th Street in downtown St. Paul. Constructed in 1987, it is apparent by the wide asphalt patches along most of the joints that severe joint deterioration has occurred. Figures 2.58 and 2.59 show the extent of the distress. It is important to note that the center portion of most of the panels appear to be in good condition.

Stillwater – Main Street North and Commercial Street

Colored concrete crosswalks and sidewalks were placed in 2012 at the intersection of Main Street North and Commercial Street in downtown Stillwater. Numerous cracks, extending across many panels, were identified in multiple locations. See Figures 2.60 and 2.61. Because the colored concrete is confined within borders of plain concrete, the cracking may be due to differences in their rate of thermal expansion.

Stillwater – 2nd Street North between Myrtle Street East and Commercial Street

Colored concrete was used in the sidewalks along 2nd Street North between Myrtle Street East and Commercial Street. This concrete was stamped with a brick pattern. The year of construction is unknown. In August 2012, deep and wide deterioration was observed at many joint locations. See Figure 2.62. This sidewalk was replaced with standard concrete sometime in 2013.

Figure 2.58 St. Paul – Widespread joint distress at intersection of 7th Street West and West 5th Street

Figure 2.59 St. Paul – Widespread joint distress at intersection of 7th Street West and West 5th Street

Figure 2.60 Stillwater – Panel cracking in new colored concrete crosswalk at intersection of Main Street North and Commercial Street

Figure 2.61 Stillwater – Panel cracking in new colored concrete crosswalk at intersection of Main Street North and Commercial Street

Figure 2.62 Stillwater – Significant joint distress in colored concrete sidewalks along 2nd Street North between Myrtle Street East and Commercial Street

Summary

This section depicted and described the performance of a wide representation of projects throughout Minnesota that included colored concrete in their construction. Many projects were recently constructed, and therefore all that could be reported on was some potential construction errors. Many projects exhibited panel cracking, either a result of possible thermal expansion restraint, or potentially some expansive materials related issues. Some projects revealed cosmetic damage, likely from snow removal equipment. A number of the older projects, as well as one newer one (Centerville), demonstrated significant joint distress. A frequent observation was that much of the colored concrete had a smooth surface texture, perhaps not the most ideal for crosswalks and sidewalks in a cold climate.

Chapter 4 will describe in more detail investigations into four of the projects highlighted above that demonstrated early or unique distresses or deterioration.

CHAPTER 3: OBSERVED CONSTRUCTION PRACTICES

Constructing Colored Concrete in Minnesota

A major component of this investigation was determining the potential causes for the early and significant distresses observed in several colored concrete projects in Minnesota. Typically, distress in concrete can be linked to two main categories of causes, those related to construction practices and/or errors, and those related to the materials and processes used to make the concrete. Of course, sometimes problems arise from a combination of those two causes.

Due to the small area and quantities of materials used in constructing a colored concrete crosswalk, it is most often placed within concrete forms or the vertical-cut edges of the main roadway material. As such, most colored concrete is placed and formed without mechanical equipment. Common leveling and finishing tools include wood 2x4 boards, concrete finishing floats, and steel trowels. Though not common, a broom is sometimes used to create the final surface texture.

To better document the range of typical placement practices for colored concrete in Minnesota, three new construction projects were visited during the summer of 2012. This section describes the equipment, processes and materials used in their construction. The results from limited sampling and testing of the colored concrete from these projects are also discussed.

Projects Visited

Forest Lake – West Broadway Avenue and 4th Street S.W. (Round 1)

The first project visit occurred on the morning of July 12, 2012. A multi-colored concrete crosswalk was being constructed across West Broadway Avenue near the intersection with 4th Street S.W. The “forms” for the colored concrete were the edges of the standard (non-colored) concrete pavement recently placed on West Broadway Avenue. To provide load transfer, epoxy coated steel dowels were inserted into holes drilled into the adjacent concrete pavement. Epoxy coated rebar was installed to provide mid-panel reinforcement. Plastic sheeting was placed over the dowels (they were allowed to poke through) and face of the adjacent slab, and draped over the non-colored concrete pavement, in order to protect it against becoming stained.

A ready-mix concrete truck arrived at the site at approximately 8:30 AM (the batch ticket from the plant was marked 7:58 AM). At this point, the research team was informed that the concrete was a “high-early” mix. Since there was not a substantial amount of extra material ordered than what was required to complete the crosswalk slab, the contractor asked the research team to wait before collecting samples of the colored concrete.

The crosswalk was poured initially with a single brown colored concrete. The concrete was leveled with a 2x4 piece of lumber, without consolidation (no vibration), and extensively finished with multiple passes of steel floats and trowels. During this process, the surface was often sprayed with a water-based compound (Confilm) to ease finishing.

Once most of the colored concrete had been placed into the crosswalk area, the research team collected what was left in the ready-mix truck and transported the material in a large plastic tub to a nearby truck station (3 minutes away) for making test samples. At 9:48 AM, plastic concrete tests began. Slump was measured at 0.50 inch, air content was measured at 5.0%, and the concrete temperature was measured at 82 degrees Fahrenheit. With much difficulty, standard flexural testing beams and compressive testing cylinders were made for strength, petrographic analysis, and other laboratory testing. The concrete began to set before all specimens could be completed. At this point, the research team returned to the site to observe the final steps of construction.

The final design for this crosswalk consisted of bands of darker color along its edges. This was accomplished by temporarily placing some thin protection boards along the lines of the different colors, and then shaking on a darker powdered color hardener. See the completed darker band in Figure 3.1.

Figure 3.1 Workers holding thin board to apply Lithochrome Colorwax

Next, the surface was thickly coated with Lithochrome Colorwax in the two different colors. A darker color wax was used on the outside two sections, while a lighter color wax was used on the middle section, which appeared to dramatically change the color of the pavement surface. The contractor noted that the Colorwax was also used as the curing method. Figure 3.1 shows the application of the Colorwax to the new colored concrete crosswalk. At approximately 2 PM, the contractor began sawing the transverse joints. See Figure 3.2.

Figure 3.2 Transverse joints being sawed into colored concrete crosswalk

When the concrete samples made by the research team were brought back to the MnDOT Maplewood Laboratory and inspected, it was clear that they had not received proper consolidation, as the concrete had already begun to set while they were being made. Consequently, no hardened concrete tests were performed on these specimens. It was determined that a second visit to this project would be beneficial to get good specimens for testing hardened concrete properties.

Forest Lake – West Broadway Avenue and 3rd Street S.W. (Round 2)

Several weeks after the first visit to the West Broadway Avenue project in Forest Lake, another opportunity to observe construction methods and obtain concrete samples came about.

On July 26, 2012, the contractor was pouring another colored concrete crosswalk, this time across 3rd Street S.W., near its intersection with West Broadway Avenue. In this particular location, the perimeter of the crosswalk consisted of concrete curbs and mainline concrete pavement. Similar to the crosswalk described previously, epoxy-coated reinforcement was used within the panels. A water main gate valve casing was also installed. Epoxy coated steel dowels were drilled and installed into the existing mainline slabs. Plastic sheeting was placed over the dowels (they were allowed to poke through) and face of the adjacent slab, and then draped over the existing curbs and mainline slabs to protect against staining. Figures 3.3 and 3.4 show the crosswalk area prior to and during the placement of the colored concrete.

The colored concrete arrived in a ready-mix truck at approximately 2:20 P.M. The construction inspector said the concrete was a “high-early” mix.It was tested for slump and air content immediately. Air content was measured at 6.6%, and slump was approximately 3 inches.

The research team filled multiple large tubs of concrete to make strength and durability specimens for this study. The concrete was transported to a nearby truck station (3 minutes away) for plastic concrete testing and casting of the hardened test specimens.

Figure 3.3 Crosswalk area prepared for placement of colored concrete

Figure 3.4 Placement of colored concrete in crosswalk area

The air content was tested again and measured at 6.9%. The slump remained at 3 inches. Beamsamples were cast for flexural strength testing, cylinders were made for compressive strength and petrographic analysis, and prisms were made for freeze-thaw durability testing.

A member of the research team remained at the construction site to observe that the colored concrete was again placed into the crosswalk without vibration, and leveled with a 2x4 piece of lumber. Within a short amount of time, longitudinal joints were tooled into the surface. The surface and edge of the slab were finished multiple times with steel trowels and floats.

Similar to the crosswalk at West Broadway Avenue and 4th Street S.W., an additional band of darker color was added to the outer edges of the crosswalk by first spraying the surface with Con-film, and then hand sprinkling colored powder on the surface. This was then worked into the surface with a hand trowel and float. Figures 3.5 through 3.7 show the steps in the construction process that were observed.

The inspector did not think curing compound would be used, however as with the previously constructed crosswalk, the presence of Colorwax on the site indicated it was most likely used for curing. The research team had left the site before it was applied. The installation of a surface texture was also not observed.

Figure 3.5 Finishing colored concrete surface (step 2 after leveling)

Figure 3.6 Hand finishing edges of colored concrete crosswalk

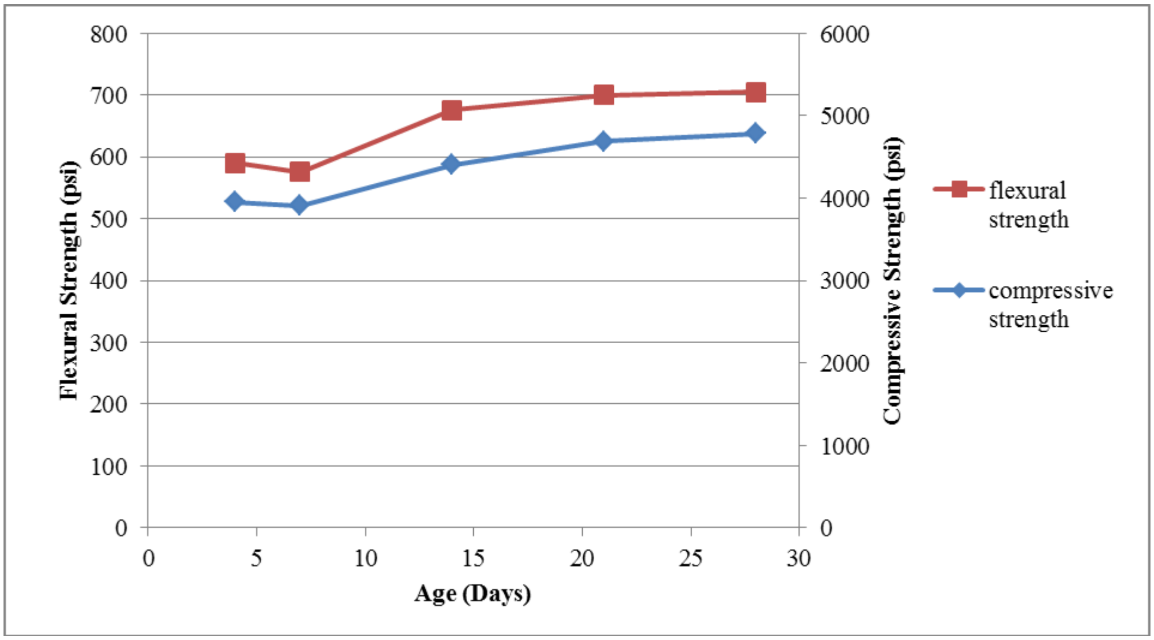
Figure 3.7 Sprinkling darker colored powdered pigment on outer portions of crosswalk

The following materials were noted to be on site during construction of the crosswalk:

- Lithochrome Color Hardener
- Lithochrome color wax Parts A and B
- Confilm

The following day, the samples were transported back to the MnDOT Maplewood Lab, where the molds were stripped. Unlike the first round of sampling at Forest Lake, these samples clearly received proper consolidation and were made before the concrete had time to set. The results of flexural and compressive strength tests are shown in Figure 3.8.

Figure 3.8 Results from flexural and compressive strength testing of colored concrete used in Forest Lake crosswalk placed on July 26, 2012



Blaine – County Hwy 14, west of University Avenue N.W.

On August 15, 2012, the research team observed the construction of a colored concrete median along County Highway 14, west of the intersection with University Avenue N.W.

The colored concrete arrived in a ready-mix truck at approximately 12:30 P.M. The concrete was colored with a red integral color that the contractor believed was produced with powdered pigment. The contractor began pouring the concrete immediately, while inspectors tested for slump and air.

The research team collected a sample of the colored concrete from the first truck and transported the material to a nearby open field to make specimens. Plastic concrete air content was measured at 4.1%, and slump was measured at 2 ¼ inches. Beam samples for flexural strength tests, cylinder samples for compressive strength and petrographic analysis, and prism samples for freeze-thaw durability were made. Near the end of this process, the contractor informed us that the first load had been rejected because of low air content. We completed making the test samples and returned to the project to collect samples from the next load. When the truckload arrived, 20 oz. of air entraining agent was added at the site to increase air content. The inspector measured 3.75 inches of slump and 6.2% air content in the load which was sampled.

Before collecting samples from this truckload, the research team stayed to observe construction of the median. The concrete was compacted using a type of vibrating screed which rested on the curb surface. See Figure 3.9. The edges were finished with steel trowels and the surface was leveled with large floats. Transverse joints were then formed into the wet concrete. The surface was finished with a broom texture. The amount of finishing used in this project seemed to be significantly less than the previous crosswalk projects which were formed without a screed. No additional color was applied to the surface, and no curing method was observed while the research team was on site.

Figure 3.9 Colored concrete median construction using vibrating screed across in-place curbs

The research team again filled multiple large tubs of concrete from the second load (initially 3.75 in slump, 6.2% air) to make more strength and durability specimens. This concrete was transported to a nearby field for sampling. At this time, the slump was 1.75 inches and air content was 5.9%. The concrete temperature was measured to be 80 degrees Fahrenheit.

Figures 3.10 and 3.11 show plots of the results from compressive and flexural strength tests on samples collected from of the two different mixes: Mix 1 (load 1), and Mix 2 (load 2). It appears that the concrete in the first load of concrete, with lower air content, had higher compressive strength than that in the second. However, both loads have more than adequate flexural strength for the type of project it was used in (median).

Figure 3.10 Results from compressive strength testing of colored concrete used in Blaine median placed on August 15, 2012

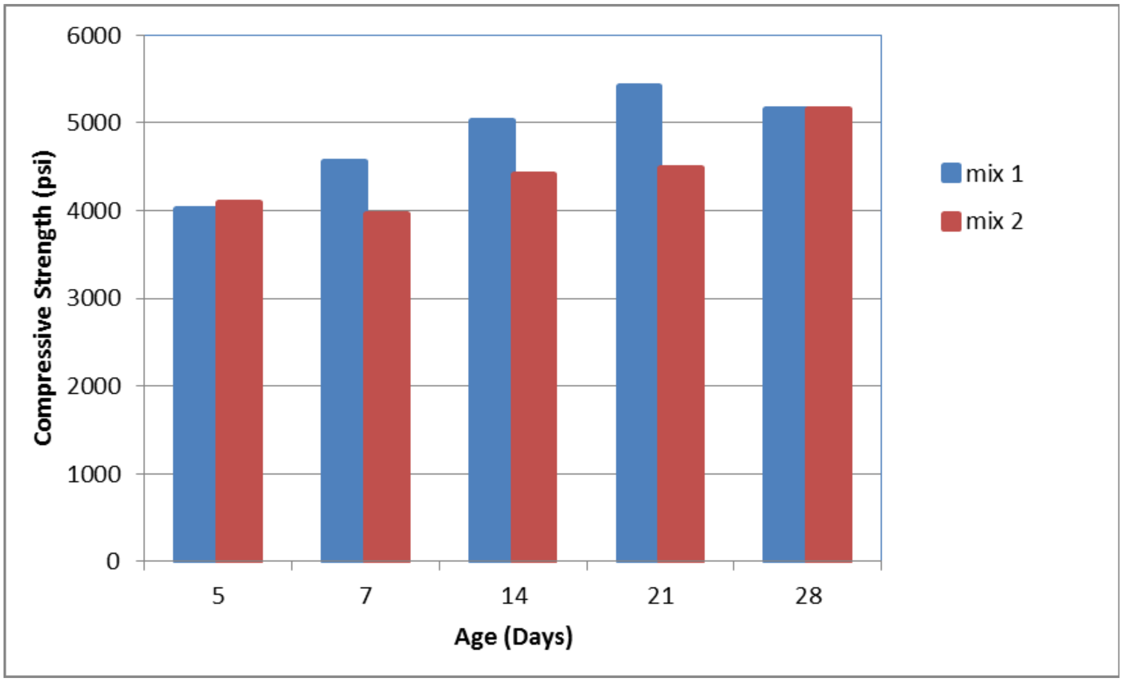
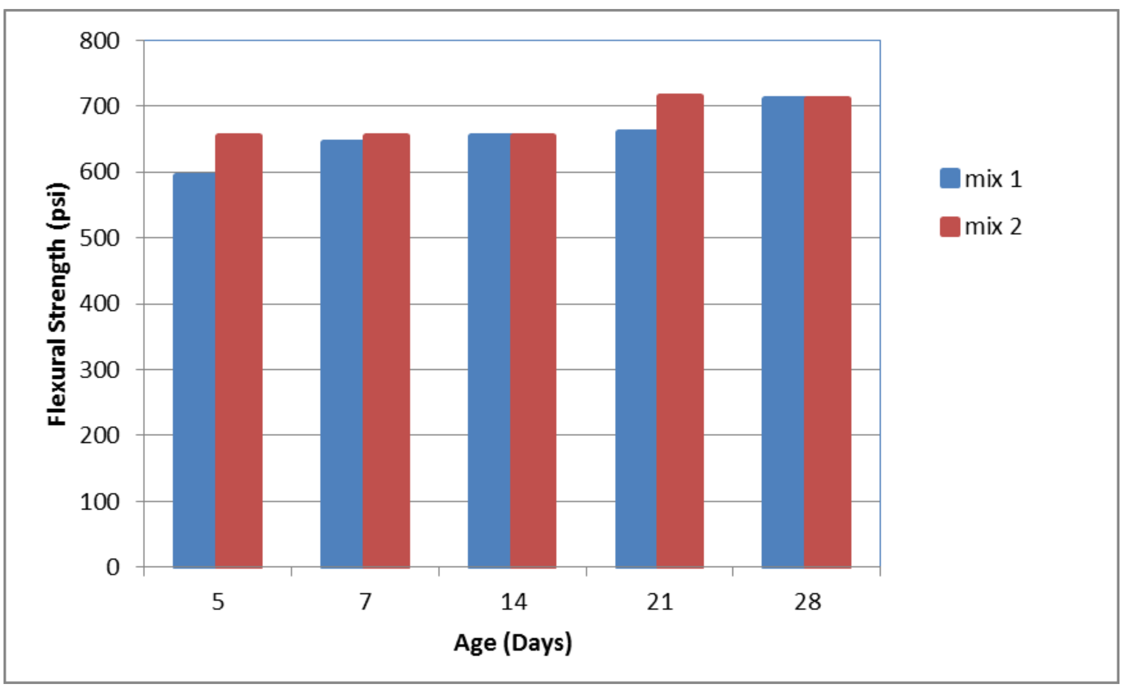


Figure 3.11 Results from flexural strength testing of colored concrete used in Blaine median placed on August 15, 2012



Brainerd – West College Drive near 4th Street S.W.

On the same day as the Blaine median construction (August 15, 2012), another member of the research team was observing the construction of a colored concrete sidewalk and curb edging onWest College Drive in Brainerd.

The colored concrete arrived in a ready-mix truck at approximately 9:30 A.M. A project inspector quickly tested a sample of the mix for slump and air content. Air content was 8.0% and slump was 3.75 inches. No research samples were collected.

The concrete was placed without vibration and leveled with a 2x4 piece of lumber. The surface of the slab was finished multiple times with steel trowels and floats. The final finish was a broom texture. Within a short amount of time, transverse joints were formed into the surface. I was informed by the inspector that the joints would be sawed deeper at a later time.

The inspector stated that curing compound would be used, however none was present at the time of the visit. He also stated that previously constructed colored concrete on a roundabout on this project had experienced random cracking due to late joint sawing by the contractor.

Figures 3.12 and 3.13 show placement of the colored PCC on this project, as well as previously place colored on a roundabout and sidewalk in figures 3.14 and 3.15.

Figure 3.12 Placement of colored concrete sidewalk in Brainerd

Figure 3.13 Applying broom texture to colored concrete sidewalk in Brainerd

Figure 3.14 Previously placed colored concrete roundabout apron on West College Drive and 4th Street S.W.

Figure 3.15 Previously placed colored concrete sidewalk and edging across median withinWest College Drive in Brainerd

Summary

To better understand some potential causes of early and unique distresses occurring in colored concrete in Minnesota, several construction sites were visited during 2012. While three projects were highlighted in this report, research team members also made short visits to other sites where colored concrete was being placed.

Based on limited testing of samples taken from the projects that were visited, it does not appear that the results of standard acceptance tests like air content and slump differ much from standard concrete. Strength testing of hardened specimens of colored concrete also did not reveal great differences from standard concrete. This does not seem too surprising, as it appears the observed distresses in colored concrete are more a function of concrete durability or thermal restraint than strength related issues.

The overall methods of placing the colored concrete that were observed were standard for non-mechanized construction. Some placement practices of concern included:

1. Lack of concrete consolidation. Most of the time a 2x4 piece of lumber was used as the leveling and consolidating tool. Of the three projects observed, only one project was observed using a vibrating screed.
2. Excessive surface leveling and finishing with steel trowels. With excessive finishing there is greater potential to create a thin layer of cement paste on the surface, which can become susceptible to scaling or freeze-thaw durability problems due to "driving" the entrained air out of the concrete.
3. Less than desirable curing procedures. In fact, at one location, the contractor stated that the City did not require curing of colored concrete. Since standard white pigmented curing compounds cannot be used, alternate curing methods must be relied upon. While the acrylic and wax-based sealers provided by the manufacture may be effective in reducing moisture loss during curing, they are unlikely to provide the heat protection and reflectance offered by common methods like white pigment curing compounds.

One observation was that the majority of the colored concrete mixes were designed as high-early strength mixes. How the mixes were designed to achieve the accelerated strength gain is one area that will have to be considered when assessing the potential causes of the early deterioration that have occurred on older projects.

CHAPTER 4: ANALYSIS OF CORE SAMPLES

Forensic Investigation of Select Projects

Of the many colored concrete projects visited during the summer and fall of 2012, four projects stood out as exhibiting significant early or unusual distresses. These projects were selected for more in-depth forensic examinations to determine the potential causes of those distresses.

The forensic investigation involved three steps. The first step was to take photographs documenting both the overall condition of each project, as well as any specific areas showing early or unusual distresses. Next, a total of seventeen core samples were extracted from both good and deteriorating areas of the selected projects. Eleven of those cores were then subjected to a petrographic analysis. Finally, two core samples were examined and analyzed further using scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDX).

This chapter describes the observed distresses, identifies the locations within each project where core samples were extracted, and presents the results of the forensic analysis.

Analysis of Select Core Samples

Although many core samples were taken from the four sites selected for the forensic analysis, the budget and time constraints only allowed for a select number of them to be examined in much greater detail. The detailed laboratory work for this project was performed by a team from American Engineering Testing, Inc. and Michigan Technological University.

The petrographic analysis was done according to ASTM standard C856, "Petrographic Analysis of Hardened Concrete." This standard includes ASTM standard C457 (hardened air content) testing. The following characteristics and properties were to be determined for each core sample:

- Distribution of coarse and fine aggregates and cement paste, and any anomalies.
- Effects of finishing and curing on the top/outer surfaces of the concrete.
- Depths of carbonation from finished or formed surfaces.
- Descriptions of cracks and microcracks, including their locations, depths, and patterns.
- Parameters of air-void systems (air content, specific surface, void-spacing factor) using the linear traverse method of ASTM C457, "Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete".
- The presence of any in-filling of air voids spaces by secondary crystalline materials such as ettringite.
- Chemically unsound aggregate particles; including alkali-silica (ASR) and alkali-carbonate reactions (ACR).

- Physically unsound aggregates; may include freeze-thaw or wet-dry cycling.
- Chemical attack due to internal (Delayed Ettringite Formation or DEF) or external sulfate attack, or other chemical attack.
- Microstructure of the paste.
- Identification of fly ash or other pozzolans and other supplementary cementitious materials such as slag cement, and their relative proportions.
- Degree of cement hydration.
- Estimation of water-to-cementitious materials ratio (w/cm).

The intention of this analysis was to attempt to determine if the early distress observed was a result of poor workmanship and placement of the colored concrete, or if a decrease in durability may have been caused by the components within the colored concrete. Appendix A contains the complete results of the petrographic analyses.

The two samples further subjected to the SEM and EDX techniques were analyzed to determine the components of the concrete at the microscopic level, as well as the chemical elements within the concrete mix. More details on these examination techniques can be found in Appendix B. Appendix B also contains the complete results submitted by the laboratory team.

The following sections will summarize and highlight the important and relevant findings from the laboratory analysis of core samples taken from the four selected projects exhibiting early or unusual distresses.

Centerville: County Hwy 14 & Progress Road

Constructed in 2008, the intersection of County Highway 14 and Progress Road in the city of Centerville, MN, consists of five different colors of colored concrete. Noticeable distress began appearing along many of the contraction joints as early as 2011. A similarly constructed colored concrete intersection one block to the west is also experiencing similar joint deterioration (see Figures 2.23 and 2.24). Figures 4.1 and 4.2 show the typical joint deterioration observed at the intersection with Progress Road.

In 2011, it appeared that the westbound traffic lane of the intersection exhibited noticeably more joint distress than the eastbound lane. By late 2013, it was apparent that the eastbound lane was destined for similar joint distresses.

In order to conduct a more detailed forensic investigation, six core samples were taken on June 11, 2012, from both distressed and sound joints, as well as several mid-panel locations. Figure 4.3 shows the coring locations. Three of the cores were examined more closely through a petrographic analysis. Note that Figure 4.4 shows standing water in the joints during coring operations. This is an indication of either very tight joints, or a very slowly draining base.

It was discovered through the core samples that keyed joints were utilized between panels of two different colors. See Figure 4.5. Both the core samples, and an ultrasonic concrete pavement thickness measuring device (MIRA), revealed that the average pavement thickness was approximately 8 inches.

The next section describes the core locations and discusses the results from the detailed analysis of select samples.

Core 14A

Core sample 14A was taken near the end of visual surface distress, in a longitudinal joint in the westbound lane of County Highway 14. The coring location is shown in Figure 4.6. The core sample showed severe deterioration within the joint near the pavement surface, however the lower portion of the joint appears to be sound, with a very tight joint crack. See Figure 4.7.

Results from the petrographic analysis of Core sample 14A can be summarized as follows:

- The paste portion of the mix was considered to be of "moderate hardness," with the paste- to-aggregate bond strength rated as “fair to poor.”
- Surface carbonation was considered to be negligible in this core sample.
- The total air content was measured to be 5.3%, with 4.0% entrained air and 1.3% entrapped air. The spacing factor was 0.007 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- Closer examination of the crack in the lower portion of the joint revealed vertical micro and macro-cracking extending from the top to the bottom of the core sample. These cracks are highlighted in Figure 4.8. The cracks were prevalent in the paste, traversing around aggregate particles.
- A close-up examination of the air voids near the joint revealed that a majority of them were completely filled with secondary ettringite crystals, thus rendering the voids unable to aid in freeze-thaw resistance of the paste. Figure 4.9 shows the filled voids.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.44 and 0.50. This exceeds the general recommended maximum of 0.45 for freeze-thaw resistant concrete [PCA Manual]. Higher water-to-cementitious ratio mixes correlate to higher porosity of the paste, which tends to allow increased amounts of moisture and deicing chemicals into the concrete.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.1 Typical joint deterioration occurring in colored concrete intersection of County Highway 14 (Main Street) and Progress Road in Centerville, MN

Figure 4.2 Typical joint deterioration occurring in colored concrete intersection of CountyHighway 14 (Main Street) and Progress Road in Centerville, MN

Figure 4.3 Overhead view of County Highway 14 and Progress Road intersection indicating locations where core samples were extracted

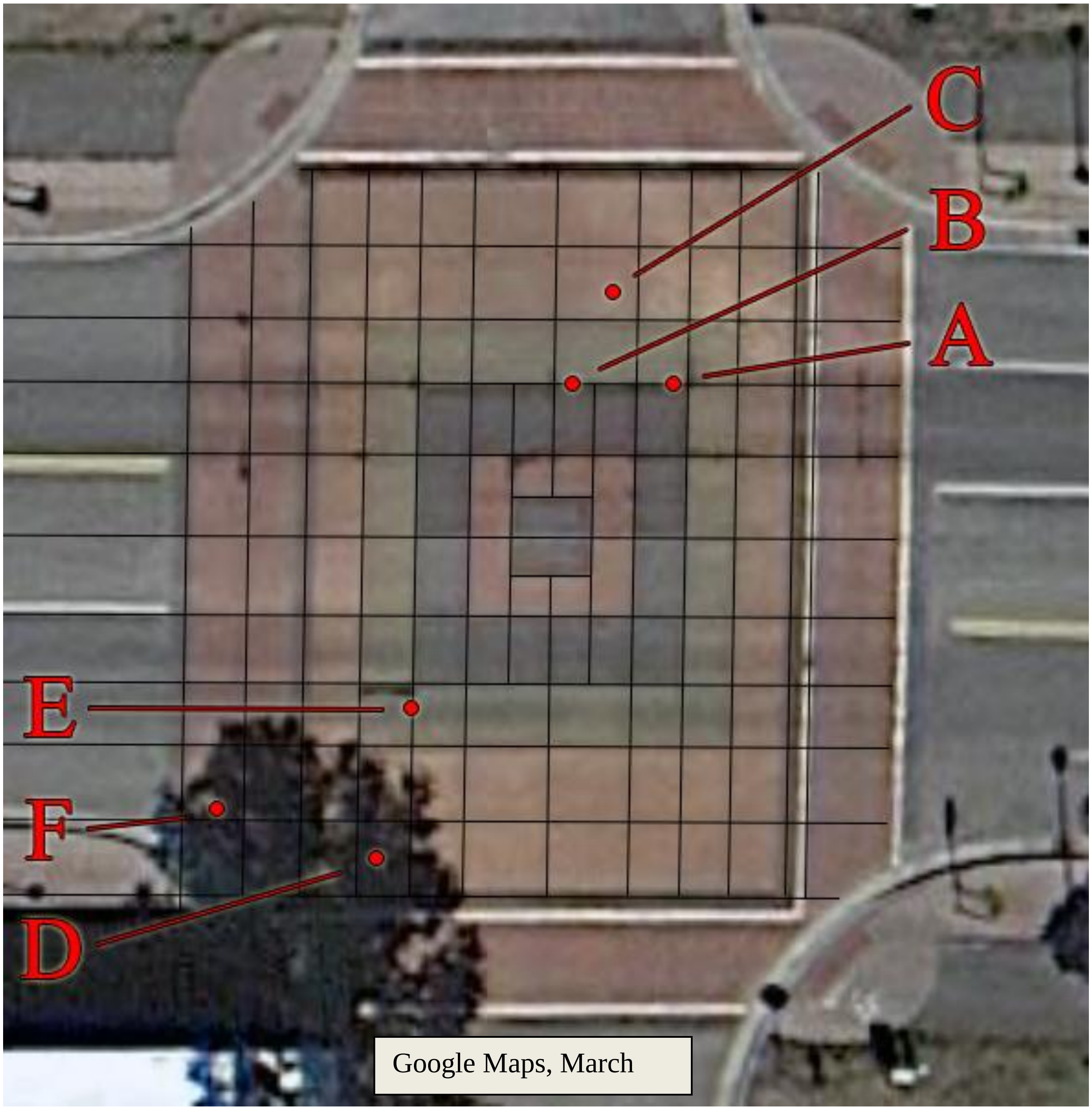


Figure 4.4 Standing water in joints from coring operation

Figure 4.5 Keyed longitudinal joint between two different color sections

Figure 4.6 Centerville - Core location 14A

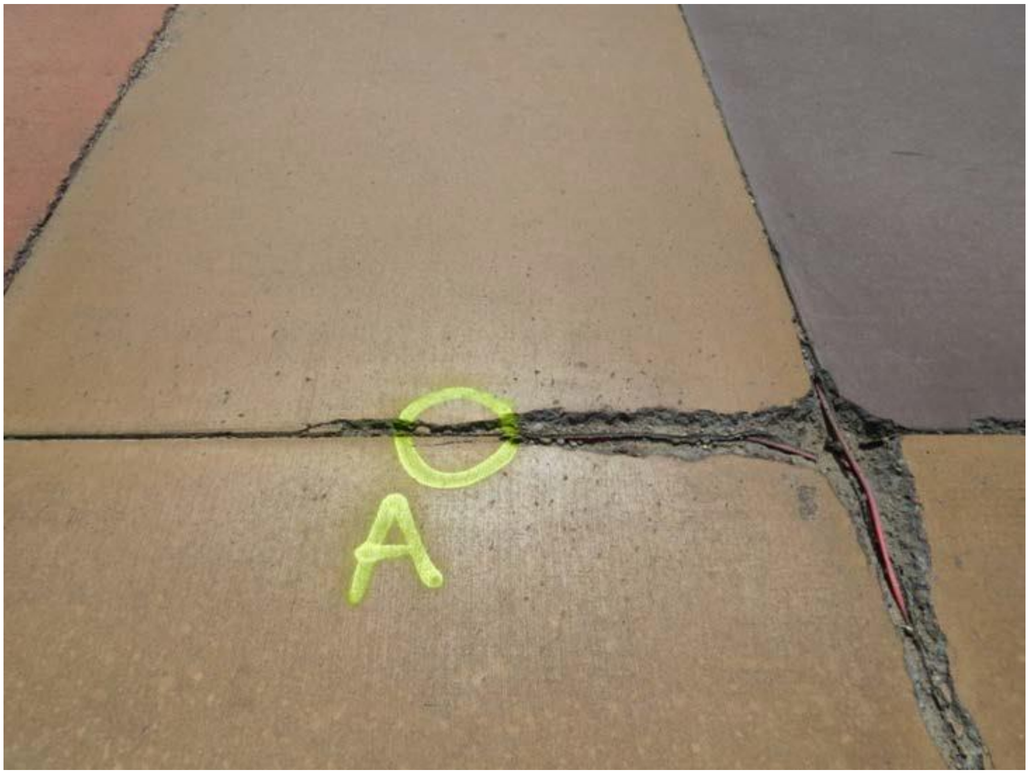
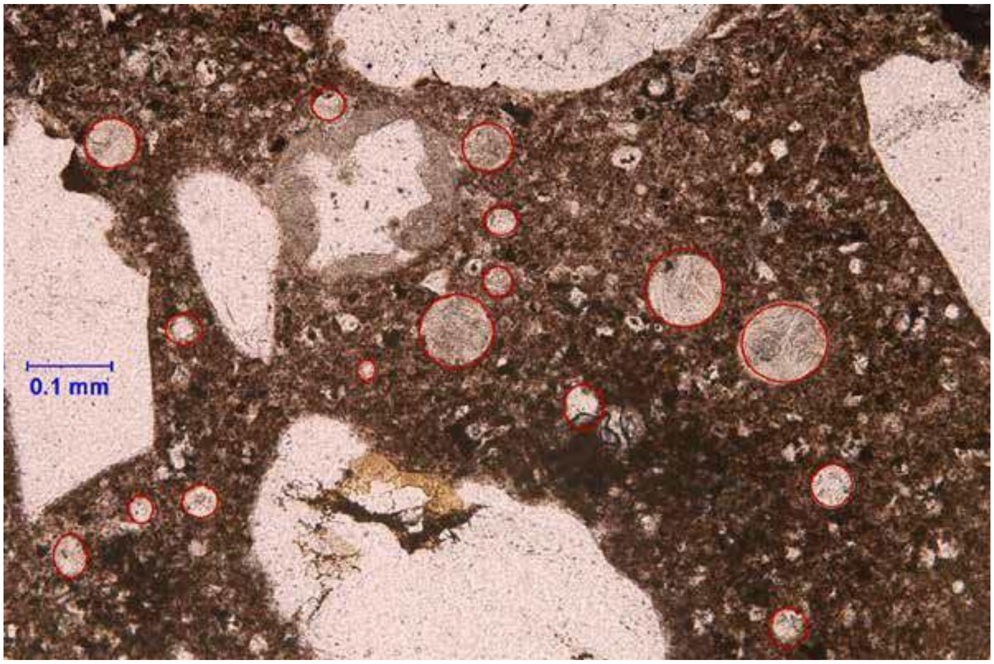


Figure 4.7 Centerville - Core sample 14A

Figure 4.8 Centerville - Vertical cracking in Core 14A, highlighted by red ink

Figure 4.9 Centerville – Voids in Core 14A filled with secondary ettringite crystals (circled in red)



Core 14B

Core sample 14B was taken several panels away, in the same longitudinal joint as Core sample A. This time the core sample straddled panels with different colors: dark red and tan. Figure 4.10 shows the location where the core sample was taken in June 2012. Figure 4.11 shows the same location in May 2013.

Core 14B was not subject to a petrographic analysis, but the condition of the core can be summarized as follows:

- The average measured core length was 8 inches.
- On the surface, the rounded edge on each side of the joint, suggests the joint was initial tooled in. The surface had very little texture.
- Examination of the core shows that the joint deterioration appears to be quite extensive in the region above the saw cut, and predominantly on the side with darker concrete. See Figures 4.5 and 4.12. It appears that a crack, located parallel and approximately 0.75 inches from the joint face, was caused by extensive deterioration immediately below the region. This is shown in Figure 4.13.
- The lower portion of the joint exhibits some tight vertical cracks on the side with the darker colored concrete. See Figure 4.14.
- The good condition of the joint near the keyway, suggests that the keyway is likely limiting the amount of water and deicing chemicals reaching the mid and lower portions

of the joint.

- Despite the joint sealant material continuing to be firmly attached to one side of the joint, the deterioration has rendered the other side to be ineffective. The crack parallel to the joint is likely allowing an increased amount of moisture into the joint, thus accelerating the deterioration.

Figure 4.10 Centerville - Core location 14B, June 2012

Figure 4.11 Centerville - Core location 14B, May 2013, showing progression of joint distress

Figure 4.12 Centerville - Core 14B showing joint deterioration predominantly on side with darker concrete. Note that a parallel crack formed above the lower deterioration.

Figure 4.13 Centerville- Top of Core 14B, showing parallel crack that formed above the region of deterioration.

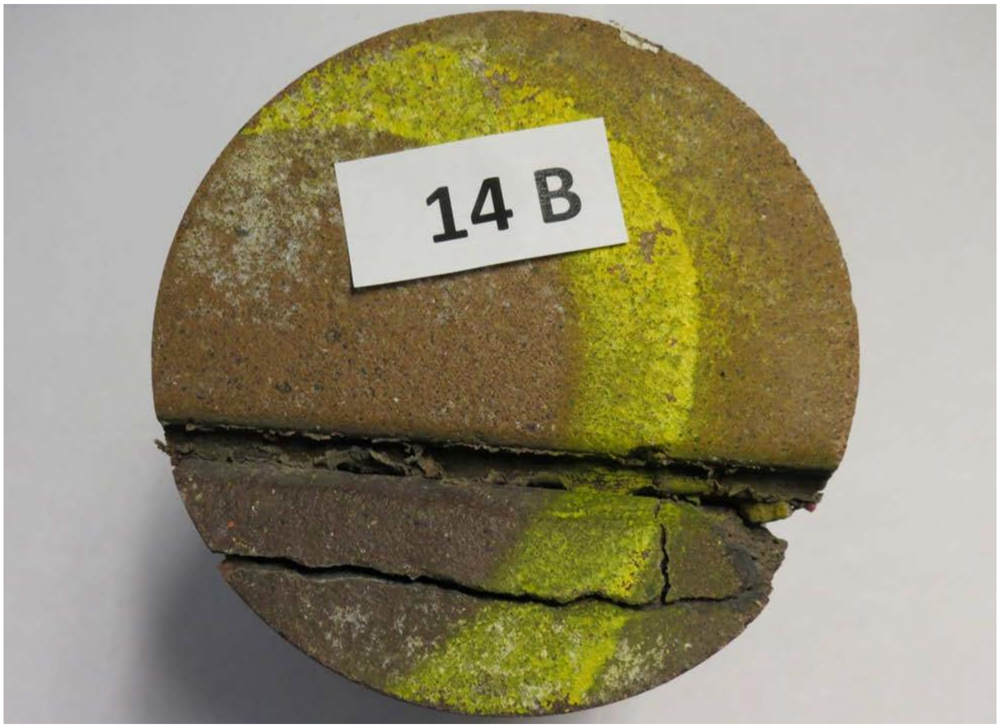
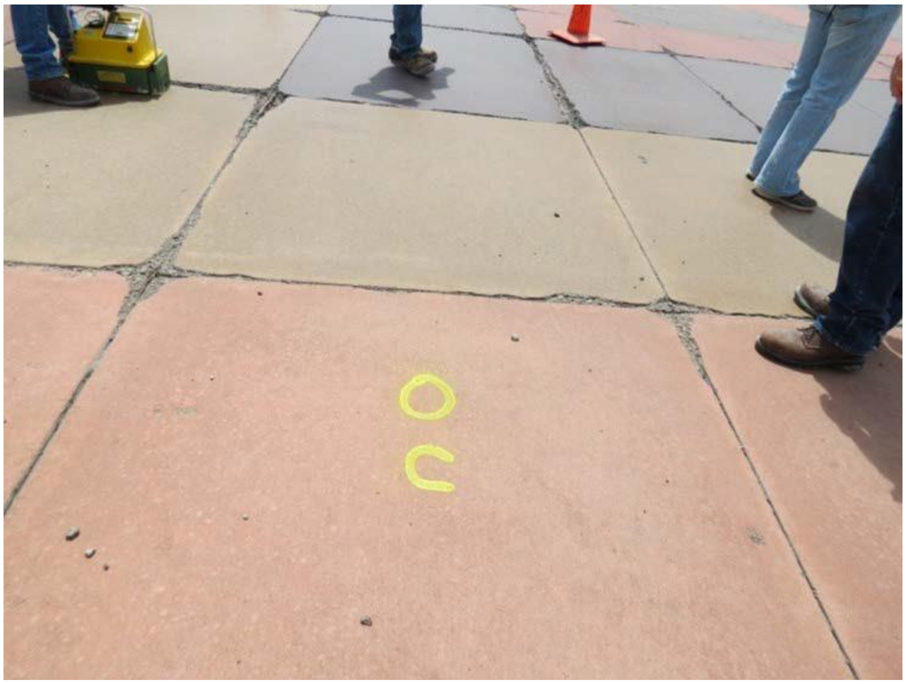


Figure 4.14 Centerville - Core 14B showing vertical cracks in darker colored side of joint near bottom of pavement

Core 14C

Core sample 14C was taken in the middle of a panel in the westbound travel lane of County Highway 14. Figure 4.15 shows the location where the core sample was taken. As with the surface, the lower portion of the core appeared to be in very good condition. Figure 4.16 shows the condition of the pavement throughout its depth.

Figure 4.15 Centerville - Core location 14C



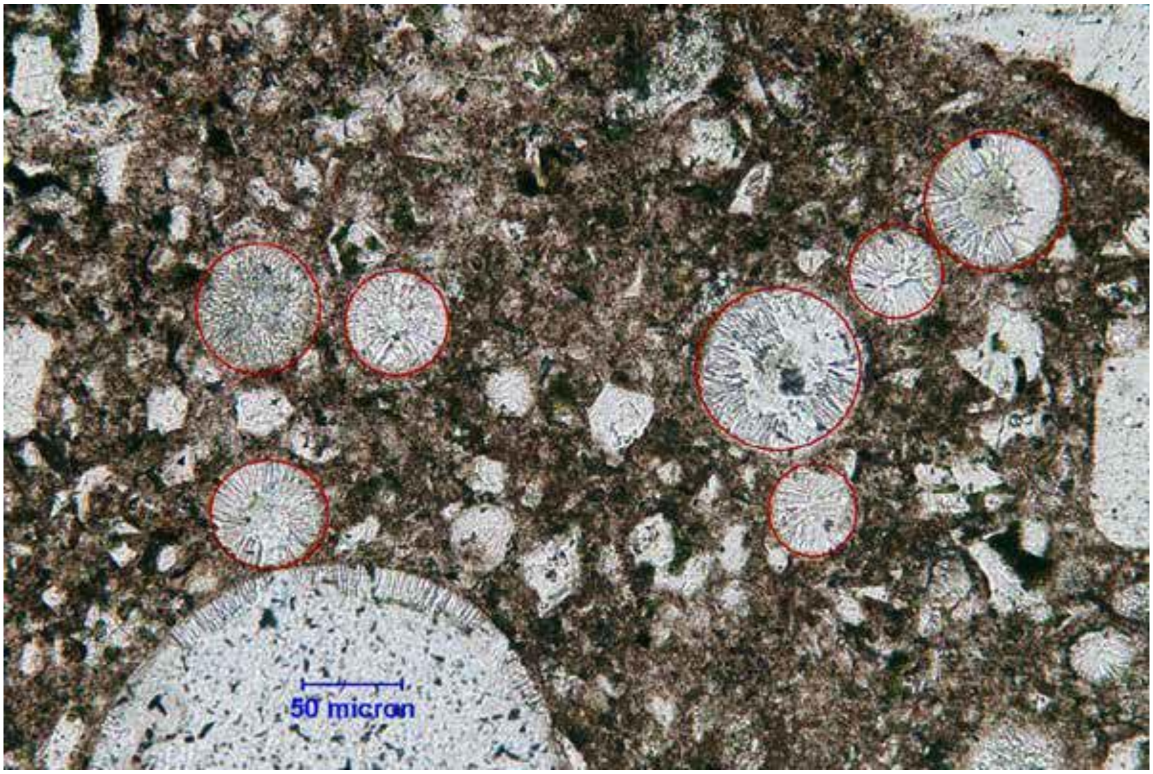
Results from the petrographic analysis of Core sample 14C can be summarized as follows:

- The paste portion of the mix was considered to be of "moderate hardness," with the paste- to-aggregate bond strength rated as "fair to poor."
- Surface carbonation was considered to be negligible in this core sample.
- The total air content was measured to be 6.1%, with 5.1% entrained air and 1.0% entrapped air. The spacing factor was 0.003 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- Closer examination of the surface revealed several fine, sub-vertical, drying shrinkage microcracks that proceed to a maximum depth of 15mm.
- A close-up examination of the smallest air voids revealed that they were partially to completely filled with secondary ettringite crystals, thus reducing the capacity of freeze-thaw resistance of the paste. Figure 4.17 shows the filled voids.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.44 and 0.49. This exceeds the general recommended maximum of 0.45 for freeze-thaw resistant concrete [10]. Higher water-to-cementitious ratio mixes correlate

- to higher porosity of the paste, which then tends to allow increased amounts of moisture and deicing chemicals into the concrete matrix.
- Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.16 Centerville - Core 14C showing good condition throughout depth

Figure 4.17 Centerville – Voids in Core 14C mostly filled with secondary ettringite crystals (circled in red)



Core 14D

Core sample 14D was taken adjacent to a transverse joint outside of the main travel portion of the eastbound lane of County Highway 14. Figure 4.18 shows the location where the core sample was taken.

Core 14D was not subject to a petrographic analysis, but the condition of the core can be summarized as follows:

- The average measured core length was 8.25 inches.
- Examination of the core shows that its overall condition was very good. See Figure 4.19.
- Consolidation of the mix and distribution of the visible air voids appeared to be adequate. Without further analysis, comments on the internal condition of the core are not justified.
- The surface appeared to have a lightly broomed texture.

Figure 4.18 Centerville - Core location 14D

Figure 4.19 Centerville - Core 14D showing good condition throughout depth

Core 14E

Core sample 14E was taken near the end of visual surface distress in a transverse joint in the eastbound travel lane of County Highway 14. Figure 4.20 shows the location where the core sample was taken. Figure 4.21 shows that, similar to core sample 14A, severe deterioration is occurring within the joint near the pavement surface, however the lower portion of the joint appears to be sound, with a very tight joint crack.

Figure 4.20 Centerville - Core location 14E

Results from the petrographic analysis of Core sample 14E can be summarized as follows:

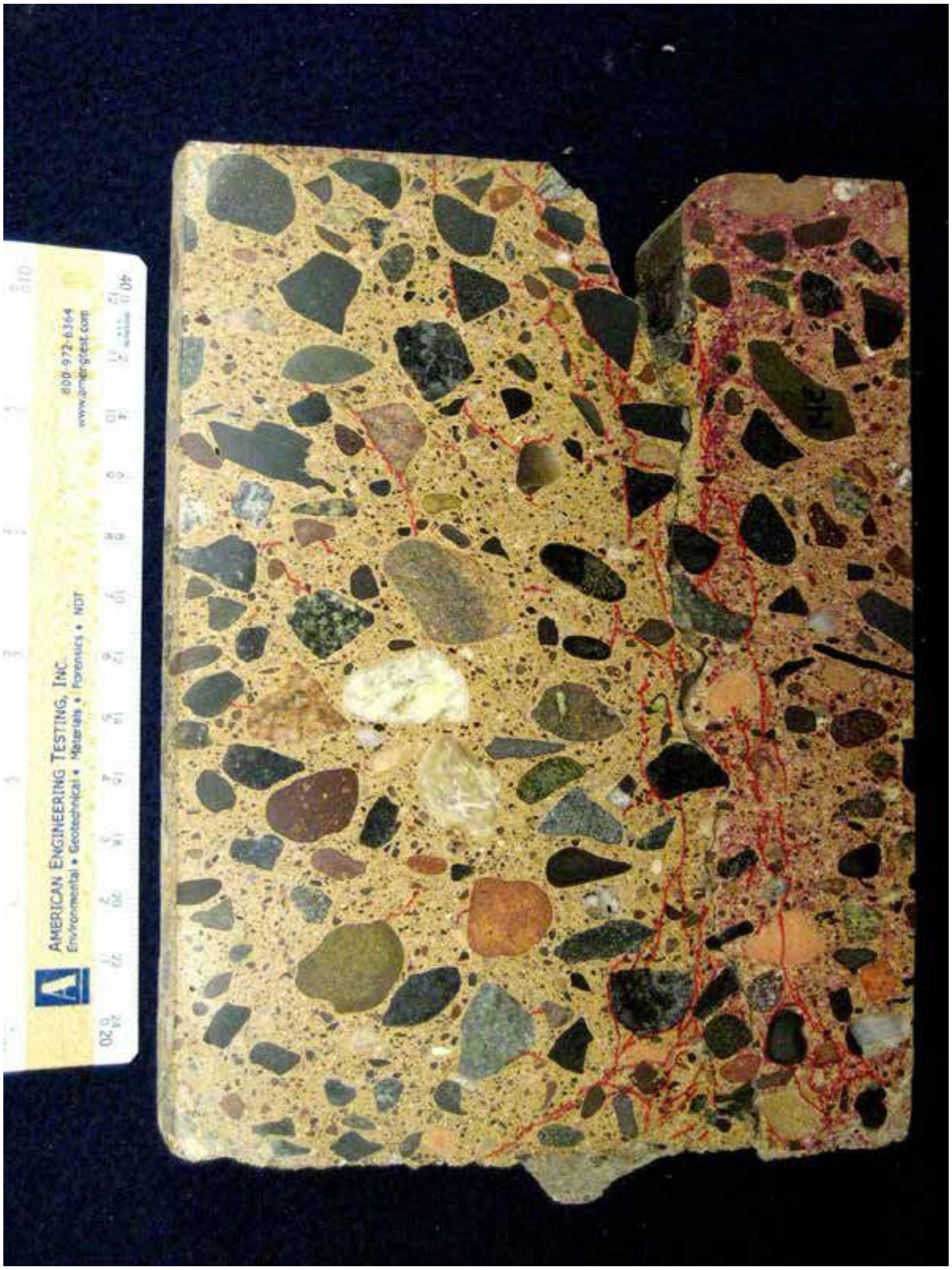
- The paste portion of the mix was considered to be of "moderate hardness," with the paste- to-aggregate bond strength rated as “fair to poor.”
- Surface carbonation was considered to be negligible in this core sample.
- The total air content was measured to be 5.4%, with 4.5% entrained air and 0.9%
- entrapped air. The spacing factor was 0.005 inches. This indicates the concrete
- originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- Closer examination of the crack in the lower portion of the joint revealed vertical micro and macro-cracking extending from the top to the bottom of the core sample. These cracks are highlighted in Figure 4.22. The cracks are prevalent in the paste, however cracks also bisected some of the aggregate particles.
- A close-up examination of the smallest air voids revealed that they were partially to completely filled with secondary ettringite crystals, thus reducing the capacity of freeze- thaw resistance of the paste. Figure 4.23 shows the filled voids.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.44 and 0.50. This exceeds the general recommended maximum of 0.45 for freeze-thaw resistant concrete [PCA Manual]. Higher water-to-cementitious ratio mixes correlate to higher porosity of the paste, which then tends to allow increased

amounts of moisture and deicing chemicals into the concrete.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.21 Centerville - Core 14E showing joint deterioration near surface

Figure 4.22 Centerville - Vertical cracking in Core 14E, highlighted by red ink



Core 14F

Core sample 14F was taken in the corner of a panel, near the edge of the eastbound travel lane of County Highway 14. The adjacent transverse and longitudinal joints showed little distress when the core sample was taken. Figure 4.24 shows the coring location.

Figure 4.23 Centerville – Voids in Core 14E mostly filled with secondary ettringite crystals (circled in blue)

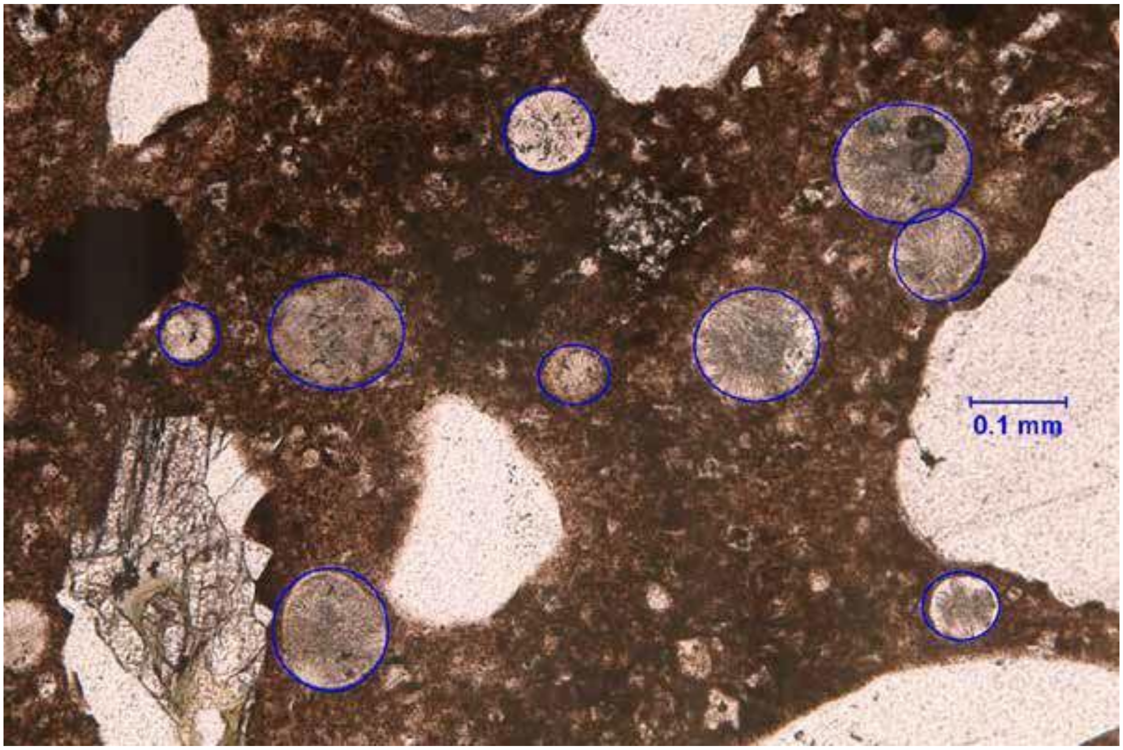


Figure 4.24 Centerville - Core location 14F

Core 14F was not subject to a petrographic analysis, but the condition of the core can be summarized as follows:

- The average measured core length was 7.75 inches.
- The surface showed no distress, and has a very lightly broomed texture.
- Examination of the core shows that it intersected the bottom portion of a neighboring joint. See Figure 4.25. There seemed to be the possibility that deterioration was occurring in the joint just above the portion extracted with the core sample. See Figure 4.26.
- The presence of several medium to large air voids suggests that the consolidation of the mix was fair to good.
- Without further analysis, comments on the internal condition of the core are not justified.

Figure 4.25 Centerville - Core sample 14F

Figure 4.26 Centerville - Core sample 14F showing possible deterioration within neighboring joint

Discussion

Based on examination of six core samples taken from various locations in the intersection, it appears that the mixes and/or construction practices resulted in colored concrete with high porosity. The high porosity, largely a result of too high of a water-to-cement ratio (for the exposure conditions), is allowing moisture and deicing chemicals to penetrate deep into the pavement. The petrographic analysis showed that both within and away from the joints, a majority of the smaller air voids are filled with ettringite crystals, thus significantly reducing the freeze- thaw resistance of the concrete. The prevalence of filled air voids and microcracking throughout the pavement indicates that the rate of deterioration of the joints will likely continue at a rapid pace, and therefore, partial-depth type repairs would not likely last long.

It is believed that deicers containing magnesium chloride have been used on this concrete. This chemical has been implicated as causing accelerated deterioration in concrete pavements, particularly in the joints [9, 11, 12]. Unfortunately, this project's budget did not allow for any of the Centerville core samples to be examined further using the SEM or EDX techniques. So it could not be determined whether deicing chemicals are adding to or accelerating the distress in the joint areas.

One aspect of concern was the prevalence of minimal surface textures on the colored concrete in this intersection. While some areas showed that a light broom texture was applied, other areas were very smooth. For both vehicular and pedestrian safety, it seems that increased friction would be more beneficial in areas like intersections and crosswalks.

<u>Vadnais Heights: County Hwy 96 & Greenhaven Drive</u>

The colored concrete crosswalks in intersections along County Highway 96 (CH96), from Shoreview to Vadnais Heights, were constructed over the time span 1998 to 2000. Similar to the intersections in Centerville, it is the author’s recollection that joint distress also appeared early in many of the CH96 intersections. The good news is that the rate of joint deterioration has been much lower than that observed in Centerville. Of interest is the newly developing and accelerating distress observed in crosswalk panels in the intersection of CH96 and Hodgson Road (see Figure 2.46).

Despite the observation of full panel distress at the Hodgson intersection, the predominant distress in most of the colored concrete crosswalks along CH96 is joint deterioration. For this study, it was decided that the joint distresses in the intersection of CH96 and Greenhaven Drive would be investigated. Figures 4.27 through 4.29 show some examples of the typical joint distress.

On June 11, 2012, five core samples were extracted from distressed joints and several mid-panel locations in the crosswalk on the northern side of the intersection of CH96 and Greenhaven Drive. Figure 4.30 shows the coring locations. Three of the cores samples were chosen for a more detailed petrographic analysis. Due to the severity of the observed distress, Core 96A was also subject to a further SEM and EDX analysis.

As previously mentioned, it appears that the colored concrete joint deterioration along CH96 has stabilized. Many of the distressed joints have partial-depth asphalt repairs, which are likely slowing the rate of moisture and deicing chemical ingress into the colored concrete.

The next section describes the core locations and discusses the results from the detailed analysis of select samples.

<u>Core 96A</u>

Core sample 96A was taken directly over a severally distressed joint in the northern crosswalk spanning Greenhaven Drive. The coring location is shown in Figure 4.31. The sample showed significant deterioration both near the top and bottom of the joint. See Figure 4.32.

Results from the petrographic analysis of Core sample 96A can be summarized as follows:

- The paste portion of the mix ranged from "relatively hard" to "soft" (near distressed regions), with the paste- to-aggregate bond strength rated as "fair to poor."
- Noticeable "mats" of ettringite and/or calcium carbonate were observed to line the joint face. A few alkali-silica reacted fine aggregate shale particles were observed in the sample. See Figure 4.33. These particles exhibited internal cracking that propagated into the paste.
- The total air content was measured to be 4.9%, with 3.4% entrained air and 1.5% entrapped air. The spacing factor was 0.004 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- Closer examination of the joint revealed vertical micro and macro-cracking extending from the top to the bottom of the core sample. These cracks are highlighted in Figure 4.34. The cracks were prevalent in both the paste and around aggregate particles.
- A close-up examination of the air voids near the top of the sample revealed they were clean and unfilled. In contrast, air voids near the joints and bottom of the sample were observed to be completely filled with secondary ettringite crystals, thus rendering the voids unable to aid in freeze-thaw resistance of the paste. Figures 4.35 and 4.36 show the air voids in the two different regions.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.42 and 0.47. In some areas of the sample, this exceeds the general recommended maximum of 0.45 for freeze-thaw resistant concrete [PCA Manual]. Higher water-to-cementitious ratio mixes correlate to higher porosity of the paste, which tends to allow increased amounts of moisture and deicing chemicals into the concrete. Flyash was observed in the mix, consistent with a 5 to 15% replacement of cement.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.27 Typical joint deterioration occurring in colored concrete crosswalks at intersection of County Highway 96 and Greenhaven Drive in Vadnais Heights, MN

Figure 4.28 Patched colored concrete crosswalk joint at intersection of County Highway 96 and Greenhaven Drive in Vadnais Heights, MN

Figure 4.29 Joint and panel deterioration occurring in colored concrete crosswalks at intersection of County Highway 96 and Greenhaven Drive in Vadnais Heights, MN

Figure 4.30 Overhead view of County Highway 96 and Greenhaven Drive intersection indicating locations where core samples were extracted.
***Source*: Google Maps, March 2013**

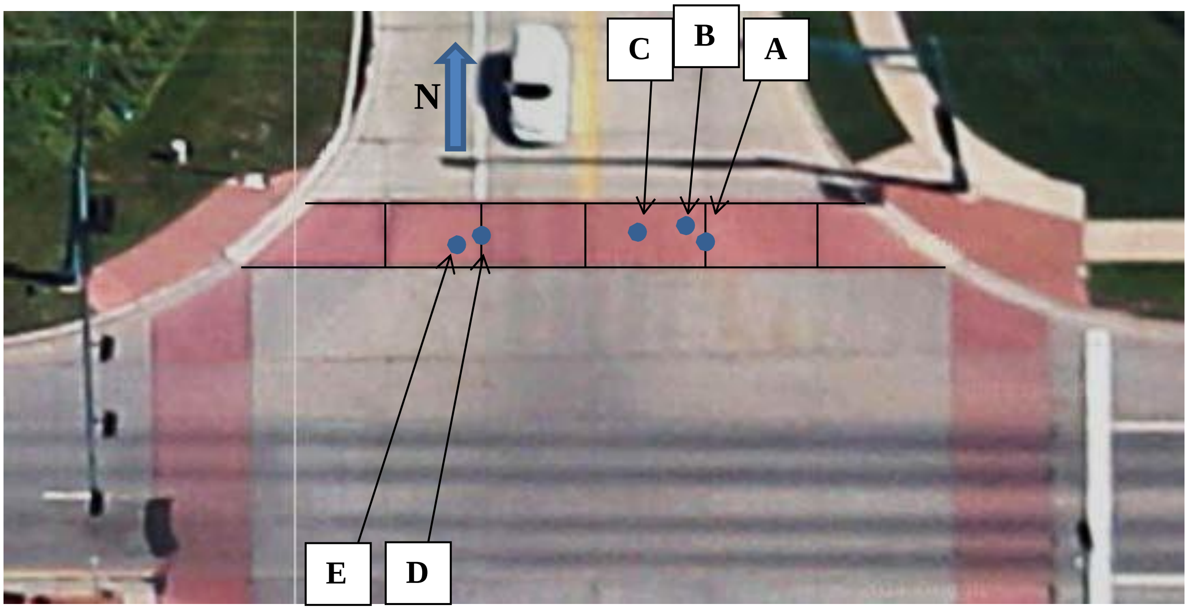


Figure 4.31 Vadnais Heights - Core locations 96A and 96B

Figure 4.32 Vadnais Heights - Core sample 96A showing significant deterioration in top and bottom regions of joint

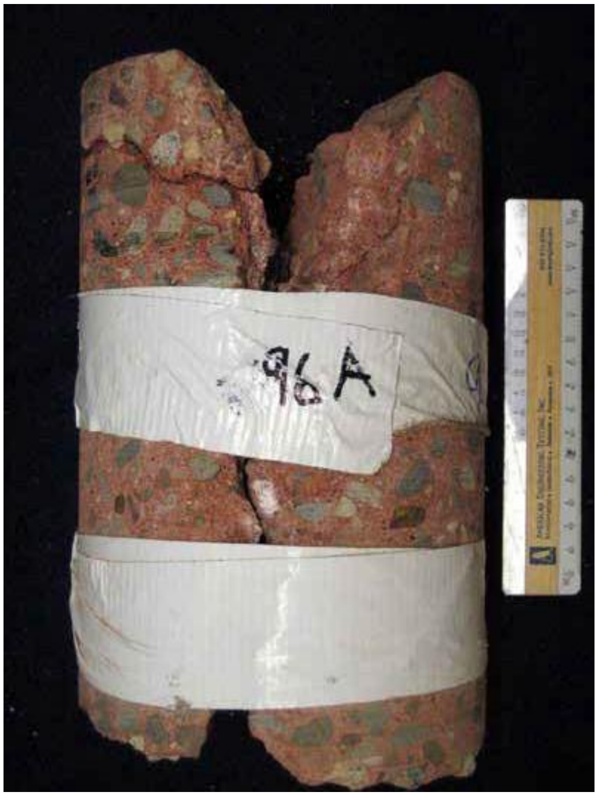


Figure 4.33 Vadnais Heights - Core sample 96A showing reactive shale particles among the fine aggregates

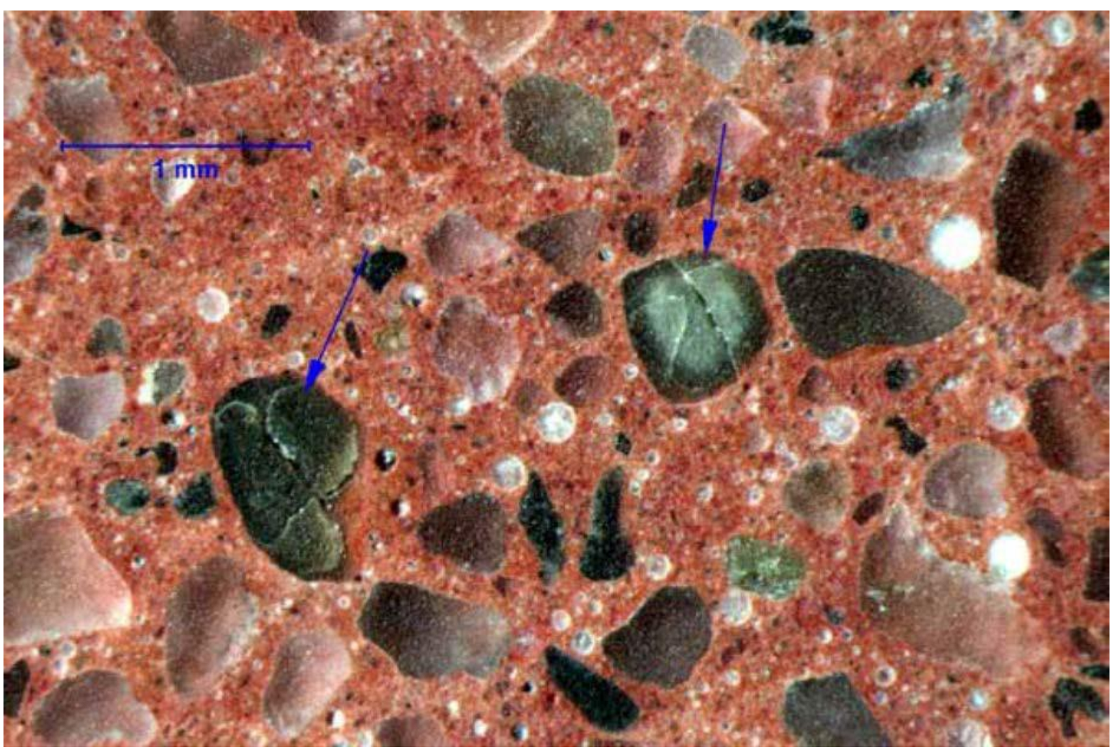
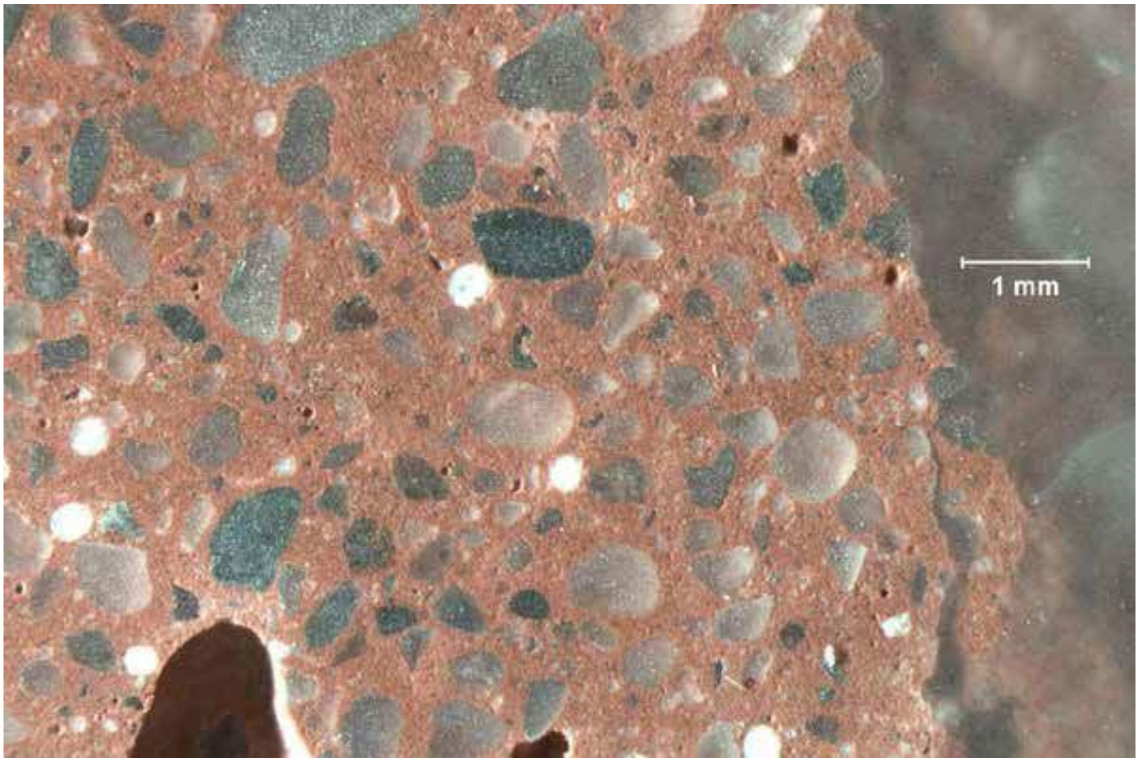


Figure 4.34 Vadnais Heights - Core sample 96A showing significant material loss near the top and bottom of the joint. Vertical cracking is also extensive parallel to the joint, highlighted by red ink.

Figure 4.35 Vadnais Heights - Core sample 96A showing unfilled air voids near top of pavement

Figure 4.36 Vadnais Heights - Core sample 96A showing air voids filled with secondary ettringite near joint and bottom of pavement



A summary of the results from the scanning electron microscope (SEM) and energy dispersive x-ray spectrometry (EDX) analysis of Core sample 96A can be summarized as follows (see Appendix B for the full report):

- The deterioration observed in this sample was identified as falling into two categories:
- chemical attack of the cement paste and chemical attack of fine aggregates.
- In Figure 4.37, the majority of the non-quartz particles in the image are highly altered cement paste or aggregate, with small inclusions of ettringite, magnesium oxides (likely dehydrated magnesium hydroxide), and other phases. The cause for this behavior is likely due to chemical attack from deicers or other weathering forces (e.g., freeze-thaw cycling).
- In Figure 4.38, the EDX image highlights the sand grains (red) and also shows a broad, low concentration distribution of magnesium (green), likely associated with magnesium chloride deicing chemicals.
- Magnesium-bearing solutions are moving through the concrete and magnesium is depositing in voids as either an oxide or hydroxide. See Figure 4.39.
- Alkali-rich fine aggregate feldspar particles are reacting with magnesium solutions (blue) moving through the concrete. See Figure 4.40. Also note that most of the aggregate particles are lined by the iron-based pigment particles (green).
- Magnesium, presumed to be from deicers, seems to be preferentially attracted to areas

with concentrated iron-based pigment. See Figure 4.41.

- Due to the single sample and small specimen size, the research team was not yet comfortable identifying the exact mechanism of the chemical attack.

Figure 4.37 Vadnais Heights – Portion of core sample 96A, showing backscattered electron image of chemically altered cement paste and aggregate near the joint

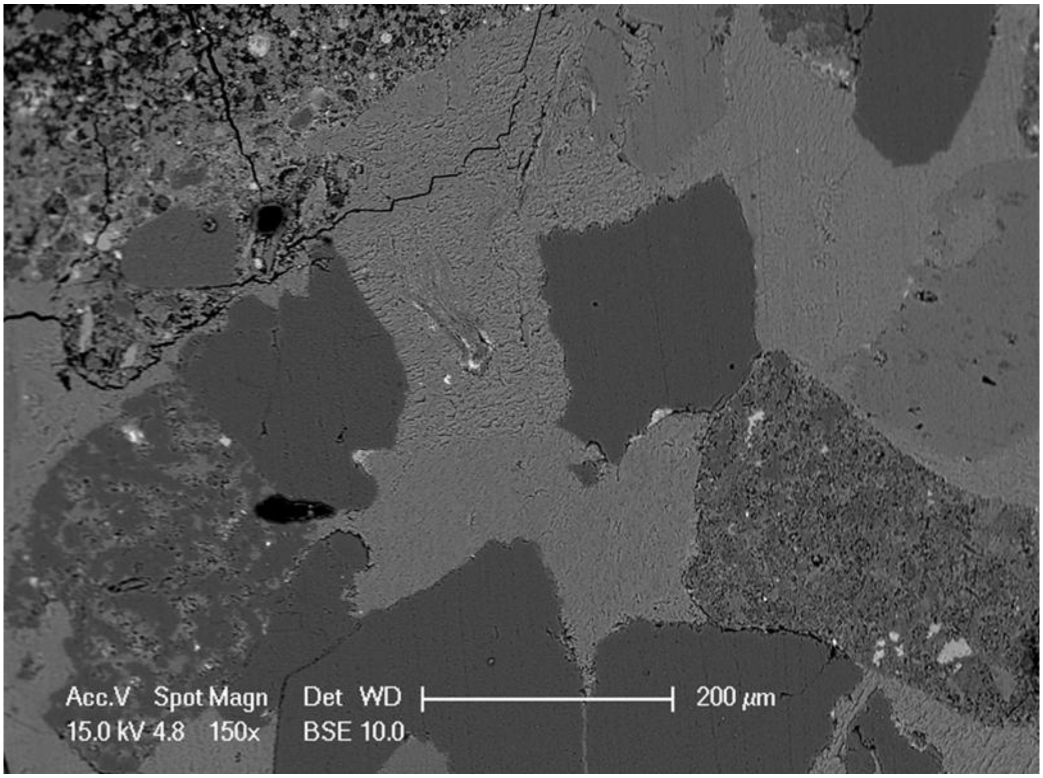


Figure 4.38 Vadnais Heights – Portion of core sample 96A, showing EDX image indicating presence of magnesium (green colors) throughout specimen

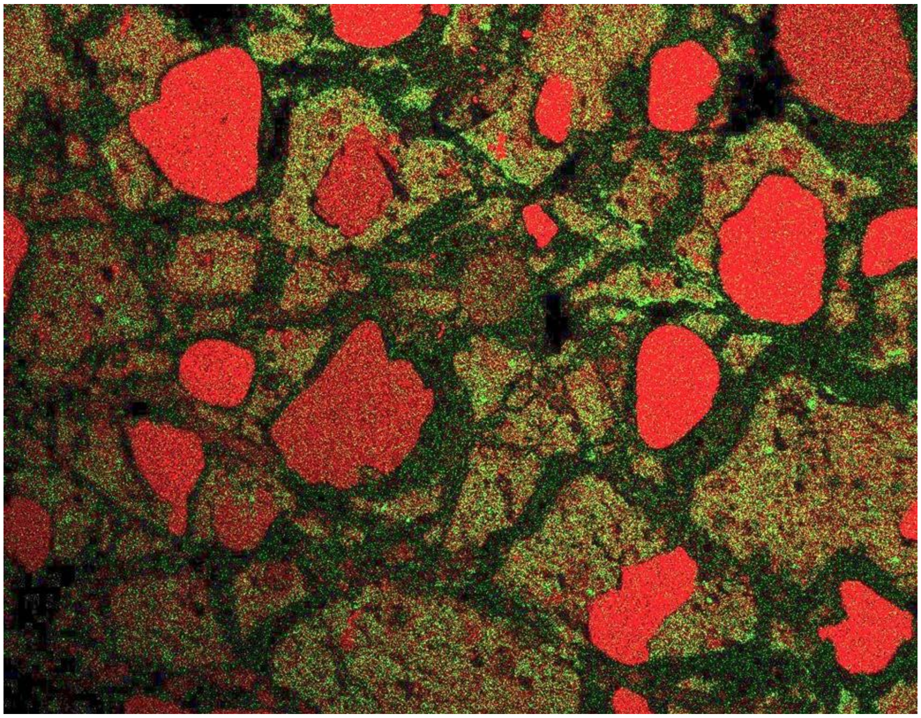


Figure 4.39 Vadnais Heights – Portion of core sample 96A, showing EDX image with magnesium oxide (yellow) filling voids

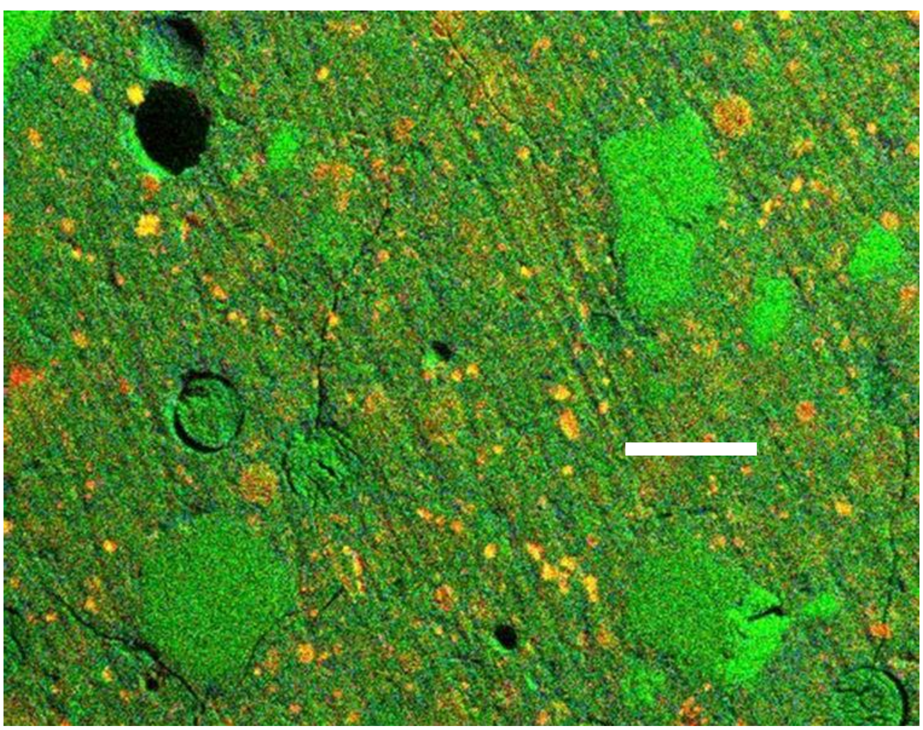


Figure 4.40 Vadnais Heights – Portion of core sample 96A, showing EDX image with magnesium (blue) infiltrating feldspar particle (marked "A" in lower right). The iron-based color pigment is indicated in green.

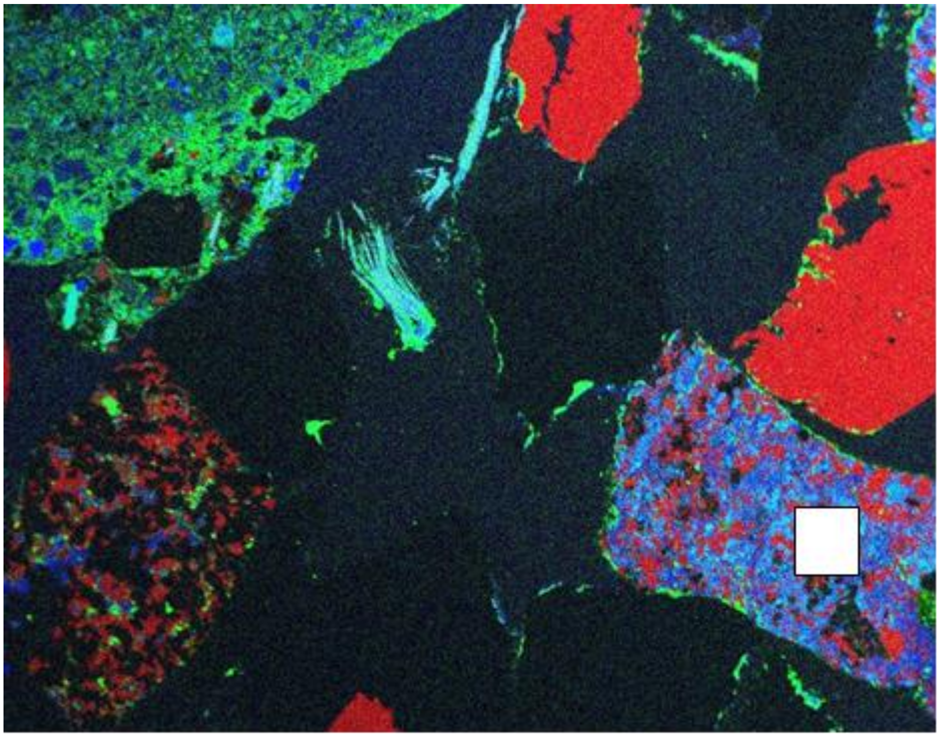
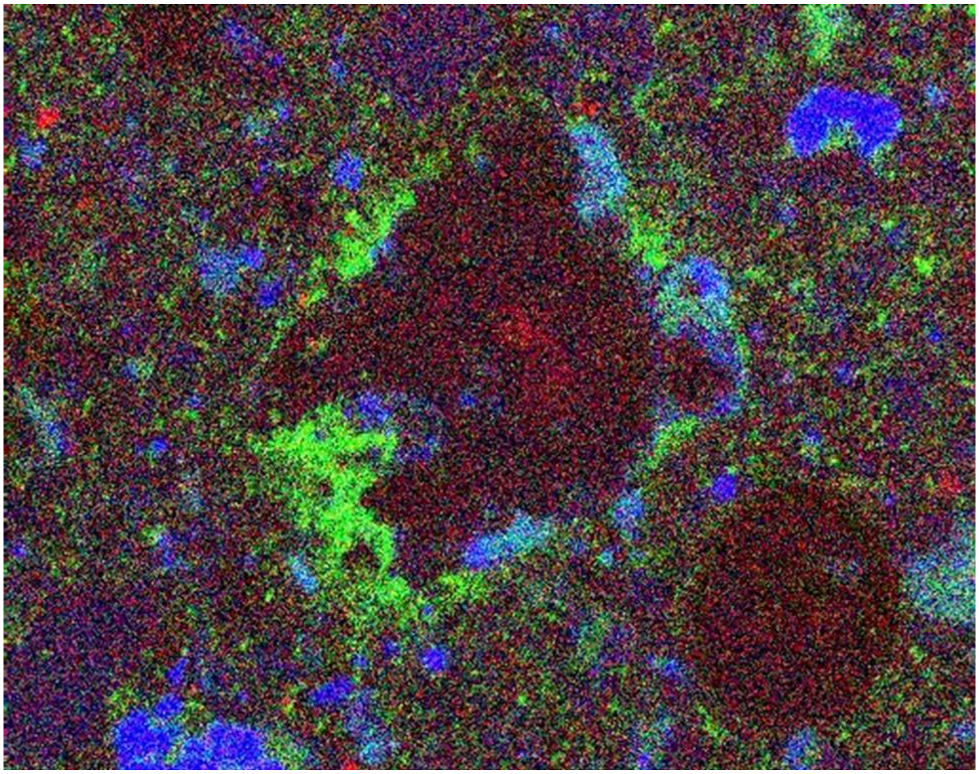


Figure 4.41 Vadnais Heights – Portion of core sample 96A, showing EDX image with magnesium (blue) and iron-based pigment (green) coinciding throughout the paste



<u>Core 96B</u>

Core sample 96B was taken approximately one foot south of core sample 96A, with one edge just touching the deterioration in the adjacent joint. Refer to Figure 4.31 for the core location.

Core 96B was not subject to a petrographic analysis, but the condition of the core can be summarized as follows:

- The average measured core length was 8 inches.
- The sides of the core sample reveal a large number of air pockets. This is likely a result
- of typical placement practices that do not include increased consolidation using vibration. See Figure 4.42.
- Other than a chip missing from the surface of the sample (likely caused during transport of the sample) there are no visible cracks or distress in the sample.

Figure 4.42 Vadnais Heights - Core 96B showing large number of air pockets throughout sample

Core 96C

Core sample 96C was taken in the middle of a panel in the crosswalk. The coring location is shown in Figure 4.43. The sample did not show any visible distress. See Figure 4.44.

Results from the petrographic analysis of Core sample 96C can be summarized as follows:

- The paste portion was deemed to be relatively hard, however the paste- to-aggregate bond strength was rated as "poor."
- Closer examination of the sample near the pavement surface revealed some carbonation depths reaching 12 mm. Vertical drying shrinkage cracks proceeded from the surface to a depth of 15 mm. See Figure 4.45.

- Similar to core sample 96A, a few alkali-silica reacted shale fine aggregate particles were observed in the sample. These particles exhibited internal cracking that
- propagated into the paste. ASR gel was noted to be lining some of the void spaces directly adjacent to the reacted shale particles.
- The total air content was measured to be 5.1%, with 3.4% entrained air and 1.7% entrapped air. The spacing factor was 0.004 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- A close-up examination of the air voids throughout the lower portion of the sample revealed that most of the finest entrained air voids were filled with secondary ettringite crystals, thus rendering the voids unable to aid in freeze-thaw resistance of the paste. Figure 4.46 shows the air voids in the lower region of the sample.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.42 and 0.47. In some areas of the sample, this exceeds the general recommended maximum of 0.45 for freeze-thaw resistant concrete [PCA Manual]. Higher water-to-cementitious ratio mixes correlate to higher porosity of the paste, which tends to allow increased amounts of moisture and deicing chemicals into the concrete. Flyash was observed in the mix, consistent with a 8 to 10% replacement of cement.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.43 Vadnais Heights - Core location 96C

Figure 4.44 Vadnais Heights - Core sample C

Figure 4.45 Vadnais Heights - Core sample 96C show drying shrinkage cracks near surface (highlighted in red ink)

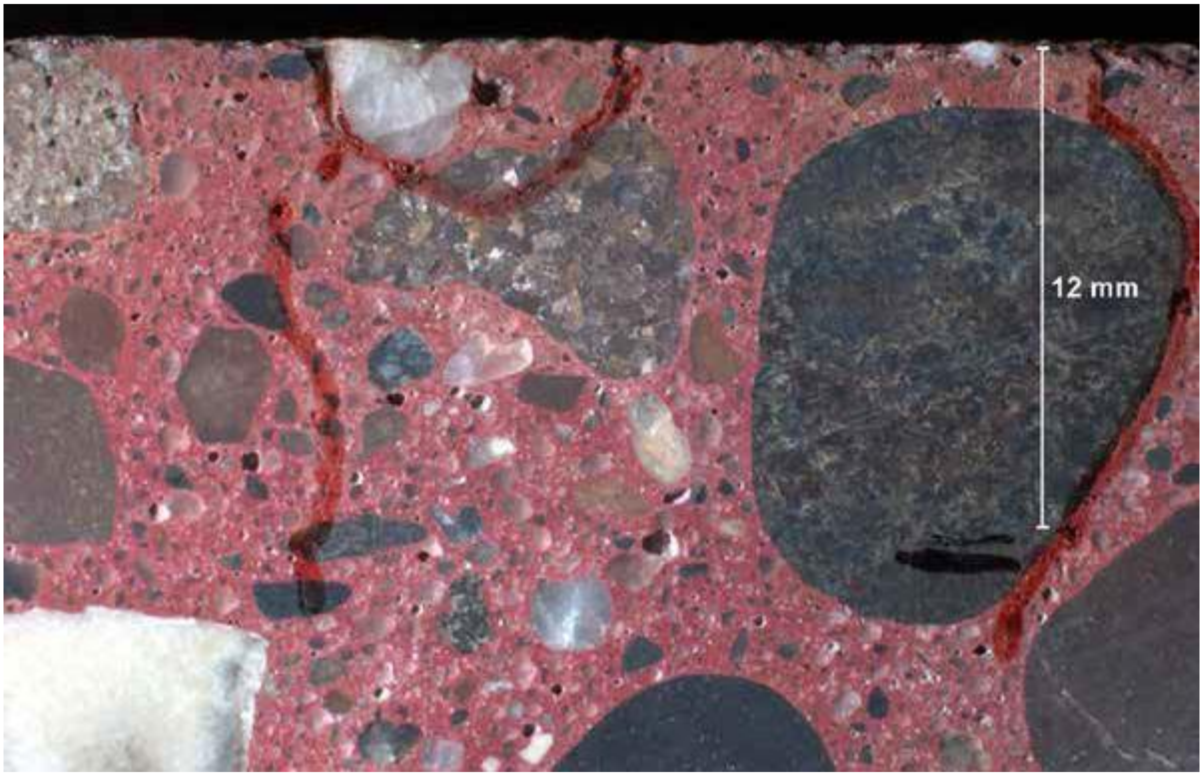
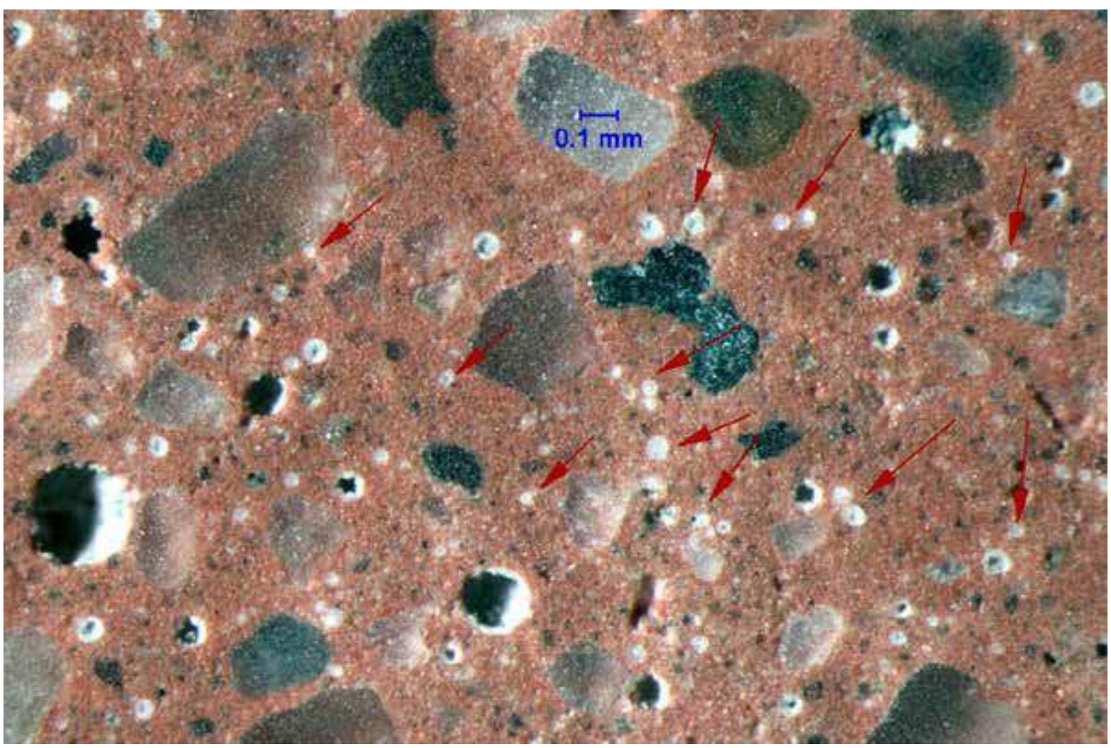


Figure 4.46 Vadnais Heights - Core sample 96C showing air voids filled with secondary ettringite near the bottom of the pavement



Core 96D

Core sample 96D was taken immediately adjacent to a severally distressed joint in the northern crosswalk spanning Greenhaven Drive. The coring location is shown in Figure 4.47. Figure 4.48 shows that the core sample had a significant amount of material missing at the mid-depth of the joint. Cracking along the joint face was evident, as shown in Figure 4.49.

Figure 4.47 Vadnais Heights - Core locations for 96D and 96E

Figure 4.48 Vadnais Heights - Core sample 96D (top of sample on right)

Figure 4.49 Vadnais Heights - Core sample 96D. Note cracking near joint face

Results from the petrographic analysis of Core sample 96D can be summarized as follows:

- The paste portion was deemed to be relatively hard, however the paste- to-aggregate bond strength was rated as "fair to poor."
- Closer examination of the sample near the pavement surface revealed numerous vertical microcracks within 25 mm of the joint crack. See Figure 4.50.
- Similar to core sample 96A, a few alkali-silica reacted shale fine aggregate particles were observed in the sample. These particles exhibited internal cracking that propagated into the paste.
- The total air content was measured to be 4.3%, with 2.7% entrained air and 1.6% entrapped air. The spacing factor was 0.007 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant. For comparison, the current air void parameters, excluding ettringite filled voids, are characterized by a 1.1% entrained-sized void volume and a 0.019 inch spacing factor.
- A close-up examination of the air voids, throughout all but the top 5mm of the sample, revealed that most of the finest entrained air voids were filled with secondary ettringite crystals, thus rendering the voids unable to aid in freeze-thaw resistance of the paste. See Figure 4.51.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.42 and 0.47. In some areas of the sample, this exceeds the general

recommended maximum of 0.45 for freeze-thaw resistant concrete [PCA Manual]. Higher water-to-cementitious ratio mixes correlate to higher porosity of the paste, which tends to allow increased amounts of moisture and deicing chemicals into the concrete.

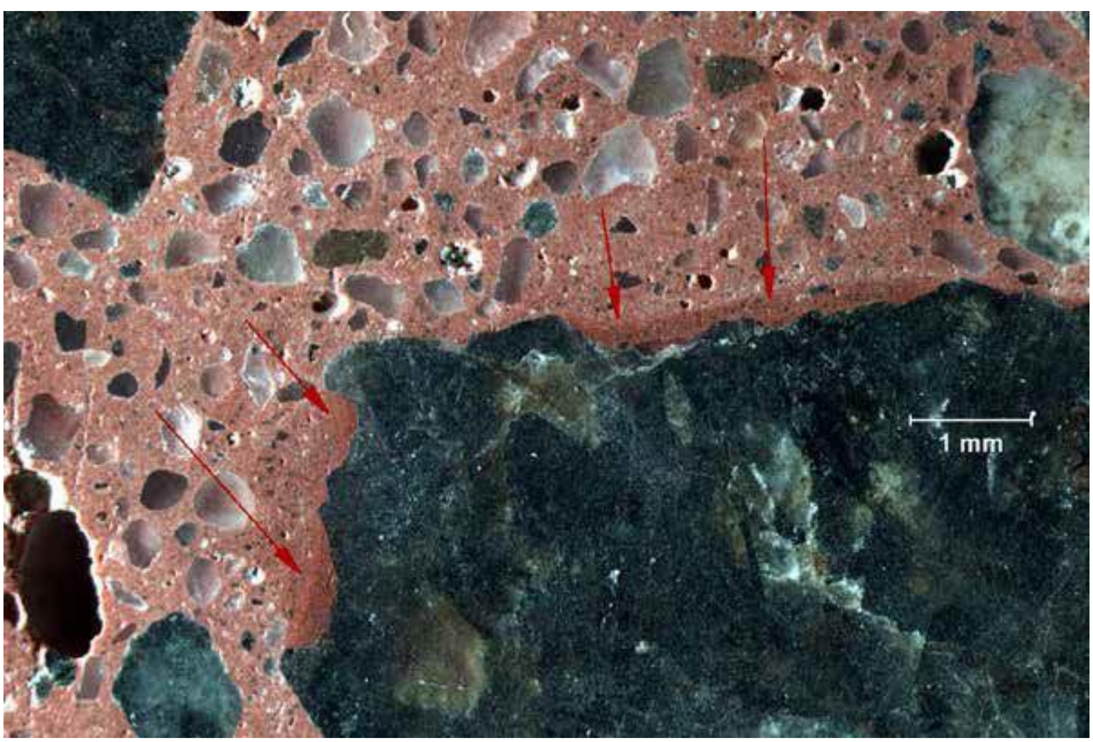
- Distinct, darker colored, denser paste of lower w/cm was observed in many concave coarse aggregate notches. This suggests that multiple additions of water during batching. See Figure 4.52.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.50 Vadnais Heights - Core sample 96D. Note microcracking near joint face (highlighted in red ink)

Figure 4.51 Vadnais Heights - Core sample 96D showing air voids (under polarized light) throughout the pavement filled with secondary ettringite (circled in red)

Figure 4.52 Vadnais Heights - Core sample 96D showing darker, low w/cm paste, indicating multiple additions of water during batching



Core 96E

Core sample 96E was taken approximately one foot southwest of core sample 96D, within the interior of a panel. Refer to Figure 4.47 for the core location.

Core 96E was not subject to a petrographic analysis, but the condition of the core can be summarized as follows:

- The average measured core length was 7.25 inches.
- The sides of the core sample appear to be in good condition, with no visible cracks or signs of distress. See Figure 4.53.

Figure 4.53 Vadnais Heights - Core 96E

Discussion

Based on examination of five core samples taken from various locations in the crosswalk, it appears that the mixes and/or construction practices resulted in colored concrete with too high of porosity. This higher porosity, largely a result of hardened paste with a water-to-cement ratio exceeding 0.45, is allowing moisture and deicing chemicals to permeate the pavement throughout its depth. The petrographic analysis showed that both within and away from the joints, a majority of the smaller air voids are filled with ettringite crystals, thus significantly reducing the freeze- thaw resistance of the concrete. The prevalence of filled air voids, microcracking, and chemical attack throughout the pavement indicates that the deterioration of the colored concrete will likely continue. The observed pace of deterioration appears to be much slower than that of the Centerville project. It may be feasible to do some full-depth joint repairs to keep the Vadnais Heights colored concrete slabs in service for a number of years, given that this situation appears to be more like that observed on 7th Street West and West 5th Street in St.Paul (see Figure 2.59).

It is almost certain that deicers containing magnesium chloride have been used on this concrete. This chemical has been implicated as causing accelerated deterioration in concrete pavements [9, 11, 12]. Further analysis of portions of the core samples using the SEM and EDX techniques clearly indicate the presence of magnesium throughout the specimen. Continued use of this type of deicing chemical will likely perpetuate the chemical attack of both the paste and fine aggregates within this colored concrete.

As indicated in the beginning of this section, neighboring intersections along County Highway 96 are experiencing not only joint deterioration, but also significant mid-panel distress. Unfortunately, this study could not examine whether the cause of that distress is related to internal expansion of the concrete due to chemical attack, or perhaps other stresses caused by neighboring pavements with differing rates of thermal expansion.

<u>Arden Hills: Lake Johanna Blvd & Tony Schmidt Park</u>

In 1999, a colored concrete crosswalk was constructed in Arden Hills across Lake Johanna Blvd (in Tony Schmidt Park on the north side of Lake Johanna). Deterioration is now occurring near both wheel paths of the eastbound lane of Lake Johanna Blvd, and near one wheel path in the westbound lane. Due to traffic flow considerations, only two core samples could be obtained, at decorative (formed, not sawed) longitudinal joint lines parallel to the distressed contraction joints. See Figures 4.54 and 4.55. These core samples, taken on August 17th, 2012, were taken simply to investigate the condition of the colored concrete near the distressed joints.

Fortunately, both core samples were subject to a petrographic examination for this study.

<u>Core LJEB-A</u>

Core sample LJEB-A was taken near the edge of a panel, over a formed decorative longitudinal joint, approximately two feet away from a distressed longitudinal contraction (sawed) joint. The coring location is shown in Figure 4.56. As shown in Figure 4.57, the only visible “distress” was the short vertical crack created during the tooling of the decorative joint.

Results from the petrographic analysis of Core sample LJEB-A can be summarized as follows:

- The average core length was 8.5 inches.
- The paste portion was deemed to be relatively hard, and the paste- to-aggregate bond strength was rated as “fair.”
- Surface carbonation was considered to be negligible in this core sample.
- The total air content was measured to be 7.2%, with 5.5% entrained air and 1.7%
- entrapped air. The spacing factor was 0.002 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- A close-up examination of the air voids throughout the sample revealed that most of the entrained air voids were filled with secondary ettringite crystals, thus rendering the voids unable to aid in freeze-thaw resistance of the paste. Many larger air voids are also lined with secondary ettringite crystals. Figure 4.58 shows the air voids at a depth of 60 mm.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.42 and 0.47. In some areas of the sample, this exceeds the general recommended maximum of 0.45 for freeze-thaw resistant concrete [PCA Manual]. Higher water-to-cementitious ratio mixes correlate to higher porosity of the paste, which tends to allow increased amounts of moisture and deicing chemicals into the concrete. Flyash was observed in the mix, consistent with a 5% replacement of cement.
- Alkali-silica reaction (ASR) induced microcracking was found in both fine and coarse aggregates, particularly within the upper portion of the core sample. This is shown in Figures 4.59 and 4.60.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.54 Crosswalk on eastbound lane of Lake Johanna Boulevard in Arden Hills. Due to access limitations, core samples were taken from a neighboring joint line.

Figure 4.55 Crosswalk on westbound lane of Lake Johanna Blvd. in Arden Hills. Due to access limitations, core samples were taken from a neighboring joint line.

Figure 4.56 Arden Hills - Core location LJEB-A

Figure 4.57 Arden Hills - Core sample LJEB-A

Figure 4.58 Arden Hills - Core sample LJEB-A showing ettringite lining and filling air voids at a depth of 60 mm

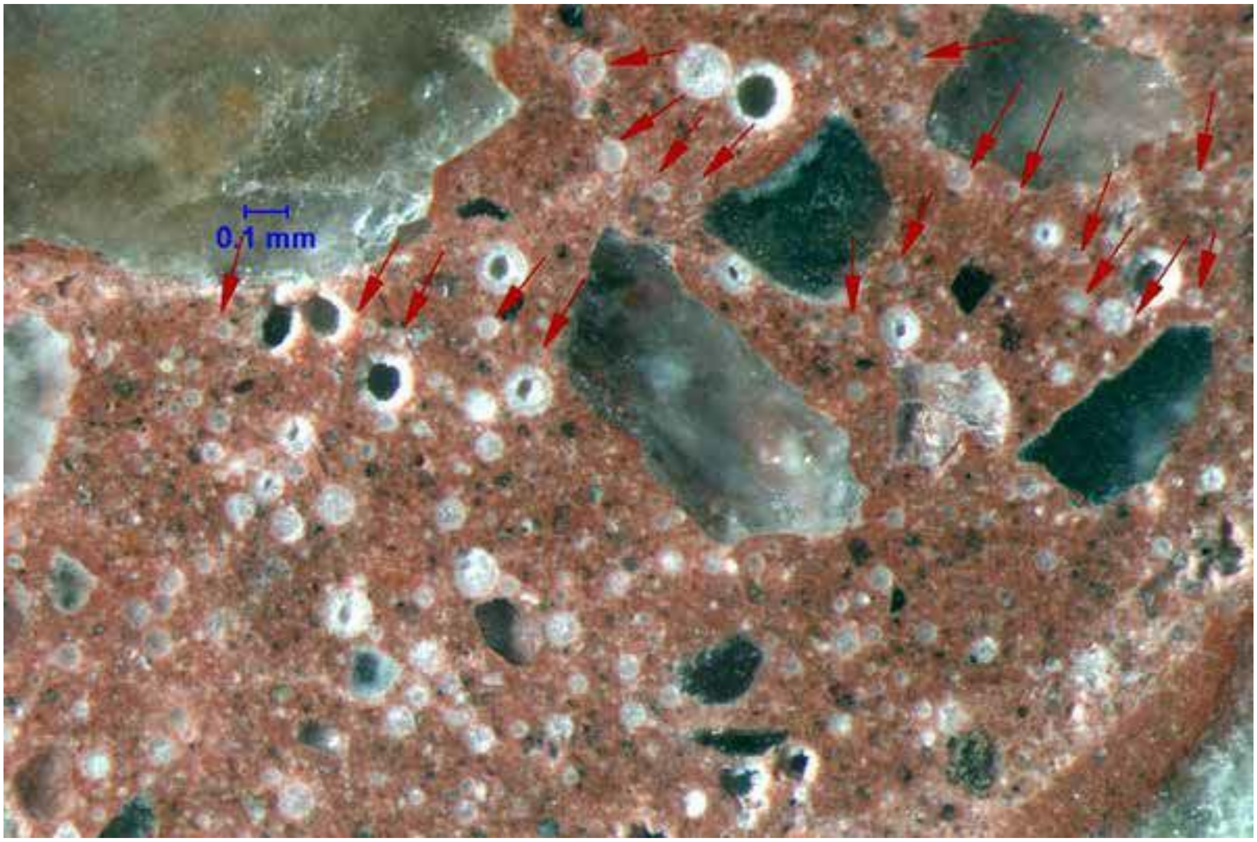


Figure 4.59 Arden Hills - Core sample LJEB-A showing vertical and horizontal ASR-induced cracks (highlighted in red ink)

Figure 4.60 Arden Hills - Core sample LJEB-A showing clear ASR gel product within microcracks traversing both the paste and a greywacke coarse aggregate particle

Core LJWB-B

Core sample LJWB-B was taken at approximately the center of a panel, over a formed decorative longitudinal joint, parallel to a distressed longitudinal contraction (sawed) joint. The coring location is shown in Figure 4.61. As shown in Figure 4.62, the only visible “distress” was the short vertical crack created during the tooling of the decorative joint.

Results from the petrographic analysis of Core sample LJWB-B were nearly identical to core sample LJEB-A:

- A close-up examination of the air voids throughout the sample revealed that most of the entrained air voids were filled with secondary ettringite crystals, thus rendering the voids unable to aid in freeze-thaw resistance of the paste. Many larger air voids are also lined with secondary ettringite crystals.
- Alkali-silica reaction (ASR) induced microcracking was found in both fine and coarse aggregates, particularly within the upper portion of the core sample. This is shown in Figures 4.63 through 4.65.
- Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.61 Arden Hills - Core location LJWB-B

Figure 4.62 Arden Hills - Core sample LJWB-B

Figure 4.63 Arden Hills - Core sample LJWB-B showing vertical and horizontal ASR-induced cracks (highlighted in red ink)

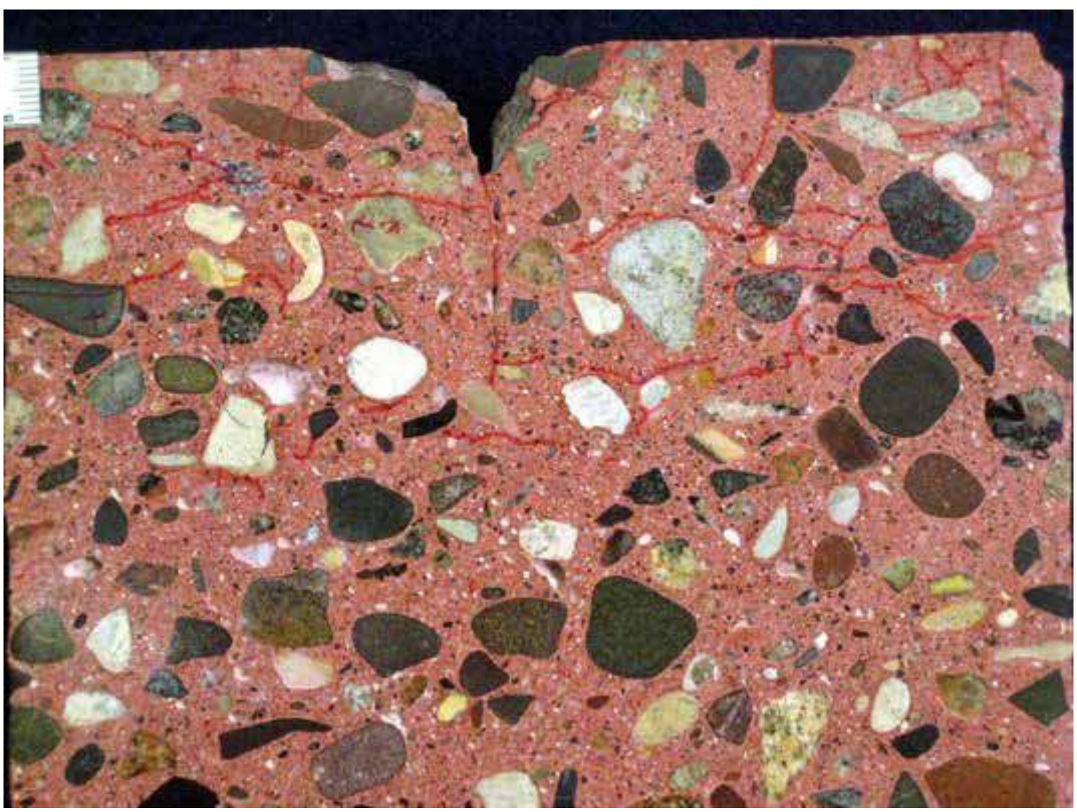


Figure 4.64 Arden Hills - Core sample LJWB-B showing clear ASR gel product within microcracks traversing both the paste and a greywacke coarse aggregate particle. Also note air voids filled with secondary ettringite.

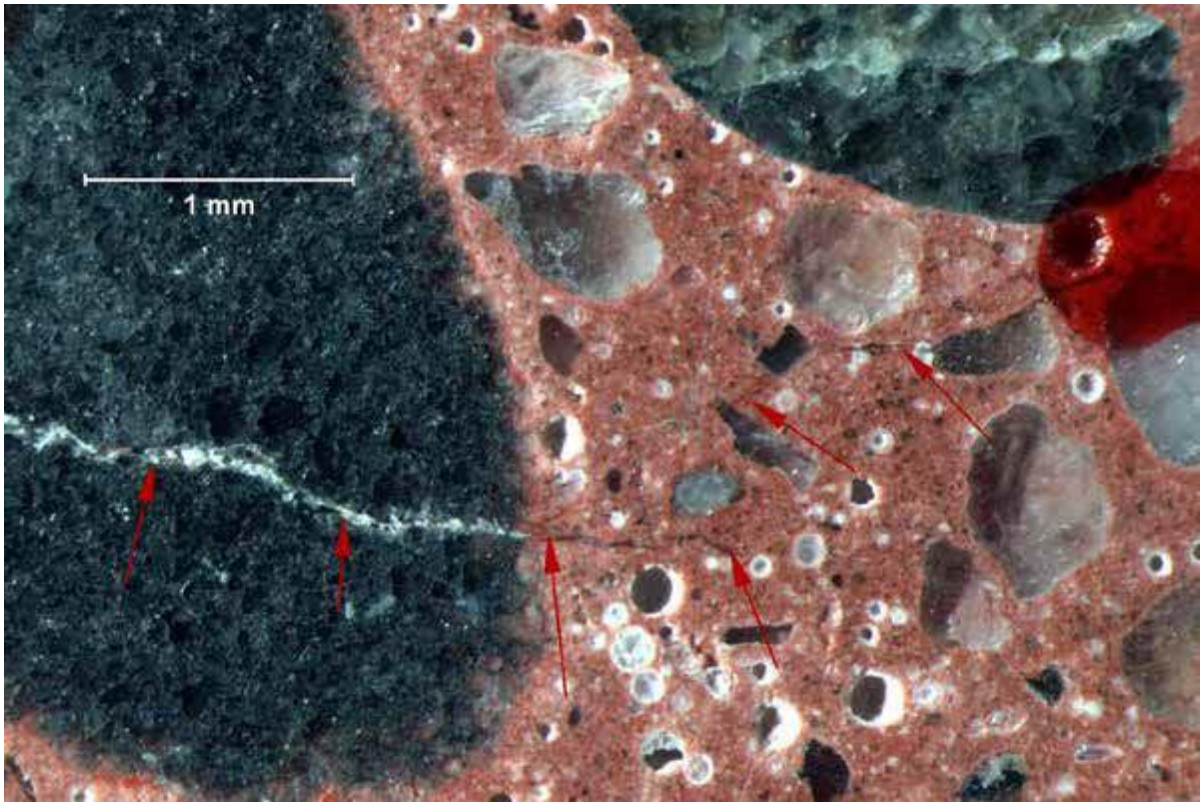
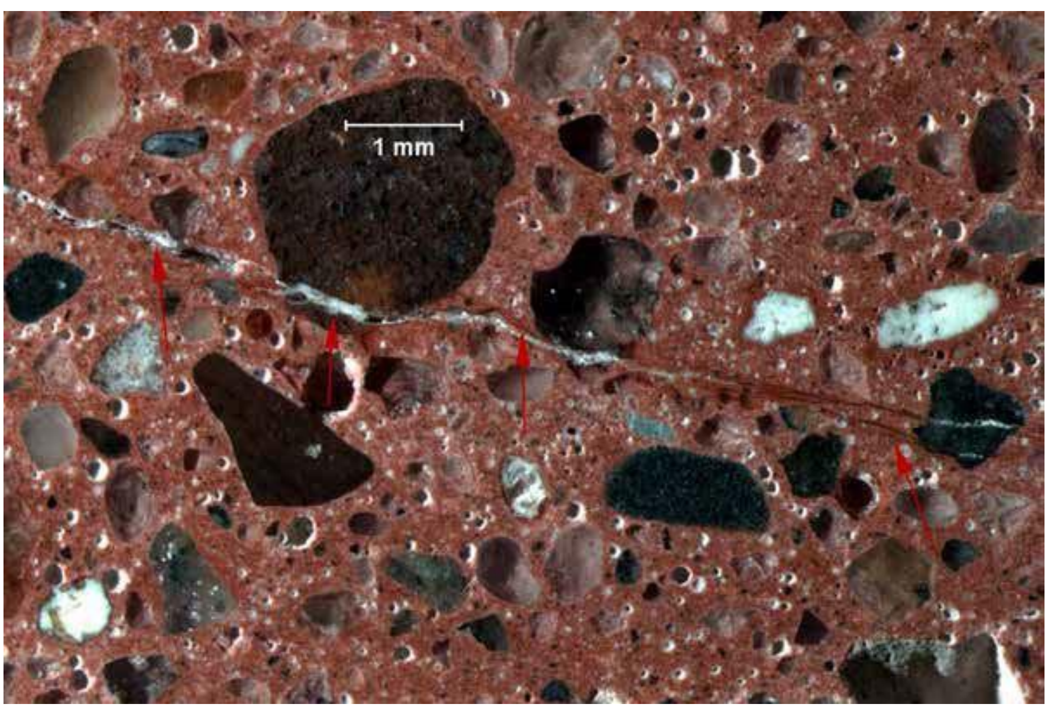


Figure 4.65 Arden Hills - Core sample LJWB-B showing white to clear ASR gel mostly filling microcracking proceeding through three reactive fine aggregates



Discussion

Despite having to take core samples some distance away from the visibly distressed longitudinal contraction joints, internal distress was found during the petrographic analysis of the two Arden Hills colored concrete core samples.

Similar to the other colored concrete project locations in this study, the petrographic analysis showed that both within and away from the joints, a majority of the smaller air voids are filled with ettringite crystals, thus significantly reducing the freeze- thaw resistance of the concrete. More concerning however, is the prevalence of microcracking filled with ASR gel, traversing both the paste and aggregates. In fact, the petrographer notes that there is no local history of ASR reaction occurring in the commonly used aggregates found in the Arden Hills colored concrete mix (i.e Greywacke). Unfortunately, the budget would not allow for closer examination of the core samples using the SEM and EDX techniques.

Given the prevalent microcracking near the surface of the concrete, it is expected that the crosswalk will continue to deteriorate, especially in the areas of high loads and moisture contents (joints). Since the distress is currently close to the surface, it may be reasonable to do partial or full-depth joint repairs to extend the service life of this crosswalk. It might also be beneficial to apply a liquid sealant material to slow the ingress of water and reduce the growth of ettringite and ASR gel.

<u>Roseville: Larpenteur Avenue and Fernwood Street</u>

Constructed in 2001, the colored crosswalks within the intersection of Larpenteur Avenue and Fernwood Street in Roseville are showing significant joint and panel distress. Figures 4.66 and 4.67 show the condition of the crosswalks. A total of four core samples were taken on August 17th, 2012, from both distressed and sound joints and panels. Figure 4.68 shows the coring locations. Three of the samples were subjected to a detailed petrographic analysis. One sample was further investigated using the SEM and EDX techniques.

The predominant distresses observed in the crosswalks include both joint deterioration and significant cracking near the edge of panels. Figure 4.69 shows that minor distress was also observed in the joints of the parking lane along Larpenteur Avenue.

The next section describes the core locations and discusses the results from the detailed analysis of select samples.

<u>*Core L&F-A*</u>

Core sample L&F-A was taken over a distressed joint in the northern crosswalk spanning North Fernwood Street. Figure 4.70 shows the core location. The sample showed severe deterioration within the joint, both near the top and bottom of the pavement. Also, horizontal cracking was occurring near the bottom of the pavement. See Figures 4.71 to 4.72.

Results from the petrographic analysis of Core sample L&F-A can be summarized as follows:

- The average core length was 8.5 inches.
- The paste portion was deemed to be relatively hard, except near the joint distress, where it was described as soft, with prevalent carbonation. This is shown in Figure
- 4.73. The paste-to-aggregate bond strength was rated as "fair."
- Vertical microcracking is prevalent along the faces of the joint, while horizontal microcracks occur both at mid-depth and near the bottom of the sample. See Figure
- 4.74.
- The total air content was measured to be 7.5%, with 6.8% entrained air and 0.7% entrapped air. The spacing factor was 0.002 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.40 and 0.45. These values lie within the recommended range for freeze-thaw resistant concrete[10].
- A close-up examination of the air voids throughout the sample revealed that many of the finest entrained air voids were filled with secondary ettringite crystals. Other voids contain Friedal's Salt. The presence of these minerals in the voids reduces the freeze-thaw resistance capacity of the paste.
- Several mildly ASR "reacted" coarse and fine aggregate particles exhibited very fine internal cracks propagating into the paste.
- The surface texture was described as smooth and worn.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.66 Distressed joints in crosswalks at intersection of Larpenteur Avenue and N Fernwood Street

Figure 4.67 Distressed joints and panels in crosswalk at intersection of Larpenteur Avenue and N Fernwood Street

Figure 4.68 Overhead view of Larpenteur Avenue and N Fernwood Street intersection indicating locations where core samples were extracted

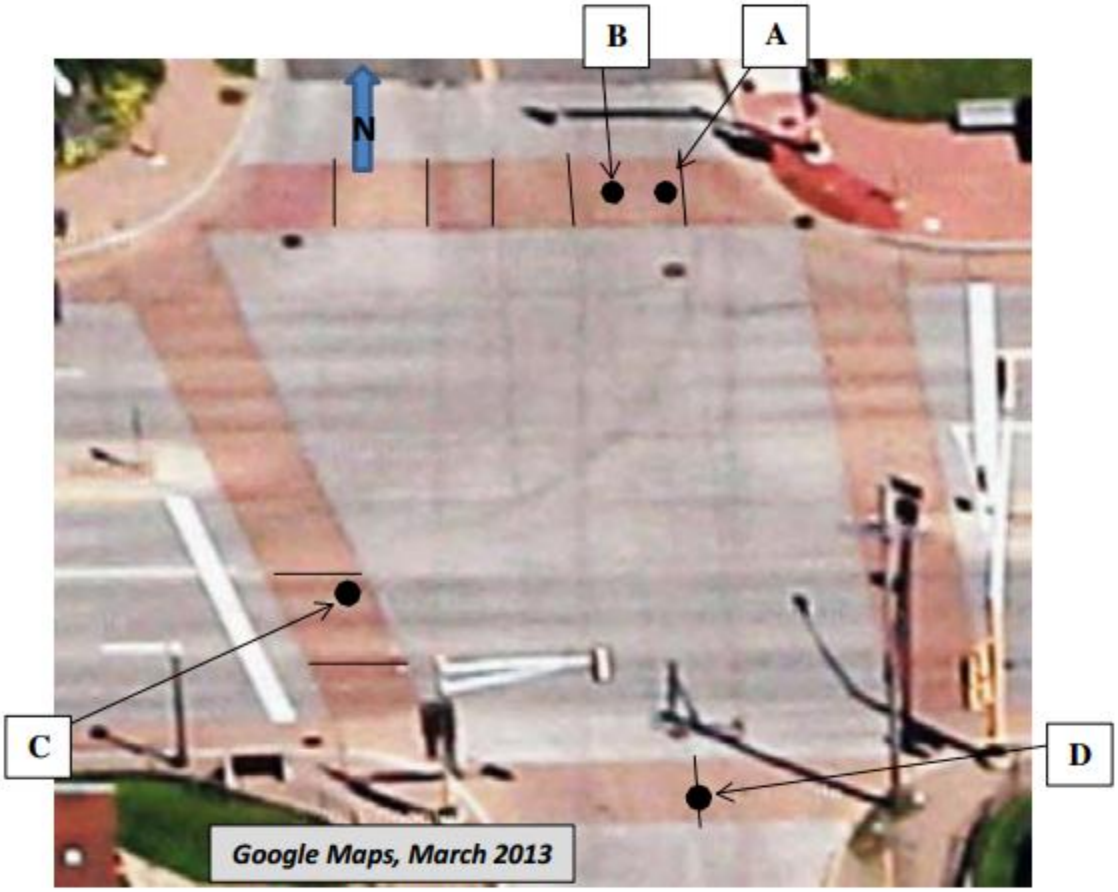


Figure 4.69 Distressed joints in parking lane along Larpenteur Avenue near Fernwood Street

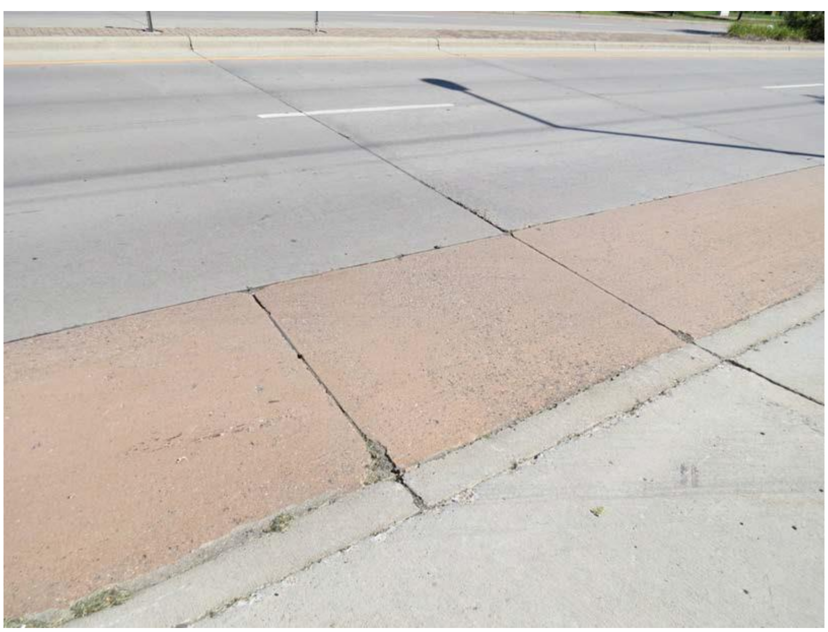


Figure 4.70 Roseville - Core locations L&F-A and L&F-B

Figure 4.71 Roseville - Core sample L&F-A showing distresses at both top and bottom of joint

Figure 4.72 Roseville - Core sample L&F-A showing distresses at both top and bottom of joint (side opposite that shown in Figure 4.71)

Figure 4.73 Roseville - Core sample L&F-A showing carbonation (unstained paste) proceeding up to 10mm depth from the joint crack plane (on right)

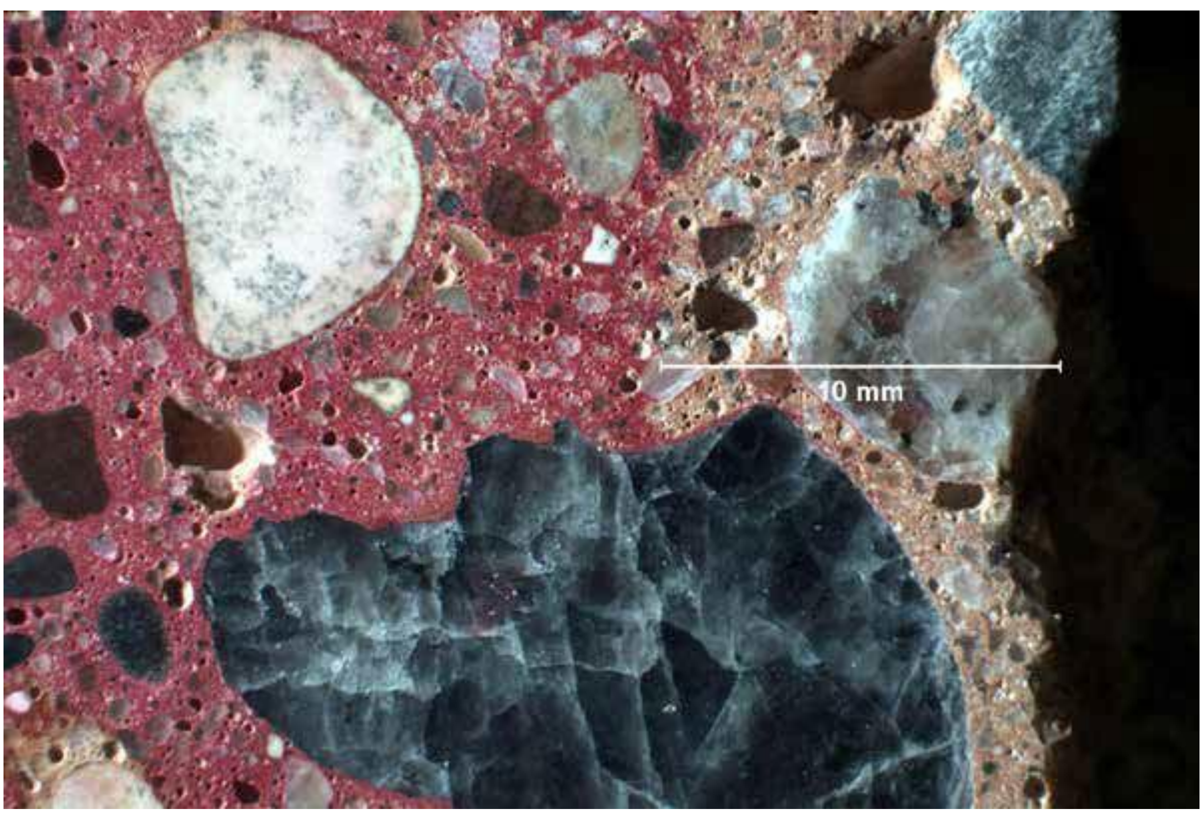


Figure 4.74 Roseville - Core sample L&F-A showing vertical and horizontal microcracking (highlighted in red ink)

Core L&F-B

Core sample L&F-B was taken in the middle of a panel in the same crosswalk as Core sample L&F-A. Figure 4.70 shows the core location. As with the surface, the lower portion of the core appeared to be in very good condition. See Figure 4.75.

Results from the petrographic analysis of Core sample L&F-B can be summarized as follows:

- The average core length was 8.75 inches.
- The paste portion was deemed to be relatively hard. The paste-to-aggregate bond strength was rated as “fair.”
- The total air content was measured to be 7.2%, with 6.4% entrained air and 0.8% entrapped air. The spacing factor was 0.003 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.40 and 0.45. These values lie within the recommended range for freeze-thaw resistant concrete[10].
- A close-up examination of the air voids throughout the sample revealed that, while some secondary ettringite crystals were lining some of the air voids, their presence was not enough to affect the freeze-thaw resistance capacity of the paste.
- Alkali-silica reaction (ASR) induced microcracking was found in both fine and coarse aggregates, as well as the paste, particularly within 60 mm from the surface. This is

shown in Figures 4.76 and 4.77.
- The surface texture was described as smooth and worn.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.75 Roseville - Core sample L&F-B

Figure 4.76 Roseville - Core sample L&F-B showing vertical and horizontal ASR-induced cracks (highlighted in red ink)

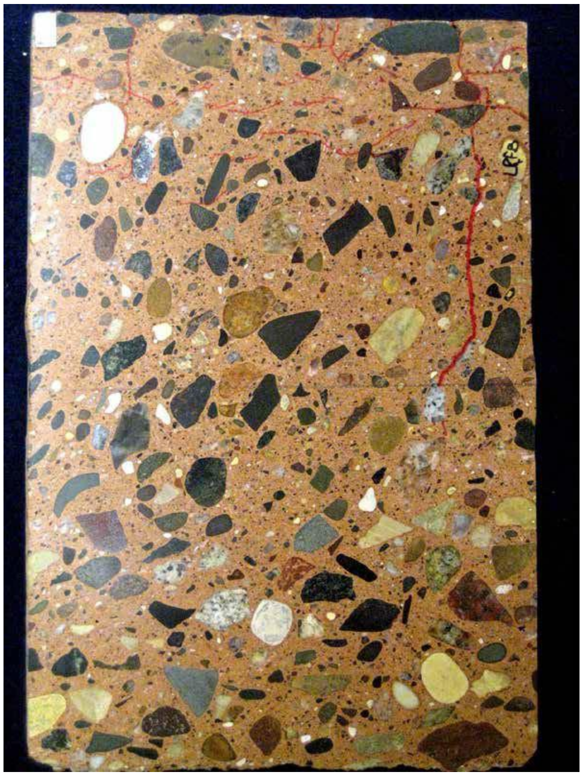
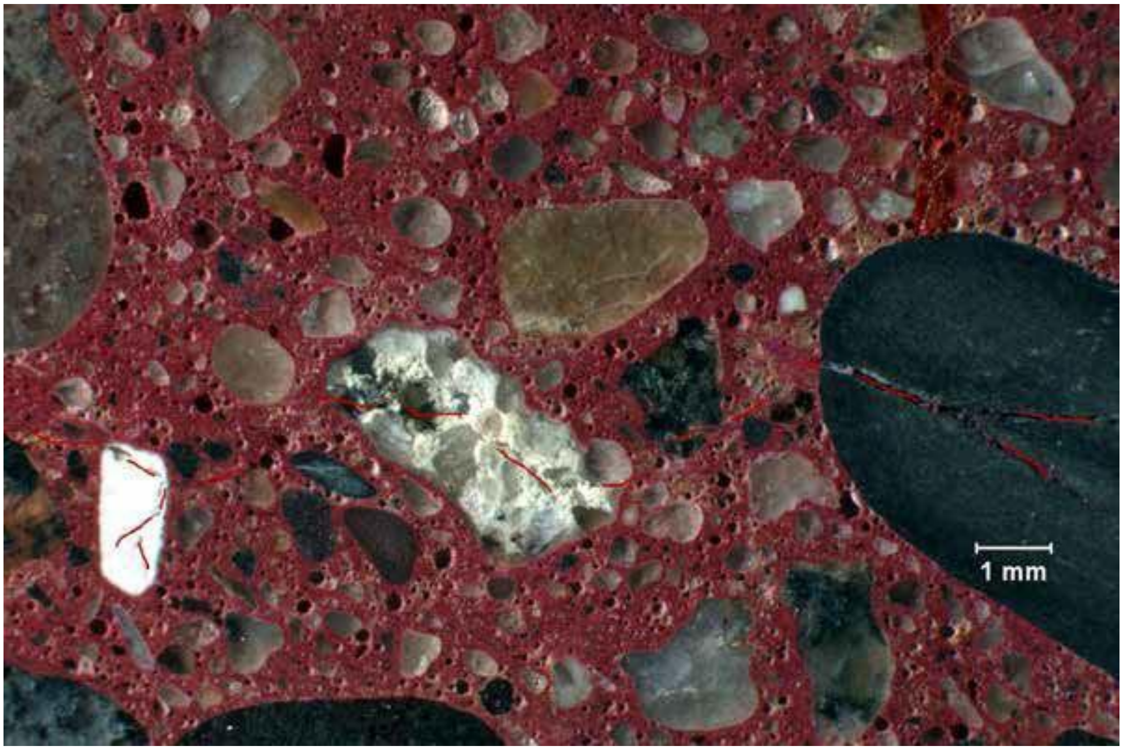


Figure 4.77 Roseville - Core sample L&F-B showing ASR gel product (highlighted in red ink) within microcracks traversing the paste, fine and coarse aggregate particles



<u>*Core L&F-C*</u>

Core sample L&F-C was taken in the middle of a panel, near some longitudinal cracking and other significant cracking along a transverse joint. Figure 4.78 shows the core location. Extensive delamination was observed in the core sample. See Figures 4.79 and 4.80.

Results from the petrographic analysis of Core sample L&F-C can be summarized as follows:

- The average core length was 8.12 inches.
- The paste portion was deemed to be relatively hard. The paste-to-aggregate bond strength was rated as "fair."
- The total air content was measured to be 7.8%, with 7.1% entrained air and 0.7% entrapped air. The spacing factor was 0.002 inches. This indicates the concrete originally contained an air void system which is consistent with the current definition of being freeze-thaw resistant.
- The water-to-cementitious ratio throughout the core sample was estimated to be between 0.40 and 0.45. These values lie within the recommended range for freeze-thaw resistant concrete[10].
- A close-up examination of the air voids throughout the sample revealed that, while some secondary ettringite crystals were lining some of the air voids, their presence was not enough to affect the freeze-thaw resistance capacity of the paste.
- Alkali-silica reaction (ASR) induced microcracking was found in both fine and coarse aggregates, as well as the paste, particularly within 50 mm from the surface. This is

shown in Figures 4.81 and 4.82. Figure 4.83 shows the prevalence of the ASR gel.

- The surface texture was described as smooth and worn.

Refer to Appendix A for additional results of the petrographic analyses.

Figure 4.78 Roseville - Core location L&F-C

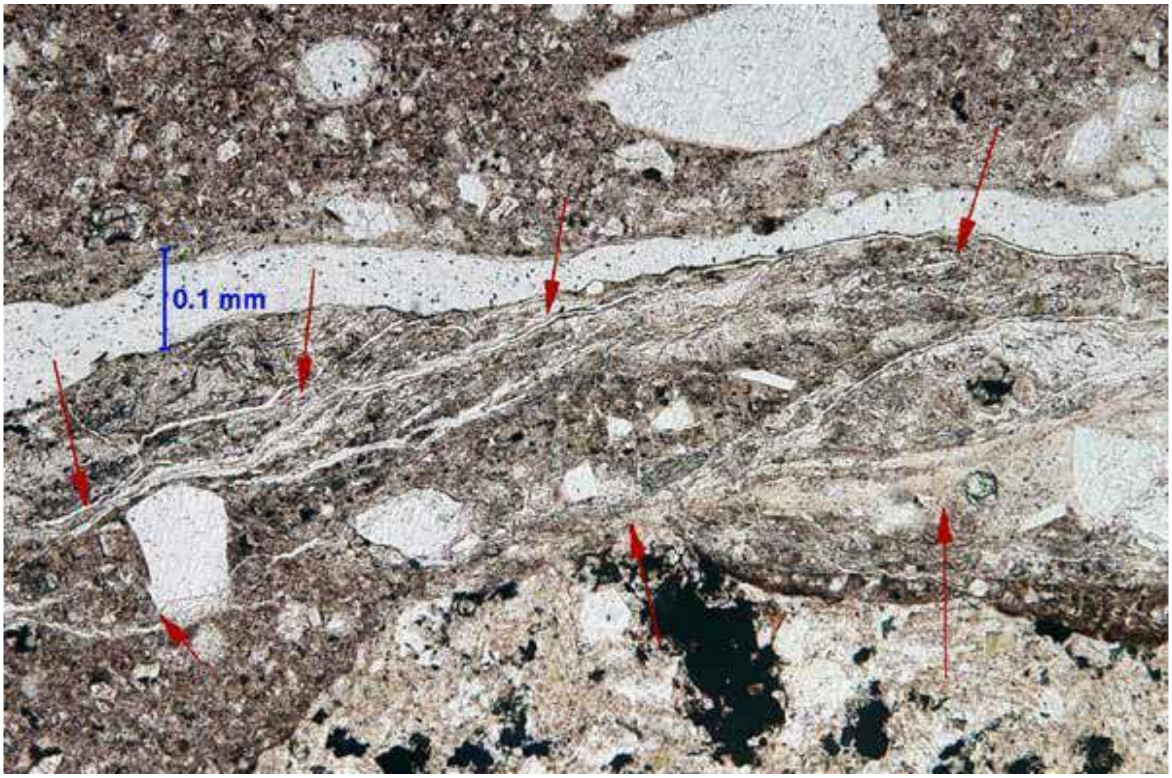
Figure 4.79 Roseville - Core sample L&F-C showing horizontal delamination crack

Figure 4.80 Roseville - Core sample L&F- C showing vertical crack up from horizontal delamination crack

Figure 4.81 Roseville - Core sample L&F-C showing vertical and horizontal ASR-induced cracks (highlighted in red ink)

Figure 4.82 Roseville - Core sample L&F-C showing ASR gel product (highlighted in red ink) within microcracks traversing the paste, fine and coarse aggregate particles

Figure 4.83 Roseville - Core sample L&F-C: Close-up view of clear ASR-gel product filling microcracks proceeding from an adjacent reactive aggregate particle (thin section under plane polarized light)



A summary of the results from the scanning electron microscope (SEM) and energy dispersive x-ray spectrometry (EDX) analysis of Core sample L&F-C can be summarized as follows (see Appendix B for the full report):

- There appears to be a high amount of larger entrained air voids, and they are often clustered. There also appears to be altered cement paste. See Figure 4.84. The altered paste was determined to generally have lower calcium contents, which is often consistent with calcium hydroxide being leached from the paste during the presence of deicers.
- Air voids at or near the affected zones were found to be filled with a calcium rich gel material (e.g., CaO ~35%, SiO_2~ 10%, MgO 1%, Al_2O_3~2%). The presence of this material was wide spread. It was co-mingled with ettringite or Freidel's Salt in many cases. This was a further indication of chemical dissolution of the cement paste.
- Figure 62 shows the repeated coincidence of magnesium and iron-based pigment in the L&F-C core sample, however the trend of these minerals grouping together was not as strong as in the 96A core sample.
- Due to the single sample and small specimen size, the research team was not yet comfortable identifying the exact mechanism of the chemical attack.

Figure 4.84 Roseville – Portion of core sample L&F-C: Backscattered electron image showing the cement paste matrix near the joint surface. Regions of the cement paste appear to be altered. Note the clustering of air voids

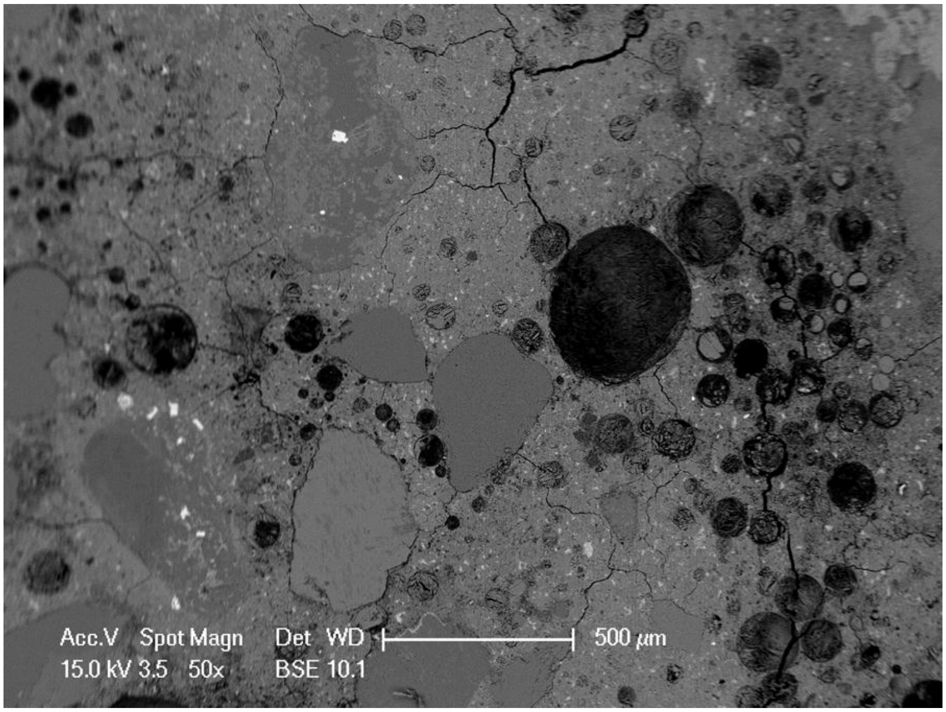
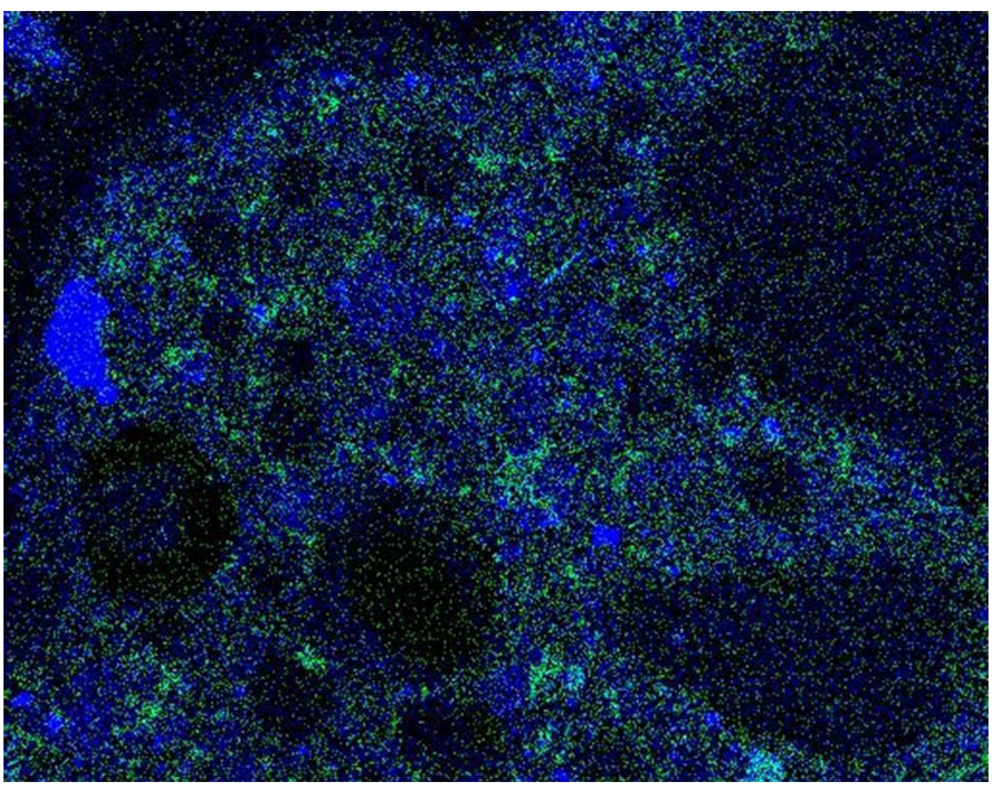


Figure 4.85 Vadnais Heights – Portion of core sample L&F-C, showing EDX image with magnesium (blue) and iron-based pigment (green) coinciding throughout the paste



Core L&F-D

Core sample L&F-D was taken over a longitudinal joint (that appeared to be in good condition) in the southern crosswalk spanning North Fernwood Street. Figures 4.86 and 4.87 show the coring location and condition of the joint at the surface. The sample showed good joint performance, with only slight widening of the joint near the bottom of the pavement. Internal aggregate interlock remains good. See Figures 4.88 to 4.89.

Core L&F-D was not subject to a petrographic analysis, but the condition of the core can be summarized as follows:

- The average measured core length was 8.75 inches.
- The sides of the core sample appear to be in good condition, with no visible cracks or signs of distress.
- The silicone joint seal was poorly bonded to one side of the joint reservoir.

Figure 4.86 Roseville - Core location L&F-D

Figure 4.87 Roseville - Core sample L&F-D (top view)

Figure 4.88 Roseville - Core sample L&F-D

Figure 4.89 Roseville - Core sample L&F-D

Discussion

The deterioration of the colored concrete at this location was less severe as seen from the surface. Examination of core samples confirmed that, unlike the other three sites in this study, secondary ettringite was not nearly as prevalent, and therefore not one of the primary causes of the distresses. Whether it is coincidental or not, it is interesting to note that the concrete in this intersection had a water-to-cement ratio less than the recommended maximum value of 0.45 for freeze thaw durability under severe climate exposure. Nevertheless, distress still occurred within both the joints and panels.

The primary distresses at this location were near-surface cracking and delamination, largely associated with alkali-silica reaction within the paste and aggregates. As mentioned for the Arden Hills site, there is cause for concern, as there is no local history of ASR reaction occurring in the commonly used aggregates used in these colored concrete mixes.

Given the prevalent delamination near the surface of the concrete, it is expected that the crosswalks in this intersection will continue to deteriorate, especially in the areas of high loads and moisture contents (joints). Since the distress is currently close to the surface, it may be reasonable to do partial or full-depth repairs to extend their service lives. It might also be beneficial to apply a liquid sealant material to slow the ingress of water and reduce the growth of the ASR gel.

As mentioned previously for the Centerville site, there should be concern for the lack of sufficient surface texture on the colored concrete in this intersection. For both vehicular and pedestrian safety, it seems that increased friction would be more beneficial in areas like intersections and crosswalks.

Summary

Four projects exhibiting distress in the colored concrete pavement were further investigated to determine potential causes. Core samples were extracted and examined using petrography, scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDX) techniques.

Examination of the core samples revealed the following observations:

- Water-to-cementitious ratios generally exceeded the maximum value of 0.45 recommended for producing concrete that is freeze-thaw durable in severe climates like Minnesota. Only the Roseville site had w/cm values generally less than 0.45. Coincidently, that is the only site that had very little ettringite crystals filling the entrained air voids.
- Many cores showed mixes with high water-to-cementitious ratios, which tend to have higher porosity. This likely led to the observed prevalence of secondary ettringite and magnesium throughout most of the core samples. Infilling of a substantial amount of entrained air voids with secondary ettringite is reducing the freeze/thaw resistance of the pavements. The use of magnesium chloride deicers has been linked in other studies to causing deterioration within concrete pavements.
- Given that all of the core samples that were examined showed that they were initially

constructed with an air void system that would provide freeze-thaw resistance, it is logical to rule out over-finishing practices during construction as the primary cause for the deterioration.

- Chemical attack was discovered in several samples. Observations ranged from soft and altered paste, to dissolving fine and coarse aggregates. The presence of alkali-silica reaction (ASR) gel, in commonly used aggregates that have not previously shown reactivity in standard concrete, is of great concern. Due to the small number of samples examined, the research team was not comfortable identifying the exact cause for the ASR and chemical attack. The prevalence of magnesium throughout the core samples is certainly one possibility, however other impurities in modern deicing materials may also be potential sources for the chemical reactions. Compatibility between concrete admixtures and color pigment is another area that was not addressed in this investigation.
- It is important to note that most colored concrete mixes are designed for high early strength gain. This impact of the higher volume of cement that these mixtures typically contain was not explicitly examined in this study.
- One interesting observation is that for all of the samples examined, the paste-to-aggregate bond was classified as poor to fair. Visible examination, as well as SEM and EDX techniques, show that pigment particles bond to the surface of aggregates, often non- uniformly. Due to the non-cementitious nature of pigments, it is likely they affect the paste–to-aggregate bond strength. While this loss of bond strength may not be enough to affect the load capacity of the concrete, perhaps it provides opportunities for freeze-thaw forces to develop the microcracking that is observed.
- Consolidation voids were present in about half of the samples examined. This is perhaps not unexpected, given the lack of vibration used during most colored concrete placements. While these voids have not affected the load capacity of these mixes, the
- voids nevertheless expedite the movement of moisture and deicing chemicals through the pavement.
- In three of the four sites examined, the microcracking within the joint regions extended from the top to the bottom of the pavement. Because of this, simple partial-depth concrete repairs are not likely suitable. In the cases where the distress is shallow, horizontal, and in the middle of the panel, milling and partial-depth repairs may be used to extend the life of the pavement. The application of penetrating sealers to slow the deterioration within joints may be another option, one that is currently being investigated as part of a national joint deterioration study.

CHAPTER 5: LABORATORY EXPERIMENTS

Determination of Component Effects on Durability

As described in Chapter 4 of this report, the main causes for the observed deterioration of colored concrete in Minnesota are reduced freeze/thaw durability, and/or unusual chemical attack from modern deicers. It was of interest in this study to understand further whether these causes were unique to colored concrete or just coincidental with other distresses being observed in standard concrete pavements in the Upper Midwest. To help answer these questions, a small laboratory experiment was designed and carried out. The laboratory experiment was designed to examine the variables of water-to-cementitious ratio and pigment content, and how they affect concrete freeze/thaw durability and vulnerability to alkali-silica reaction (ASR).

Experimental Design

To help understand some potential causes for the colored concrete distresses occurring in the intersection of Larpenteur and Fernwood in Roseville, it was decided to duplicate as close as possible the typical mixes placed in 2000. Modern day equivalent materials, such as aggregates from the same quarry, were gathered and proportioned according to the original mix design worksheet shown in Figure 5.1. Note that the original mix was designed to gain high early strength, and there was a 15% replacement of cement with Class C flyash. Because of the high early strength requirement, the cementitious content in the original colored concrete mix was increased, and therefore the design water-to-cementitious ratio was 0.33. Unfortunately, this lowering of the w/cm due to high cementitious content was not accounted for the in the mixes produced for the laboratory study. As shown in Table 5.1, the test mixes kept the same cementitious content, but increased the quantity of water significantly to meet the test w/cm ratios of 0.40 and 0.43. The new recommended upper limit of 0.43 for w/cm ratio is however, for standard strength colored concrete mixes. What should have been done was to calculate the equivalent high early strength w/cm ratio corresponding to a standard mix w/cm of 0.43. Nevertheless, it will be described later what effect the extra amount of mix water might have had on the test results that were produced.

Figure 5.1 Copy of original mix design worksheet for Larpenteur and Fernwood colored concrete placed in July 2000

Low S.P. #	62-630-45		Engineer	Paine	
Bridge #			Inspector	ESSLER	
Batch Plant	AGGREGATE INDUSTRIES # 5			Report # 1 CONT.	
Material	Size/ Type	Pit # or Manufact.	Specific Gravity	Absorp. Factor	Mix 3A21 HEF
Admix	A MIX250				
Cement	LAF	DAVT1	3.15		592
Fly Ash	PORTAGE2	Flyash			104
Fine Agg.	SAND	11904	2.64	0.008	1077
Coarse Agg	13mm-	11904	2.69	0.014	303
Coarse Agg	19mm-	11904	2.69	0.014	909
Coarse Agg	19mm+	11904	2.73	0.009	808
Design Water					232
Total Dry Solids Volume					

Table 5.1 Mix proportions for laboratory specimens produced in this study

Lab Mix, SSD (pcy) (1)	Mix #1- Control- No pigment - 0.43 w/cm	Mix #2- Pigment 4%- 0.43 w/cm	Mix #3- Pigment 4%-0.40 w/cm	Mix #4- Pigment 6%- 0.43 w/cm
Lafarge Davenport (lbs)	592	592	592	592
Portage Fly Ash (lbs)	104	104	104	104
Lakeville +3/4", Coarse Aggregate. (lbs)	742	742	757	742
Lakeville -3/4", Coarse Aggregate. (lbs)	823	823	839	823
Lakeville -1/2", Coarse Aggregate. (lbs)	274	274	280	274
Lakeville Fine Aggregate (lbs)	966	966	985	966
Water (lbs)	299.0	299.0	278.4	299.0
Vinsol Resin, Air Entrainer (oz/cwt)	0.8	0.8	0.9	0.8
Pigment, % by weight of cementitious	---	4.0	4.0	6.0
Water to Cementitious Ratio	0.43	0.43	0.40	0.43
Fresh Properties				
Unit Weight, pcf	144.0	145.2	144.8	146.0
Slump (in)	4.00	4.00	3.25	3.75
Air Content (%)	7.0	6.2	6.8	6.0

As shown in Table 5.1, test specimens were cast for four different mixes. The control mix, Mix #1, had no color pigment added, and was produced with the new recommended upper limit on water-to-cementitious ratio for colored concrete of 0.43. Mix #2 duplicated Mix #1, with the addition of colored pigment at the manufacturer's recommended dosage of 4% (by weight) of the total cementitious material. Mix#3 duplicated Mix #2, except the water-to-cementitious ratio was lowered to 0.40, in order to determine its effect of concrete durability. Finally, Mix #4 duplicates

Mix #2, except that a higher percentage of pigment was added to determine its effect on both durability and alkali-silica reactivity.

Once the equivalent components were secured, specimens for ASTM C666 (Resistance of Concrete to Rapid Freezing and Thawing) and ASTM C1567 (Potential Alkali-Silica Reactivity) tests were cast for the four different mix designs. For the ASTM C666 test, three 3 inch by 3 inch by 11.25 inch prisms were cast for each mix design. For the ASTM C1567 test, three 1 inch by 1 inch by 11.25 inch prisms were cast for each mix design. The results presented in the following section are the average value from each set of three test specimens.

Laboratory Test Results

Table 5.2 presents the results from the ASTM C666 freeze/thaw testing. As one can see, there were no significant differences in freeze /thaw performance between the four mixes. In addition, the high RDM values at 300 cycles demonstrate that if the mixes had been produced with less water (see section above describing error in quantity of mix water), it is likely they would have performed even better when subject to this test.

Table 5.2 ASTM C666 relative dynamic modulus (RDM) values, %, after 300 freeze/thaw cycles

Mix #1-Control-No pigment - 0.43 w/cm	Mix #2-Pigment 4%-0.43 w/cm	Mix #3-Pigment 4%-0.40 w/cm	Mix #4-Pigment 6%-0.43 w/cm
94	89	97	92

Figures 5.2 and 5.3 present the results from the ASTM C1567 testing (potential for ASR) with the fine and coarse aggregate portion of the mixes, respectively. The expansion of the specimens containing cement, flyash, fine aggregates and pigment surprisingly increased with time. In addition, the amount of expansion surpassed the C1567 recommended limit of 0.10% expansion after 14 days. In contrast, the specimens containing cement, flyash, coarse aggregates (crushed to fit into the prism) and pigment did not show significant differences between the colored and non-colored mixes. In this case, the specimens again surpassed the recommended limit of 0.10% expansion after 14 days.

With regards to the inadvertent extra mixing water added to the mixes, it is unlikely the ASR results would be significantly different, as the standard water-to-cementitious ratio recommended by the ASTM C1567 standard test protocol is 0.47 [11].

Figure 5.2 ASTM C1567 potential ASR expansion test results for prisms containing fine aggregates

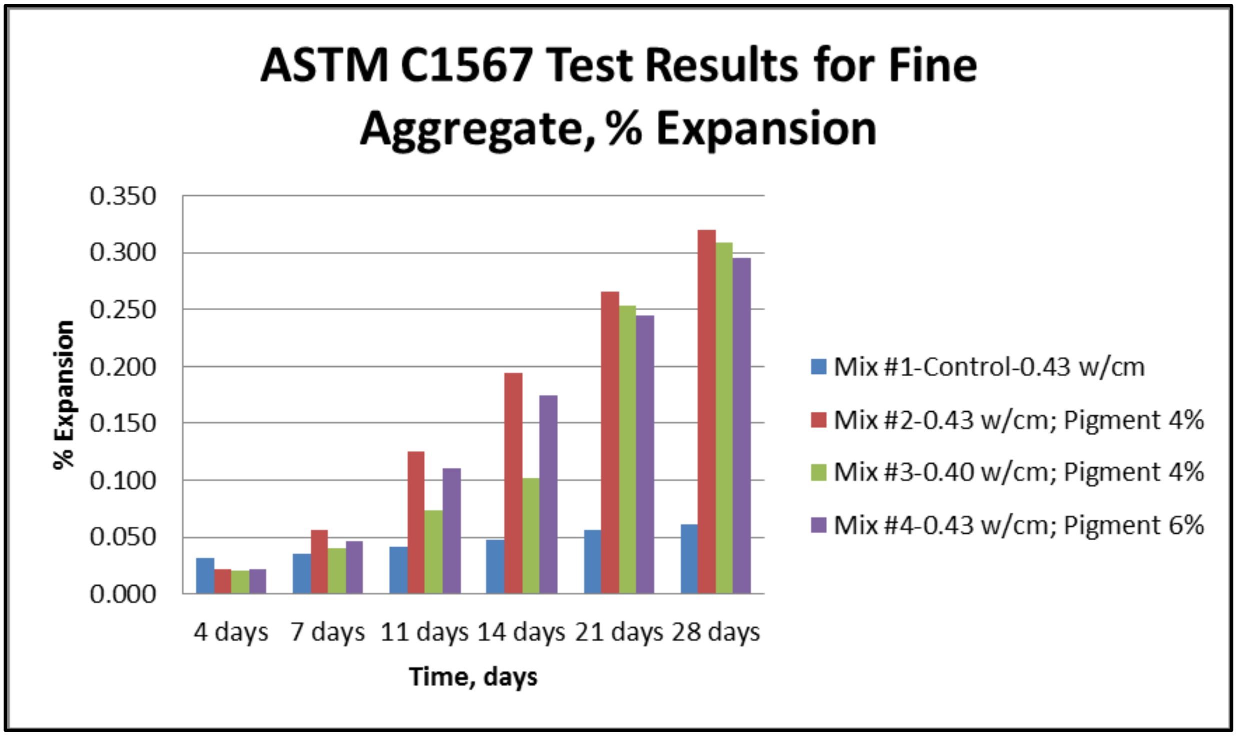
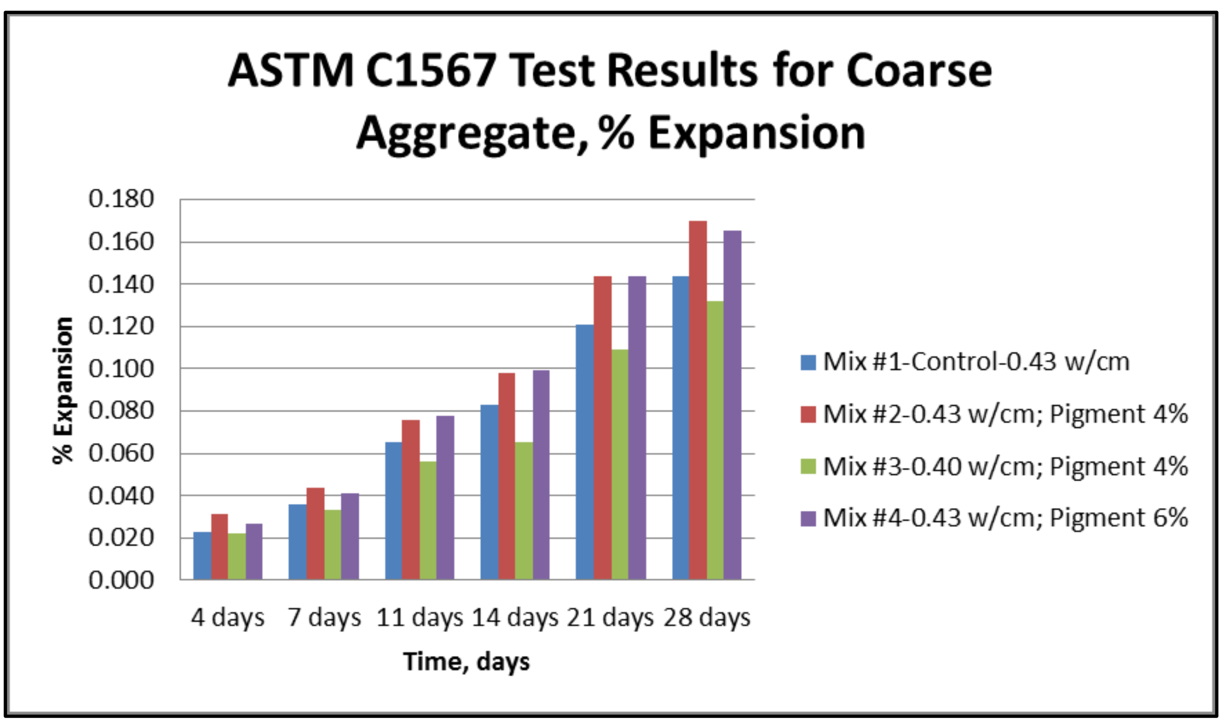


Figure 5.3 ASTM C1567 potential ASR expansion test results for prisms containing coarse aggregates



Discussion

Based on the ASTM C666 testing done in the laboratory, it appears the addition of pigment to concrete has little effect on its freeze/thaw durability. The use of a slightly lower water–to-cementitious ratio, 0.40 compared to 0.43, did seem to increase the durability test results slightly, although the sample size is too small to draw conclusions. It is clear that lower water–to-cementitious ratios ($\leq$ 0.43) result in freeze/thaw durable colored concrete mixes.

Analysis of the ASTM C1567 test results revealed that there is a strong tendency for alkali-silica reactivity when adding colored pigment to the cement, flyash and fine aggregates used in the mixes tested in this study. There was only a slight difference in expansion of the prisms for specimens containing the cement, flyash and coarse aggregates used in the mixes. In both cases however, the recommended limit of 0.10% expansion after 14 days was exceeded. What is of concern is that this alkali-silica reactivity is not typically associated with the coarse and fine aggregates used in this study, particularly when they are used in non-colored concrete. Unfortunately, due to the very limited number of samples tested in this study, it is not clear whether this was an anomally or not. What we do know is that ASR was identified in both the fine and coarse aggregates in the core samples pulled from the Larpenteur and Fernwood intersection, which is what the laboratory mixes were patterned after. To determine the true cause of the ASR in both the laboratory samples and the core samples, a much more extensive investigation would need to be done.

It is important to emphasize the very small number of specimens tested in this study. Drawing conclusions about the potential performance of colored concrete pavements based on this laboratory study is not advised at this time.

CHAPTER 6: THERMAL RESPONSE

Thermal Characteristics of Concrete Pavement

Understanding and accounting for the thermal characteristics of a material is one of the primary keys to successful engineering design. This is particularly true with concrete pavements, where the forces involved can be quite tremendous. One example can be seen in Figure 6.1, where a colored concrete median developed very dramatic and destructive buckling. Figure 6.2 shows that in other cases, it simply produces unwanted cracking. As shown in these figures, it is apparent that the understanding of the thermal behavior of colored concrete is very important.

This section describes the results of a small and simple experiment that demonstrates the thermal characteristics of colored concrete.

Figure 6.1 Buckled median caused by expansive forces in colored concrete

Experimental Test Slabs

To characterize the thermal behavior of colored concrete, small test slabs were constructed at the MnROAD facility in Albertville, MN. This site was chosen to take advantage of the ability to collect longer term data from sensors embedded into the test slabs. To characterize the difference between standard concrete and colored concrete, three slabs were built side by side. These slabs can be seen in Figure 6.3.

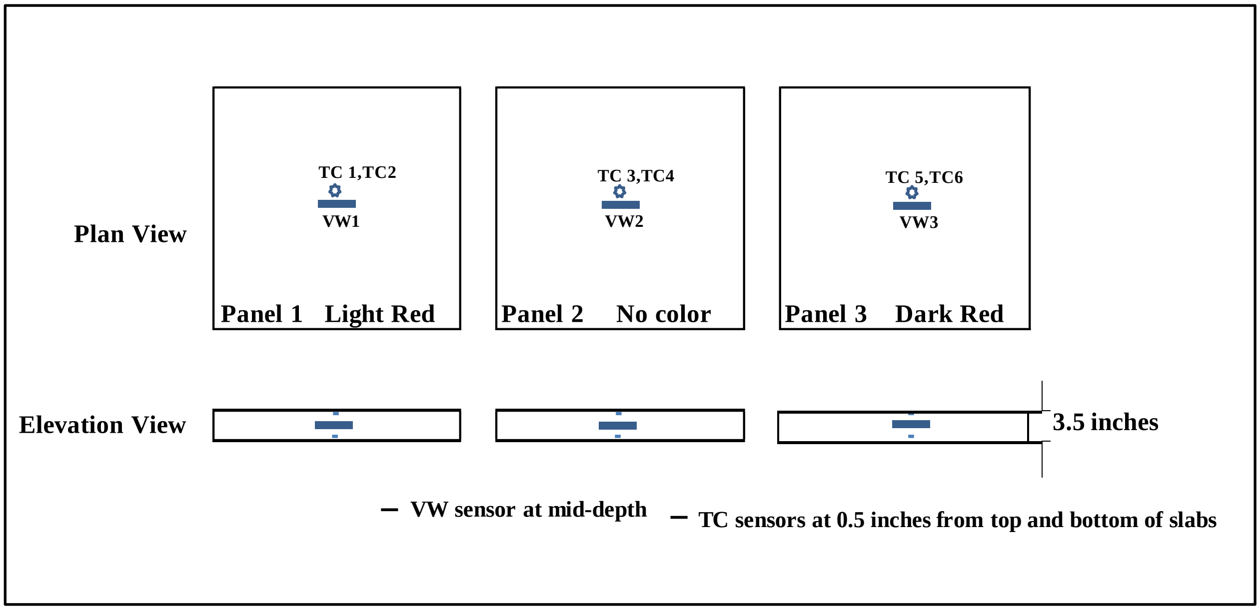
Figure 6.2 Crack in sidewalk, likely produced by expansion of neighboring colored concrete strip

Figure 6.3 Concrete test slabs built at the MnROAD facility to evaluate the difference in thermal behavior under field conditions

The test slabs were constructed on September 17th, 2013. The dimension of each slab was 3.5 inches thick by 4 feet square. They were constructed using MnDOT 3U18 concrete patch mix. As shown in Figure 6.3, one panel was produced without color, while the other two had pigment added to create lighter and darker colored concrete panels.

Embedded thermocouple wire sensors were installed near the center of each slab to measure internal concrete temperature near the top and bottom of each slab. One vibrating wire strain sensor was also installed at the mid-depth of each slab, to measure its expansion and contraction with changing temperatures. Figure 6.4 depicts the test slabs and sensor locations. The sensors were installed and operating during the placement of the concrete.

Figure 6.4 Description of MnROAD colored concrete test slabs, including locations of embedded sensors



Temperature Readings

Thermocouple data, from the first 30 days after the slabs were constructed, was analyzed to determine the difference in temperature response from the three slabs. Figure 6.5 shows the responses from the thermocouple sensor near the surface of each slab for several days of the week following construction. It is evident from the plot that the darker colored slab, Panel 3 (as recorded by thermocouple number 5), experiences noticeably higher temperatures near the slab surface than both the lightly-colored and non-colored slabs. In fact, the light red slab experienced only 2% higher top slab temperatures on average than the non-colored slab, while the dark red slab experienced about 30% higher temperatures. As expected, temperature differences near the bottom of the three slabs were very small.

Besides a simple comparison of temperature differences between the concrete pavement slabs, it is often times more important to characterize temperature gradients within the slabs. Temperature gradients, commonly defined as the difference in temperature between the top and bottom of a slab, can have a strong influence in the overall shape of a slab, thus resulting in unsupported areas beneath the slabs. The physical response to temperature gradients in a slab is often referred to as curling. This curling can result in higher stresses between neighboring slabs, which can lead to issues such as those depicted in Figures 6.1 and 6.6. Analysis of the data from the MnROAD slabs showed that the light red slab experiences 25% higher temperature gradients than the non-colored slab, while the dark red slab experiences 80% higher temperature gradients than the non-colored slab. And while the use of joint expansion materials can often help alleviate such expansion stresses between panels, their effect can be reduced if incompressible materials get into the joint during extreme cold conditions, thus decreasing the available expansion space.

Thermal Expansion Response

As with most solid objects, concrete pavements expand as they get warmer. The rate at which materials expand and contract is defined by a material property called the coefficient of thermal expansion (COTE). A typical COTE value for concrete is 8 µe/ºC. A concrete slab will expand and contract at this rate as long as it is free to expand in all directions. Since concrete pavements are connected systems that lie outside on the ground, their thermal response is influenced by factors such as friction from the underlying base, restraint from neighboring slabs, and solar radiation. Therefore, when characterizing the thermal behavior of colored concrete pavements, we need to determine the rate of thermal expansion (RTE) of the slab system. Since the test slabs in this study were constructed independent of each other, the main influences on RTE are the friction at the base of the slab, and the color of the slab. Since all of the slabs were constructed on the same type of base, is it assumed in this analysis that their base friction is similar (equal). This just leaves their color difference as the variable in the experiment.

As mentioned previously, to measure the thermal expansion response of the test slabs in this study, vibrating wire strain sensors were embedded into the test slabs. Locations of the sensors in the slabs are depicted in Figure 6.4. Since the sensors are constructed from a material other than concrete, their data must be temperature corrected when determining the mechanical strain of the concrete pavement. The mechanical strain is defined as the relative change in slab length compared to a starting baseline length. More information on MnROAD VW sensor temperature corrections and the determination of a starting baseline length can be found in a report by Burnham and Koubaa[12].

Interestingly, while the slab temperatures measured in the three slabs behaved quite differently, the mechanical strain trends were different. On average, the mechanical strain for the light red slab was 10% higher than the non-colored concrete, while the mechanical strain for the dark brown slab was 18% higher than the non-colored concrete. Figure 6.7 shows a one day trend in mechanical strain for the three slabs. It is clear that colored concrete slabs expand at a greater rate than standard non-colored concrete slabs. Therefore, designers must carefully consider thermal expansion response when laying out a project with different colored concretes next to each other.

Figure 6.5 Temperature responses near surface of experiment slabs at MnROAD

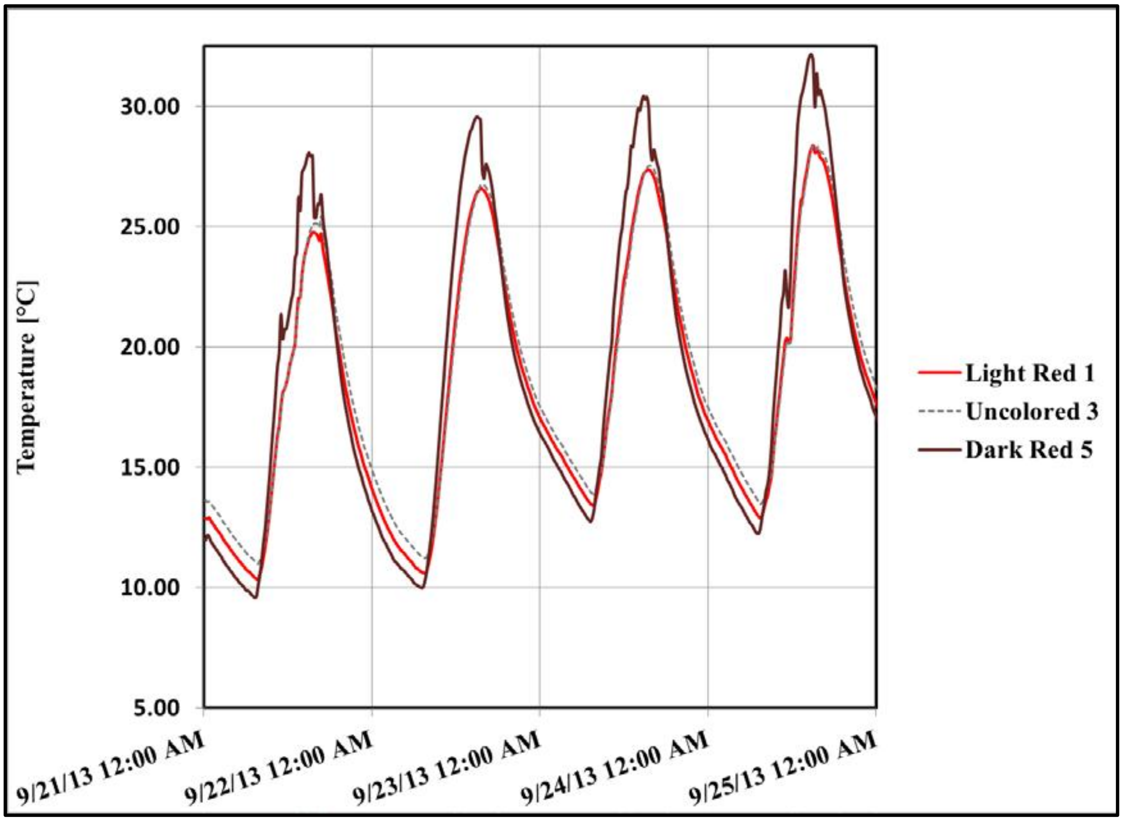
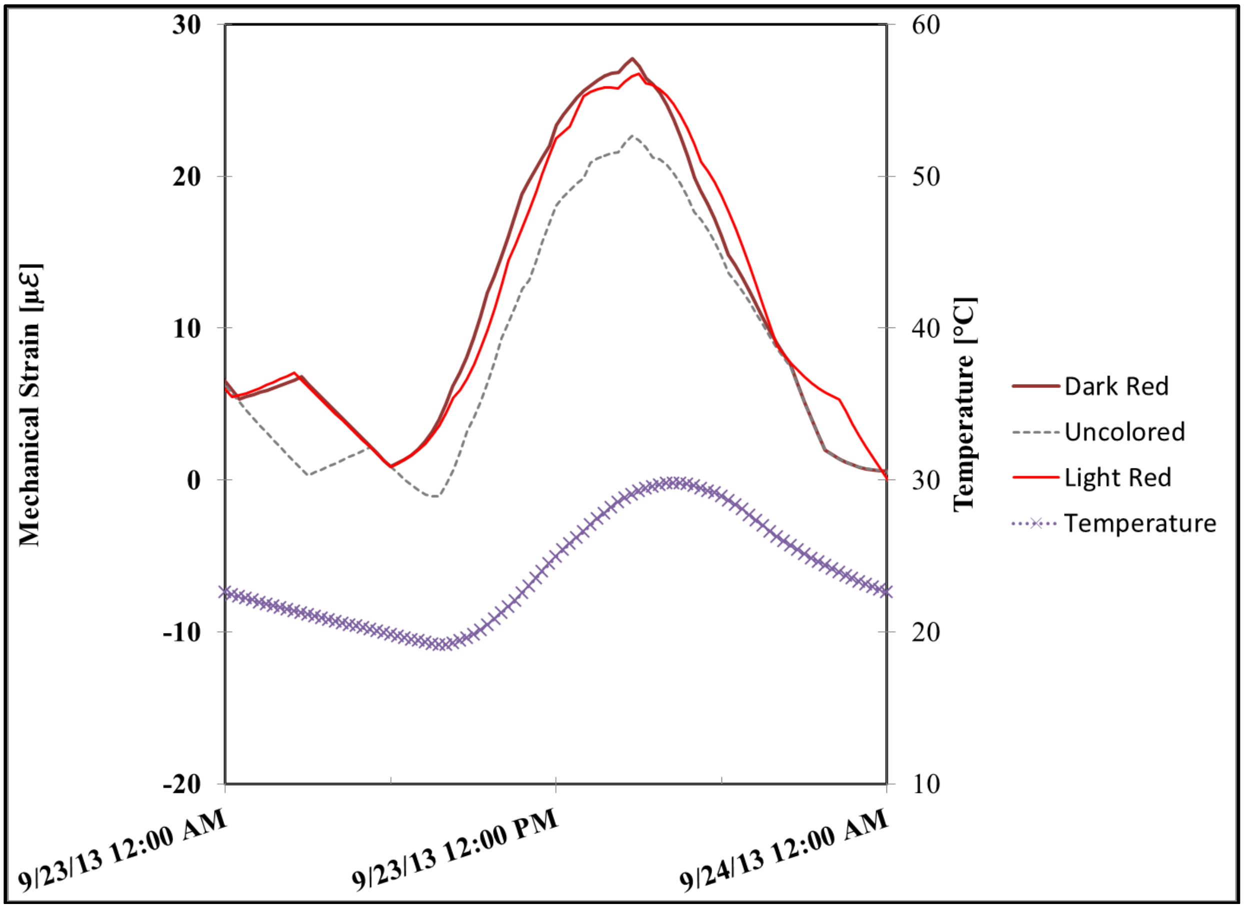


Figure 6.6 Expansion of slab near surface, due to temperature gradients, may lead to surface spalling near the edge of panels

Figure 6.7 Trend in mechanical strain for experiment slabs at MnROAD



CHAPTER 7: RECOMMENDED CONSTRUCTION METHODS AND MIX DESIGN SPECIFICATIONS

Construction Methods for Colored Concrete Pavements

Current Methods

Chapter 3 of this report highlighted the observations of some recent construction projects involving the placement of colored concrete pavements and structures. Those observations, in addition to knowledge gained from other pavement experts during the time of this study, revealed some common elements in the current construction methods used for colored concrete roads, medians and sidewalks. The methods associated with construction of colored concrete pavements (mainly crosswalks) can be summarized as follows:

1. A common practice for constructing roads with colored concrete crosswalks, is to place the mainline non-colored concrete pavement with a slip-form paver, and then leave exceptions (headers and/or block-outs) for the areas that are later in-filled with the colored concrete crosswalk. This practice leads to extra hand work near the areas where the crosswalk is poured. Hand work often results in less uniformly consolidated concrete that can be more susceptible to future distresses (even in the non-colored concrete areas).
2. Most colored concrete used to construct crosswalks is hand placed and finished. This typically involves consolidation simply through the act of striking off and leveling the surface with a piece of lumber. The consolidation using lumber alone often leads to less consolidation than desired, which then ultimately results in larger air pockets that can expedite the movement of deicing chemicals down through the pavement. During the research team's visits to construction sites, only one contractor used a vibrating screed for leveling and mix consolidation of colored concrete (in a median).
3. Also associated with hand finishing of colored concrete, is excessive troweling to smooth the surface and create joints and rounded edges. This practice can result in creating a thin weak layer of paste that is susceptible to surface scaling. Fortunately (and surprisingly), surface scaling and loss of significant air content near the surface was not a common observation in the colored concrete crosswalks examined in this study.
4. Observed methods for curing of colored concrete ranged from the use of a pigment manufacturer supplied colored curing "wax", to projects where no curing was used (a contractor stated that the city did not require curing of colored concrete).
5. As noted throughout this report, it was a common observation that much of the colored concrete placed was finished smoothly. Given the location and function of crosswalks and sidewalks, it seems that users would expect and benefit from a properly textured surface.

Recommended Improvements

While the findings of this study suggest that current construction practices for colored concrete are not the primary cause of the observed distresses, it has been demonstrated that one of the solutions to mitigating future problems will be to construct denser and better consolidated concrete. The following recommendations are likely to provide the necessary improvements that will produce more durable and functional colored concrete pavements:

1. To reduce the required handwork associated with exceptions in the mainline pavement, it is suggested to continuously slip-form the (non-colored) pavement past the area of the crosswalks, and then come back later to saw and remove the concrete in preparation for the installation of the colored concrete. To improve the performance of the crosswalk, it is recommended that crosswalks be connected to the neighboring concrete through the use of dowels. Guidance can be found in the procedures recommended by MnDOT for full-depth joint repairs [16]. Finishers should take care to ensure that a bump is not created by the colored concrete crosswalk. This can lead to damage of the edges of crosswalk by snow removal equipment.
2. It is recommended to follow the latest recommendations and guidelines for the placement of durable and functional concrete in Minnesota. Recently updated guidelines for flatwork construction in Minnesota can be found in a March 2014 report titled: “Minnesota Concrete Flatwork Specifications”[13]. Since the majority of colored concrete will continue to be placed using hand methods, it is important that the workers involved understand the importance of full consolidation of the mix, as well as the avoidance of over-finishing the surface. When possible, use a vibrating screed to level and consolidate the mix. If a screed is not available, supplement leveling and consolidation of the mix with the use of pencil type vibrators. Do not however over- vibrate the mix, as this may alter the entrained air system within the concrete.
3. Colored concrete is darker and less reflective than standard concrete, and therefore it tends to heat-up and hardened quickly in sunny conditions. At no time should the surface have water added to help finish a mix that has already started to harden. This may lead to scaling of the surface in a short amount of time. Coordinate your placement and finishing teams such that these operations are completed well before the concrete begins to harden.
4. Apply appropriate curing techniques at the proper time. As with any concrete, proper curing is necessary for long term durability. Curing colored concrete can be challenging, as common white pigmented compounds cannot be used. Common curing materials for color concrete included color waxes and clear compounds. Unfortunately, both of these methods lack the heat reducing reflectance provided by white pigmented curing compounds. Therefore, steps should be taken to devise ways to keep the colored concrete cool while it is curing with those compounds applied to them. This could be techniques involving shade provided by elevated tarps or curing blankets, or by simply scheduling pours during times of minimal sun exposure.
5. The most common locations in the roadway for colored concrete are crosswalks and sidewalks. Not only must the concrete be decorative, but it must also be functional, by providing safe passage to both vehicles and pedestrians. Therefore, it is imperative that adequate surface texture be constructed into the surface of these structures. At a minimum, ***a broom texture at least 1 mm deep*** *must be applied to the surface prior to application of*

the curing method.

Further guidance on the construction of durable concrete structures in Minnesota can always be found be contacting the MnDOT Concrete Office.

Recommended Mix Design Specifications

Producing durable colored concrete mixes is no different than producing durable non-colored concrete mixes. Much experience and development goes into the current concrete mix design specifications used by MnDOT. These specifications produce mixes that have been shown to perform well in concrete pavements subjected to the extreme climate of Minnesota. Components of the specifications are designed to create mixes that are very dense (to reduce permeability), yet have adequate air void systems to protect against freeze/thaw damage. Perhaps the biggest change in the specifications came in the late 1990's, when the specified water-to-cementitious ratio (w/cm) limit was lowered to 0.40 for slip-form paving mixes. Other changes included well- graded aggregates that result in less paste in the mix. Finally, the substitution of cement in the mix, with other supplemental cementitious materials like flyash and slag, has helped to mitigate tendencies toward the development of issues like alkali-silica reactivity.

While lower w/cm mixes have been successfully adopted for slip-form paving in Minnesota, they can pose challenges for hand-placed concrete, like that used in most colored concrete structures. Lower w/cm mixes tend to be much stiffer and produce less bleed water, and therefore can be more difficult to place and finish by hand. Fortunately, a broad range of chemical concrete admixtures (i.e. water reducers) are now available that can help to create colored concrete mixes that are both durable and easy to place. *To help avoid potential workability issues associated with lower w/cm mixes,* ***it is recommended that hand-placed colored concrete be produced with a maximum w/cm of 0.43.*** This should go a long way in producing colored concrete mixes that are less permeable than the mixes commonly produced in the past. It is important to note that specifying w/cm can be misleading, as was experienced by the research team during the laboratory testing in this study. A majority of the colored concrete currently placed in crosswalks in Minnesota is specified and designed to have early strength development. Therefore, the water-to-cementitious ratio must be adjusted (significantly downward) for the extra cementitious material added to the mix to provide the early strength gain.

Since the majority of colored concrete is produced in ready-mix plants, it is not practical to recommend and follow the MnDOT specifications for well-graded aggregates. Nevertheless, it is important to understand the source of the aggregates being used at the ready-mix plant, to avoid aggregates that have shown a history of being susceptible to alkali-silica reactivity. Given the findings of ASR in this study, there may be combinations of color pigment, fine aggregates, and/or deicing chemicals that may have to be avoided, or mitigated with supplemental cementitious materials. The findings from the limited laboratory work in this study demonstrated that ASR was developing even with 15% flyash in the mix. Much more research must be done before final specification recommendations can be made with regards to durable aggregate types and methods of ASR mitigation for colored concrete.

For freeze/thaw durability, it is important to create an adequate and well-distributed air void system in colored concrete. And given the observations in this study of secondary ettringite filling the air void systems of colored concrete, it is imperative the beginning air content follows the recommended specifications. Following MnDOT specifications, it is recommended that colored concrete pavement mixes being designed and produced with a target total air content of 7.0% (+2.0%, -1.0%), before consolidation.

As with the construction methods, further guidance on the creating mix designs that produce durable colored concrete pavements in Minnesota can be found be contacting the MnDOT Concrete Office.

CHAPTER 8: REPAIR AND REHABILITATION TECHNIQUES

Introduction

As with standard concrete pavements, colored concrete pavements can experience both structural related and materials related distress over time. Due however to the inherent architectural aspect of colored concrete pavements, many standard concrete pavement repair and rehabilitation techniques are either not suitable, or need modification to be accepted. It is therefore of interest, and the objective of this task, to identify suitable repair and rehabilitation techniques for distressed colored concrete pavements. As shown in previous tasks in this study, structural load related distress has been minimal in the colored concrete pavement sections surveyed. Therefore the focus of this task was to determine suitable repair and rehabilitation techniques for primarily materials related distress.

Since the application of colored concrete to pavements in Minnesota has gained popularity only recently, many of these pavements are newer, and therefore have not received repairs or rehabilitation. Repairs to the sections in Ramsey County, constructed in the late 1990's, have primarily consisted of filling the deteriorated joints with asphalt patch mix. While unsightly, and counter to the original intent of the pavement, this repair does seem to provide some restoration of service, although maintenance of the patches is likely to be frequent. The intent of this chapter is to provide longer term repair and rehabilitation solutions that maintain the original architectural or functional aspect of colored concrete pavements. It is organized first by distress type, then by potential repair and rehabilitation options.

Joint Deterioration

One of the primary reasons for this study was the observation of significant early age joint deterioration in a number of projects containing colored concrete pavements, sidewalks, and medians. See Figures 8.1 and 8.2 for examples. The repair or rehabilitation techniques available for this type of distress depend on the type of deterioration in the joints. Standard techniques used for the repair of normal (non-colored) concrete can often be considered, except if color matching is important to the owner.

Before any repair or rehabilitation technique is considered, the cause and extent of the distress must be determined. The best way to do this is to examine core samples extracted from the distressed joints. Other simple and low cost techniques, such as chain dragging, can be used to map the extent of deteriorated or delaminated areas. Finally, more extensive distress surveys can be conducted using non-destructive techniques like ultrasonic tomography or ground penetrating radar, but these techniques can be rather expensive.

Once the suspected cause and extent of the distress has been identified, the suitable repair and rehabilitation techniques can be considered. Concrete repair guidelines suitable for the Minnesota climate are readily available[14]. These guides help identify appropriate techniques to apply for specific types of distress in concrete joints and slabs. While not specifically designed to address repairs of colored concrete, these techniques have been proven to add significant life to standard concrete pavements.

Figure 8.1 Example of joint distress in older pavement. Suitability for repair must be determined via core samples or other test methods.

Figure 8.2 Example of joint distress in newer pavement. Suitability for repair must be determined via core samples or other test methods.

It is important to note that if the distress is expansive in nature (i.e. ASR), or it has been developing rapidly, often the only viable repair solution is to remove and replace the entire slab.

The next sections highlight several of the repair techniques that may be suitable to the types of joint distress occurring in colored concrete in Minnesota.

Partial–Depth Repairs

Partial-depth repairs may be effective if it is determined that the joint distress is present only in the upper third of the depth of the slab. Note that most of the joint deterioration observed during this study extended the full depth of the joint, and in these cases, partial-depth concrete joint repairs will not likely to perform well for very long. If the existing colored concrete has a high water-to-cementitious ratio, and therefore high permeability through the mix, the remaining concrete that the patch material is trying to bond to will likely continue to develop distress as well. If, however, it is determined that the distress is caught early, and is only present near the surface of the pavement, partial-depth repairs can be used to extend the life of the pavement for many years.

If deemed appropriate, standard partial-depth concrete repair techniques, referred to as Type B repairs in MnDOT's concrete pavement rehabilitation guidelines[14,15], can be used. The repair material can be colored with pigment to match the existing slabs (within reason). Alternatively, non-colored patch material can be placed and left as is, or the repair and surrounding areas can be blended together using a stain, dye or colored surface treatment.

Full–Depth Repairs

As noted previously, most of the joint deterioration observed during this study extended the full depth of the joint. Figure 8.3 shows one such example. If the underlying cause of the distress is high permeability within the existing colored concrete, establishing new joints may not prevent the continuing formation of distress within the slabs.

If deemed appropriate, standard full-depth concrete repair techniques, referred to as Type C3D repairs in MnDOT's concrete pavement rehabilitation guidelines[14,15], can be used. The repair material can be colored with pigment to match the existing slabs (within reason). Alternatively, non-colored patch material can be placed and left as is, or the repair and surrounding areas can be blended together using a stain, dye or colored surface treatment.

With each of the repair systems described above, it is important to reseal any contraction and contraction joints. The ingress of water and deicing chemicals are the primary driver of deterioration in concrete pavement joints. Once the joints have been resealed, it is very important to maintain that seal through periodic inspection and a routine resealing program.

Full Slab Deterioration

In cases where the deterioration and distress extends beyond the joints and substantially into the slab, repair options are typically limited to full-depth slab replacement, or a limited number of surface treatment options.

Figure 8.3. Core sample showing deterioration along the entire length of the joint. The red lines highlight microcracking near the joint face.

<u>Full–Depth Slab Replacement</u>

Several cases were found in this study that demonstrated the need for full-depth slab replacement. Figures 8.4 through 8.6 show three such examples. The slabs in the Figure 8.4 project are too deteriorated internally to support most types of repair. The extensive thermal stress cracking and buckling shown in Figure 8.5 also requires full-depth slab replacement. In this situation, additional consideration must be given to provide adequate stress relief, due to the differing thermal expansion rates of the darker colored concrete, the standard concrete curbs, and structures such as manholes. The rapid acceleration in joint deterioration in the colored concrete intersection shown in Figure 8.6 would also be a suitable candidate for full-depth slab removal. As identified in Figure 8.3, when a concrete system is inherently too porous due to a high water- to-cementitious ratio, and the air system has been compromised by secondary ettringite, it is unlikely partial or full-depth joint repairs, or penetrating sealant materials, could effectively slow the rate of deterioration. Full-depth slab replacement can be done using standard MnDOT Type D repair guidelines [14,15]. The replacement concrete can be colored with pigment to match neighboring slabs (within reason). Alternatively, non-colored patch material can be placed and left as is, or the repair and surrounding areas can be blended together using a stain, dye or colored surface treatment.

Figure 8.4 Deterioration of the slabs is too extensive, therefore requiring full slab replacement.

Another full-depth slab replacement technique that could restore or maintain the architectural or functional aspect of colored concrete, might be to replace the distressed colored concrete with a colored interlocking concrete paver system. Materials and construction guidelines for these pavements can be found on the Interlocking Concrete Pavement Institute website[16]. An example of an intersection constructed with interlocking concrete pavers can be seen in Figure 8.7. Repairs in this type of system are far easier than full-depth colored concrete systems.

Figure 8.5 Cracking and buckling of colored concrete median. This type of distress requires a full-depth slab replacement.

Figure 8.6 Accelerated joint deterioration occurring throughout intersection. The potential for continuing distress at new joint faces (created during repair process) necessitates full-depth slab replacement.

Figure 8.7 Interlocking concrete paver system in St. Paul, MN intersection.

Surface Treatments

If the distress in a colored concrete pavement is caught early enough, there are surface treatments that could be applied to slow the deterioration. Although still under development and study, some benefit has been shown through the application of penetration sealant materials like epoxy, high molecular weight methacrylate (HMWM), lithium, silane, siloxane, or soy methyl ester (SME)[17,18,19]. Many of these materials are transparent when applied, and therefore should be suitable for use on colored concrete pavements.

To avoid problems with potentially ineffective treatments, it is recommended to consult the approved products list maintained by the MnDOT Concrete Office and Bridge Office. Products on these lists have undergone rigorous review and testing, and are often suitable for heavy traffic applications.

Alternative Surface Coloring Methods

As mentioned in many of the repair options above, concrete repairs can be made with standard (non-colored) concrete, and then surfaced with a thin colored material. Perhaps the simplest option is to use special stains or dyes designed for coloring concrete. Due to their minimal penetration into the concrete, this option is likely to be short lived in typically pavement situations where heavy snow plows are used to maintain the road. Certainly areas like medians and sidewalks would tend to retain their color for much longer periods. The benefit to this option is that it can be applied and maintained by local road maintenance crews.

Another viable alternative is to use a slightly thicker material that utilizes some kind of binder in conjunction with a very thin lift of colored aggregate or media. These are often referred to as "High Friction Surface Treatments." They provide additional benefit in that the binder, often a polymer or epoxy, also serves to seal the surface of the concrete, thus reducing future ingress of water and deicing chemicals. One drawback however, is that on an existing pavement, the height of the treatment may result in a slight bump, although many colored concrete crosswalks already exhibit this behavior due to current construction methods (infilling). It may be possible (but at added cost) to create a slight recession in the pavement using a micro-milling or grinding machine to create a suitable finished profile. Durability and lifespan of these treatments are still under investigation, however 3 to 5 years before retreatment seems reasonable. Again, one benefit to this system is that it can be applied and maintained by local road maintenance crews.

To avoid problems with potentially short-lived surface treatments, it is recommended to consult the approved products list maintained by the MnDOT Concrete Office and Bridge Office. Products on these lists have undergone rigorous review and testing, and are often suitable for heavy traffic applications.

Summary

Due to the observation of early distress in colored concrete pavements, medians and sidewalks in Minnesota, there was a need to investigate suitable repair techniques that are both durable and cost effective. The objective of this task was to identify such suitable repair techniques.

Depending on the cause and extent of the deterioration in the colored concrete, many repair techniques normally suited to standard (non-colored) concrete were identified. These included partial or full-depth joint repairs, or full-depth slab replacement. Interlocking concrete paver systems were also introduced as a viable alternative to full-depth slab replacement. Suitable surface treatments such as penetrating sealers were also discussed. Many of these types of materials remain under investigation as to their effectiveness and longevity.

Finally, alternative surface coloring methods were introduced. Examples included concrete stains, dyes, or the application of a colored "High Friction Surface Treatment." These options are desirable due to their inherent ability to provide a wide range of colors suitable for blending in repair areas, including those utilizing standard (non-colored) concrete patching materials.

CHAPTER 9: SUMMARY AND RECOMMENDATIONS

Summary

The primary objectives of this study were to document the material behavior and construction aspects of colored concrete pavements in Minnesota, as well as to investigate the potential causes of early distresses occurring in those types of pavements.

The report began by describing the typical applications of colored concrete in Minnesota, including streetscaping and safety delineation. Also discussed were the research needs and objectives. The research was needed due to multiple observations of early distress in both newer and older colored concrete crosswalks, medians, and sidewalks. Objectives included determining the potential causes for the distress, developing improved mix design specifications, recommending improved construction techniques, and providing suitable methods of repair. The coloring components for producing colored concrete were described. What was notable was the lack of available research and information on the behavior of coloring additives in concrete pavements. The coincidence and implications of recent research findings related to joint deterioration in non-colored concrete was also discussed. The principal objective of this study was to determine what distress mechanisms might be unique to colored concretes used in streets and roadways in Minnesota.

The focus of Chapter 2 was to highlight many of the Minnesota roadway projects containing colored concrete. A database was created listing 45 locations, with 26 of the locations described in more detail, including photos showing early distress. With the recent surge in construction of colored concrete in Minnesota roadways, many projects were too new to comment on anything other than potential construction errors. Many projects exhibited panel cracking, either a result of possible thermal expansion restraint, or potentially some expansive materials related issues. Some projects revealed cosmetic damage, likely from snow removal equipment. A number of the older projects, as well as one newer one (Centerville), demonstrated significant joint distress. Concern was expressed over the frequent observation of colored concrete crosswalks and sidewalks with a smooth surface texture.

During this study, several construction sites where new colored concrete was being placed were visited. The focus of the visits was to document the unique aspects of constructing colored concrete crosswalks, medians, and sidewalks. All but one of the sites involved non-mechanized hand placement of the colored concrete. Some placement practices of concern included lack of concrete consolidation, excessive surface leveling and finishing with steel trowels, and less than desirable curing procedures. The majority of the colored concrete mixes were designed as high-early strength mixes. The association of these types of mixes with the observed distresses was not investigated in this study. Based on limited testing of samples taken from the projects that were visited, it does not appear that the results of standard acceptance tests like air content and slump differ much from standard concrete. Strength testing of hardened specimens of colored concrete also did not reveal great differences from standard concrete. Those results did not seem too surprising, as it appears the observed distresses in colored concrete are more a function of concrete durability or thermal restraint, rather than strength related issues.

To meet the objective of investigating the potential causes of early distresses occurring in colored concrete pavements in Minnesota, a forensic examination of four projects exhibiting such distress was carried out. The primary methods of investigation included field visual distress surveys, and close examination of core samples using petrography, scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDX) techniques.

Examination of the core samples revealed the following observations:

- Water-to-cementitious ratios of the mixes were determined to generally exceed the maximum value of 0.45 recommended for producing concrete that is freeze-thaw durable in severe climates like Minnesota. Only one site in Roseville had w/cm values generally less than 0.45. Coincidently, that is the only site that had very little secondary ettringite crystals filling the entrained air voids.
- Secondary ettringite and magnesium were detected in many locations throughout a majority of the core samples. Presence of these minerals was deemed to be caused by the high porosity of the mixes. Infilling of a substantial amount of entrained air voids with secondary ettringite was determined to be reducing the freeze/thaw resistance of the pavements.
- Most core samples showed that the pavement was initially constructed with an air void system that should provide freeze-thaw resistance in the Minnesota climate. It was deduced therefore, that over-finishing practices during construction are not a principal cause for observed deterioration. The lack of observed surface scaling also supports this conclusion.
- Chemical attack was discovered in several core samples. Observations ranged from soft and altered paste, to dissolving fine and coarse aggregates. The presence of alkali-silica reaction (ASR) gel, in commonly used aggregates that have not previously shown reactivity in standard concrete, is of great concern. Due to the small number of samples examined, the research team was not comfortable identifying the exact cause for the ASR and chemical attack. The prevalence of magnesium throughout the core samples is certainly one possibility, however other impurities in modern deicing materials may also be potential sources for the chemical reactions. Compatibility between concrete admixtures and color pigment is another area that was not addressed in this investigation.
- Most colored concrete mixes are designed for high early strength gain. The impact of the higher volume of cement that these mixtures typically contain was not explicitly examined in this study.
- For all of the samples examined, the paste-to-aggregate bond was classified as poor to fair. Visible examination, as well as SEM and EDX techniques, show that pigment particles bond to the surface of aggregates, often non-uniformly. Due to the non-

cementitious nature of pigments, it is possible that they may affect the paste–to-aggregate bond strength. While this loss of bond strength may not be enough to affect the load capacity of the concrete, it may be possible that it provides opportunities for freeze-thaw forces to develop the microcracking that is observed.

- Consolidation voids were present in about half of the core samples examined. This is perhaps not unexpected, given the lack of vibration used during most colored concrete placements. While these voids have not affected the load capacity of these mixes, the voids nevertheless expedite the movement of moisture and deicing chemicals through the pavement.
- In three of the four sites examined, the microcracking within the joint regions extended from the top to the bottom of the pavement. Because of this, simple partial-depth concrete repairs are not likely suitable.

To explore the effects of water-to-cementitious ratio and color pigment quantity on the freeze/thaw durability and vulnerability to alkali-silica reaction (ASR) of colored concrete, a small number or specimens were cast in the laboratory. Based on ASTM C666 (freeze/thaw durability) results, it appears the addition of pigment to concrete has little effect on its freeze/thaw durability. The use of a slightly lower water–to-cementitious ratio, 0.40 compared to 0.43, did seem to increase the durability test results slightly, although the sample size is too small to draw conclusions. It is clear that lower water–to-cementitious ratios (≤0.43) result in freeze/thaw durable colored concrete mixes. Analysis of the ASTM C1567 (ASR susceptibility) test results revealed that there is a strong tendency for alkali-silica reactivity when adding colored pigment to the cement, flyash and fine aggregates used in the laboratory mixes tested in this study. There was only a slight difference in expansion of the prisms for specimens containing the cement, flyash and coarse aggregates used in the mixes. In both cases, the recommended limit of 0.10% expansion after 14 days was exceeded. What is of concern is that this alkali-silica reactivity is not typically associated with the type of fine aggregates used in this study, particularly when they have been used in non-colored concrete. Due to the very limited number of specimens tested in this study, it is not clear whether these results were an anomaly or not. What we do know is that ASR was identified in both the fine and coarse aggregates in the core samples pulled from the Larpenteur and Fernwood intersection, which is what the laboratory mixes were patterned after. To determine the true cause of the ASR in both the laboratory specimens and the core samples, a more extensive investigation shouold be done. It is again important to emphasize the very small number of specimens tested in this study. Drawing conclusions about the potential performance of colored concrete pavements based on this limited laboratory study is not advised at this time.

Besides joint distress, the other major type of distress observed in colored concrete crosswalks and sidewalks was cracking that appeared to be associated with thermal expansion forces. To quantify the difference in thermal expansion between colored and non-colored concrete, small instrumented test slabs were constructed at the MnROAD facility. Temperature data showed that darker colored slabs experience about 30% higher surface temperatures than non-colored concrete. These increased temperatures result in measured expansion of darker colored concrete slabs of up to 18% greater than non-colored concrete slabs. It is therefore very important that designers consider thermal expansion response when laying out a project with different colored concretes next to each other.

The following recommendations were made for both improving the construction methods and mix design specifications for full-depth colored concrete placed in future roadway projects:

1. Continuously slip-form the (non-colored) pavement past the area of the crosswalks, and then come back later to saw and remove the concrete in preparation for the installation of the colored concrete. This reduces the problems associated with hand work of the non-colored concrete around the areas of the colored crosswalk.
2. Follow the latest recommendations and guidelines for the placement of durable and functional concrete in Minnesota. These guidelines are provided by the MnDOT Concrete Office.
3. When possible, use a vibrating screed to level and consolidate the mix. If a screed is not available, supplement leveling and consolidation of the mix with the use of pencil type vibrators. Do not over-vibrate the mix, as this may alter the entrained air system within the concrete.
4. Educate construction personnel on the importance of not adding extra water to the surface to help finish a mix that has already started to harden. This may lead to scaling of the surface in a short amount of time. Coordinate your placement and finishing teams such that these operations are completed well before the concrete begins to harden.
5. Apply appropriate curing techniques at the proper time. Common curing materials for color concrete included color waxes and clear compounds. Consider that both of these methods lack the heat reducing reflectance provided by white pigmented curing compounds. Take steps to keep the colored concrete cool while it is curing. Potential techniques include providing shade, or scheduling pours during times of minimal sun exposure.
6. Consider the functional aspects of colored concrete in crosswalks and sidewalks by providing, at minimum, a broomed surface texture.

This study focused next on describing some suitable repairs for distressed colored concrete pavements in Minnesota. While standard repair techniques for non-colored concrete can be used to repair projects with distressed colored concrete, many of these techniques are not suitable for the projects identified in this study. Since many of the projects were identified as having ettringite-filled air voids throughout the slab, attaching new concrete repair material to the existing material would not likely perform for very long before joint distress would re-form.

This is not to say that if deterioration was detected early enough, that partial depth repairs could not significantly extend the life of a colored concrete pavement. It however seems impractical to monitor pavements in such a fashion. Of course full slab replacement is always feasible, yet not always economical. Color matching existing concrete is feasible, but can be quite tricky due to variations in available aggregates and cement sources. Research is currently underway to determine whether topical sealers could be applied that would effectively and economically seal and protect colored concrete from today's aggressive deicing chemicals.

Finally, alternative surface coloring methods were introduced. Examples included concrete stains, dyes or the application of a colored "High Friction Surface Treatment." For repairs of existing colored concrete areas, these options are desirable due to their inherent ability to blend in or completely cover even non-colored concrete repair materials. They can also provide the additional benefit of increased surface friction that is desired in areas where colored concrete is typically placed. Surface applied stains, dyes, and high friction surface treatments can also be used on new projects in lieu of full-depth color concrete. And while they may require more frequent maintenance than full-depth color concrete, they can be applied over more durable non- colored concrete slabs that have demonstrated life-spans of many decades. Lastly, interlocking colored concrete paver systems were suggested as a viable alternative to full-depth colored concrete. These systems have been shown to provide the same decorative function, with good long-term performance and simple maintenance requirements.

Recommendations

This study resulted in a number of significant observations with regarding to the performance of colored concrete crosswalks, medians, and sidewalks in Minnesota. Based on these observations, as well as findings from a limited set of laboratory tests and field experiments, the following recommendations are provided to help improve the design and construction of colored concrete in Minnesota roadways:

- Produce colored concrete mixes with water-to-cementitious ratios no greater than 0.43.
- To achieve workability during placement, utilize appropriate modern admixtures in the mix. Remember to adjust (reduce) the w/cm ratio for mixes designed for high-early strength gain.
- Follow current MnDOT concrete placement and mix design specifications, which are routinely updated to provide the most durable concrete structures in Minnesota.
- Improve placement methods, especially consolidation of the mix using vibration. Take care to not over-vibrate the mix.
- Due to their inherent location and function, ensure that an adequate and durable surface is constructed during the finishing process. At minimum, a broom texture should be
- applied.
- Use proper and adequate curing techniques. Alternative curing materials and methods may have to be devised to accomplish this.
- Consider and allow for extra thermal expansion of colored concrete when placed next to non-colored concrete or other fixed structures.
- Consider alternatives to deicing chemicals that have been shown to damage concrete.
- While modern day alternative deicing chemicals have improved safety for the traveling public, they have been shown to cause damage to many of our recent concrete mixes.

- Consider only suitable repairs. Without a thorough understanding of the internal condition of a concrete slab, repairs may not be long lived or cost effective.
- Consider alternative methods of coloring concrete crosswalks, medians and sidewalks.
- Surface applied colored stains, dyes, or high friction surface treatments or other concrete coloring coatings are continually improving, and may provide the decorative, safe, and durable functions that agencies desire. Interlocking colored concrete paver systems may also be a viable option for new construction or repairs.
- Due to the many unanswered questions related to the true mechanisms of the chemical attack on the colored concretes identified in this study, further research studies are needed that investigate far more specimens from both the field and laboratory.

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APPENDIX A: PETROGRAPHIC ANALYSIS REPORT

REPORT OF CONCRETE ANALYSIS

PROJECT:
Petro. Analysis of Colored Concrete Pavement
MNDOT Contract 01219

REPORTED TO:
MN Department of Transportation
Office of Materials and Road Research
1400 Gervais Avenue
Maplewood, MN 55109

ATTN: Alexandra Akkari

AET PROJECT NO: 24-00469

DATE: October 26, 2012

INTRODUCTION

This report presents the results of laboratory work performed by our firm on eleven (11) hardened concrete core samples submitted by representatives of the MN Department of Transportation on June 13, 2012 (cores 14A, 14C, 14E, 96A, 96C, 96D), and August 22, 2012 (cores Larpenteur Ave. Fernwood St. A, Larpenteur Ave. Fernwood St. B, Larpenteur Ave. & Fernwood St. C, Lake Johanna EB A, and Lake Johanna WB B). Our work was authorized on August 3, 2012. We understand the cores were obtained from a pigmented concrete pavement currently under evaluation for premature joint distress. Reportedly, the Hwy 14 project was paved in 2008, the Hwy 96 project was paved in 1999, the Larpenteur Fernwood project was completed in 2001, and the Lake Johanna project was paved in 1999. The scope of our work was limited to performing petrographic analysis on the eleven core samples to document the general overall quality and condition of the concrete cores and determine the cause of joint distress.

CONCLUSIONS

Based on our observations and testing, we believe:

1. & Individual cores taken from three of the four projects exhibited concentrated distress at the joints. The distress is characterized by corner or thinner "sliver" spalling and highly concentrated, sub-vertically oriented, incipient spalling along the depth of the joints. Tooled control joints in the Lake Johanna project were not "activated" and exhibit isolated shallow corner spalling. Mid-panel cores L F B and L FC and Lake Johanna cores LJ EB A and LJ WB B displayed concentrated, sub-horizontally oriented microcracking induced by alkali silica reaction of the coarse and fine aggregates generally within a maximum of 76mm (3") of the top surface.

2. & All eleven concrete cores originally contained well distributed, purposefully entrained, air void systems with documented air void parameters considered freeze-thaw resistant under severe exposure conditions.

3. & The pigmented concrete appears more susceptible to in-filling of the entrained air void system by ettringite than non-pigmented and lower w/cm concretes studied previously. The in-filling of the entrained air void system with secondary ettringite likely produces concrete of limited freeze-thaw resistance at saturated joints. Additionally, in the cases of the pigmented pavement at Larpenteur Fernwood and Lake Johan, traditionally sound coarse and fine glacial aggregates exhibit developing to advanced alkali-silica reaction. The offending aggregates are comprised of siliceous graywackes, granites, cherts, and quartzites common in extensively utilized deposits of glacial gravels and sand in MN which have traditionally proven innocuous in many types of concretes under a wide variety of exposure conditions. The trigger for the unexpected alkali silica reaction is unclear and will require further study of the exposure history and the original concrete making materials.

4. & In the distressed joint 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. 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.

5. & Most of the concrete represented by the cores was generally placed at a "moderate" w/cm; estimated to be between 0.42 and 0.50. Cores from the Larpenteur Fernwood project were placed at a moderately low w/cm; estimated to be between 0.40 and 0.45. Cores 96A and 96C contained flyash as a replacement of portland cement and a trace of residual slag cement. The replacement of portland cement by flyash was visually estimated at 5-15%. Core 96D, from the same project, contained a trace of residual slag cement and no flyash. Cores LJ EB A and LJ WB B contained an amount of flyash visually consistent with a 5% replacement of portland cement. Overall, the estimated w/cm s were judged to be generally 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. All concretes contained a finely disseminated mineral pigment.

6. & Distress in portions of cores 96A and L&F A is a yet fully described chemical attack possibly 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 microcracking within this still-intact paste, generally within 10mm of the spalled near-vertical joint surface and unlike that typically associated with freeze-thaw action, is currently devoid of secondary minerals other than calcium carbonate. Calcium carbonate is an innocuous mineral.

7. & Core 14A was centered and taken directly though a silicone sealed, tooled and sawcut control joint. The core exhibits "sliver" and corner spalling at the top surface to 60mm depth and severe incipient spalling to 20mm into the concrete along the length of the control joint. The silicone joint sealant was only intermittently bonded with the present joint surfaces. The effective entrained air void system was compromised by ettringite fillings within at least 20mm of the joint plane. The concrete was placed at a somewhat excessive w/cm for exterior pavement. No ASR was observed. Core 14E exhibits a similar condition.

8. & Core 96A was centered and taken directly through an apparent control joint. The distress in the core was defined by severe mass lost at the top surface from corner spalling and incipient vertical spalling up to 37mm depth into the concrete along the depth of the joint plane. "Altered", softer and lighter colored paste was observed in portions of the outer 7mm of the concrete directly adjacent to the distress joint plane. The altered paste requires further chemical analysis to describe its composition further. Original air void parameters were of good quality and included a 3.4% entrained-sized void volume and a 0.004" spacing factor. Secondary ettringite fills most finer entrained sized voidspaces throughout the sample and has compromised the effectiveness of the air void system. Current air void parameters, outside of the top approx. 5mm of the core, and greater than 125mm depth from the top surface and 40mm distance from the distress, appear to offer no freeze-thaw resistance. The concrete was placed at a somewhat excessive w/cm for exterior pavement.

9. & Core 96D was taken offset from the apparent joint and no evidence of the original joint detail remained. The distress in the core was characterized by loss of mass along the entire depth of 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. The concrete no longer contains an air void system due to significant air void filling by ettringite throughout its depth. Original air void parameters include a 2.7% entrained-sized void volume and a 0.007" spacing factor. Secondary ettringite fills numerous finer entrained sized voidspaces throughout the sample and has compromised the effectiveness of the air void system. Current air void parameters, excluding ettringite filled voids, are characterized by a 1.1% entrained-sized void volume and a 0.019" spacing factor. Intact concrete paste appears hard and unaltered. The concrete was placed at a somewhat excessive w/cm for exterior pavement.

10. & Core L&F A was centered and taken directly though a silicone sealed, tooled and sawcut control joint. The core exhibits intermittent "sliver" and corner spalling at the top surface to 50mm depth and severe incipient spalling to 20mm into the concrete along the length of the control joint. The silicone joint sealant was only intermittently bonded with the present joint surfaces. The effective entrained air void system was compromised by

ettringite fillings within at least 20mm of the joint plane. Portions of the outer up to 10mm of paste directly adjacent to the vertical distressed joint surface exhibited an "altered" appearance, with lighter coloration and a significantly softer paste. Some of this outer 10mm of paste is carbonated and some is free of calcium hydroxide. The concrete was placed at a somewhat excessive w/cm for exterior pavement. ASR was not observed. Significant sub-horizontal cracking occurs below 165mm depth in the core.

11. & Mid-panel cores L&F B and L&F C exhibit anomalous alkali-silica reaction (ASR) of normally sound siliceous glacial gravel and sand particles. The ASR is generally confined to the top 60mm of both cores as mostly sub-horizontal microcracking proceeding through reactive, siliceous, coarse and fine aggregate. ASR gel product lines or fills much of the microcracking and adjacent or intersecting voidspaces. "Map" (sub-vertical) cracking is present in the top surfaces of the core. A major sub-horizontal macrocrack in core L&F C was most likely induced by structural or freeze-thaw forces in the ASR distressed zone.

12. & Cores LJ EB A and LJ WB B were taken through "un-activated" tooled control joints. The joints exhibit some shallow spalling. In the case of core LJ WB B, the spalling appears to have been produced by impacting of the surface; producing cracking proceeding through a hard, sound, and durable coarse aggregate particle. Some exposed coarse and fine aggregates adjacent to the spalling exhibit a ground or crushed appearance. The two cores exhibit anomalous alkali-silica reaction (ASR) of normally sound siliceous glacial gravel and sand particles. The ASR is generally confined to the top 76mm of both cores as mostly sub-horizontal microcracking proceeding through reactive, siliceous, coarse and fine aggregate. ASR gel product lines or fills much of the microcracking and adjacent or intersecting voidspaces. The cores exhibit significant secondary ettringite filling of fine entrained air voids below several millimeters depth from the top surfaces.

SAMPLE IDENTIFICATION

Sample ID:	14A	14C	14E	96A	96C	96D
Sample Type:	151mm (6") Diameter Hardened Concrete Cores					
Sample Length:	202mm (8")	205mm (8")	194mm (7 5/8")	240mm (9 1/2")	210mm (8 1/4")	200mm (7 3/4")

Sample ID:	L F A (Larpenteur Ave. & Fernwood St.)	L F B (Larpenteur Ave. & Fernwood St.)	L F C (Larpenteur Ave. & Fernwood St.)	LJ EB A (Lake Johanna)	LJ WB B (Lake Johanna)
Sample Type:	151mm (6") Diameter Hardened Concrete Cores				
Sample	215mm	215mm	207mm	215mm	200mm

Length:	(8 1/2")	(8 1/2")	(8 1/8")	(8 1/2")	(7 3/4")

TEST RESULTS

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 the general concrete properties is as follows:

1. & The coarse aggregate in all eleven cores was similar in composition and was comprised of 19mm (3/4") nominal sized natural glacial gravel that generally appeared well graded and exhibited good overall distribution. The coarse aggregate appears to originate from Superior Lobe glacial till. The fine aggregate in all eleven cores was a natural quartz, feldspar, and lithic glacial sand.

2. & The paste in all eleven cores was pigmented. The paste in cores 14A, 14C, and 14E was of "moderate hardness" with the paste/aggregate bond considered fair to poor. The paste in cores 96A, 96C, and 96D was "relatively hard" with the paste/aggregate bond judged to be fair to poor. The paste in cores L&F A, L F B, and L&F C was "relatively hard" with the paste/aggregate judged to be fair. The paste in cores LJ EB A and LJ WB B was "relatively hard" with the paste/aggregate judged to be fair.

3. & In general, the top surface condition of the cores was lightly textured to traffic worn and somewhat smooth. Carbonation ranged from mostly negligible in core 14A up to a 37mm maximum depth, intermittently, along microcracking in core L&F C.

4. & Most of the concrete represented by the cores was generally placed at a "moderate" w/cm; estimated to be between 0.42 and 0.50. Cores from the Larpenteur Fernwood project were placed at a moderately low w/cm; estimated to be between 0.40 and 0.45. Cores 96A and 96C contained flyash as a replacement of portland cement and a trace of residual slag cement. The replacement of portland cement by flyash was visually estimated at 5-15%. Core 96D, from the same project, contained a trace of residual slag cement and no flyash. Cores LJ EB A and LJ WB B contained an amount of flyash visually consistent with a 5% replacement of portland cement.

Air Content Testing

Sample ID	14A	14C	14E	96A	96C	96D
Total Air Content (%)	5.3	6.1	5.4	4.9	5.1	4.3
“Entrained” Air (%) voids < 1mm (0.040”)	4.0	5.1	4.5	3.4	3.4	2.7

"Entrapped" Air (%) voids > 1mm (0.040")	1.3	1.0	0.9	1.5	1.7	1.6
Spacing Factor, in.	0.007	0.003	0.005	0.004	0.004	0.007

Sample ID	L F A (Larpenteur Ave. & Fernwood St.)	L F B (Larpenteur Ave. & Fernwood St.)	L F C (Larpenteur Ave. & Fernwood St.)	LJ EB A (Lake Johanna)	LJ WB B (Lake Johanna)
Total Air Content (%)	7.5	7.2	7.8	7.2	6.3
"Entrained" Air (%) voids < 1mm (0.040")	6.8	6.4	7.1	5.5	5.0
"Entrapped" Air (%) voids > 1mm (0.040")	0.7	0.8	0.7	1.7	1.3
Spacing Factor, in.	0.002	0.003	0.002	0.002	0.003

TEST PROCEDURES

Laboratory testing was performed on August 3, 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 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.

American Engineering Testing, Inc.	American Engineering Testing, Inc.
Report Prepared By:	Report Reviewed By:
__________________________	__________________________
Gerard Moulzolf, PG	David L. Rettner, PE
Vice President/Principal Petrographer	Sr. Vice President/Principal Engineer
MN License #30023	MN License #20458

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

Project No.	24-00469	Date:	October 15, 2012
Sample ID:	14A	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. & Sample Dimensions: Our analysis was performed on one lapped side of a 202mm (8") x 145mm (5 3/4") x 43mm (1 5/8") thick section (in two pieces) and two 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 151mm (6") diameter x 202mm (8") long core taken directly through a distressed tooled and sawcut joint. The thin sections were located at between approx. 0mm and 75mm depth and 105mm and 185mm depth in the core from the top surface.

2. & Surface Conditions:
Top: Fairly smooth, very lightly traffic worn surface; exposing some fine aggregate surfaces. Bottom:Rough, irregular, formed surface; placed on a crushed bituminous-rich base.

3. & Reinforcement: None observed.

4. & General Physical Conditions: The core was taken directly through a distressed tooled and sawcut pavement joint. The joint is characterized by an originally rounded - tooled penetration; diamond sawcut (scored) to approximately 61mm depth. The resulting joint crack proceeds the depth of the core in near vertical orientation. Both sides of the top surface of the core at the joint have vertically scaled/spalled. The spalling on one side of the joint is still in place (incipient). The joint was originally sealed with a red foam backer rod and a light gray silicone-like sealant. The approx. 7mm thick (without meniscus) sealant appears to have had limited bond with the tooled and sawcut joint surfaces. The joint surface crack surface exhibits a "dirty" appearance to approximately 25mm depth from the bottom of the sawcut and is mostly coated with white secondary ettringite the remaining length of the core. Concentrated sub-vertical microcracks (incipient scaling/spalling) occur generally on both sides of the joint crack and within 20mm of the joint plane. The microcracking generally occurs within the paste only. Below 188mm depth, the microcracking becomes nearly horizontal. The core exhibits tight residual interlock between the two slabs along the joint crack. The joint plane proceeds around coarse aggregate particles. Several, fine, sub-vertical drying shrinkage microcracks proceed up to 2mm maximum depth from the top surface. Carbonation ranged from negligible up to 1.5mm depth from the top surface; "spiking" along the drying shrinkage microcracking. Carbonation, along the spalled joint plane, proceeded continuously up to 10mm from the joint crack and up to 20mm depth, intermittently, along sub-vertical microcracking. The coarse aggregate appeared hard, sound, and durable. No evidence of ASR associated with the coarse aggregate was observed.

The concrete was fairly well consolidated, with a few scattered consolidation voids measuring up to 10mm. The concrete was purposefully air entrained and contains a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Air void parameters include a 4.0% entrained-sized void volume and a 0.007" spacing factor. Secondary ettringite lines most voidspaces and fills many of the smallest entrained-sized voidspaces below approx. 10mm depth from the top surface. Void fillings of secondary ettringite increase with depth from the top surface and decrease with depth from the plane of the joint. The concrete within at least 20mm of the joint plane appears to have very limited freeze-thaw resistance due to the void fillings.

II. &Aggregate

1. &Coarse: 19mm (3/4") nominal sized, superior lobe glacial gravel consisting predominately of basalt, rhyolite, graywacke, and granite with smaller amounts of sandstone, carbonate, and iron oxide. The coarse aggregate appeared well graded and exhibited good overall distribution.

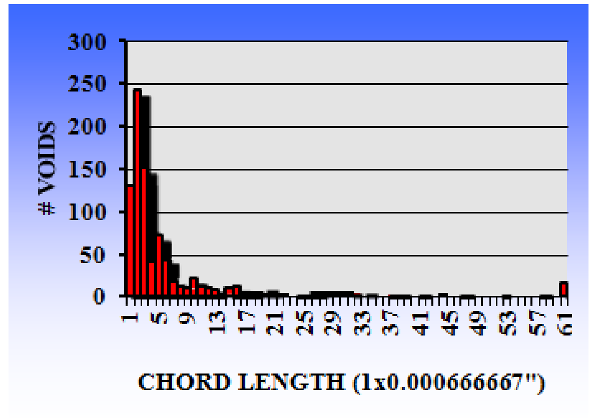
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, siltstone and shale.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 5.3% total.
2. &Depth of carbonation: Ranged from negligible up to 1.5mm depth from the top surface of the core; proceeding deepest along sub-vertical drying shrinkage microcracking. Proceeded up to 10mm depth from the joint crack: proceeding the deepest adjacent to the spalled sawcut section of joint.
3. &Pozzolan presence: None observed.
4. &Paste aggregate bond: Poor
5. &Paste color: Pigmented with color similar to Moderate Yellowish Brown (Munsell® 10YR 5/4). Slightly darker than 14E. Sub-vitreous.
6. &Paste hardness: Moderately hard (>Moh's 3). Somewhat softer (<Moh's 3) in the carbonated paste adjacent to the joint distress.
7. &Microcracking: Several, very fine, sub-vertical drying shrinkage microcracks proceed up to 2mm depth from the top surface of the core. Numerous, other, fine, shrinkage microcracks were observed scattered in the paste at various depths and orientations in the core. "Severe", concentrated sub-vertical microcracking (incipient spalling/scaling) occurs generally within 20mm of the joint crack.
8. &Secondary deposits:Secondary ettringite lines most voidspaces and fills many of the smallest entrained-sized void spaces below approx. 10mm depth from the top surface. Void fillings of secondary ettringite increase with depth from the top surface and decrease with depth from the plane of the joint.
9. & w/cm: Estimated at between 0.44 and 0.50 with approximately 7 to 9% residual portland cement clinker particles.
10. Cement hydration: Alites: Mostly fully. Belites: Well to fully.

Sample ID: 14A (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Core

Dimensions: 151mm (6") diameter by 202mm (8") long

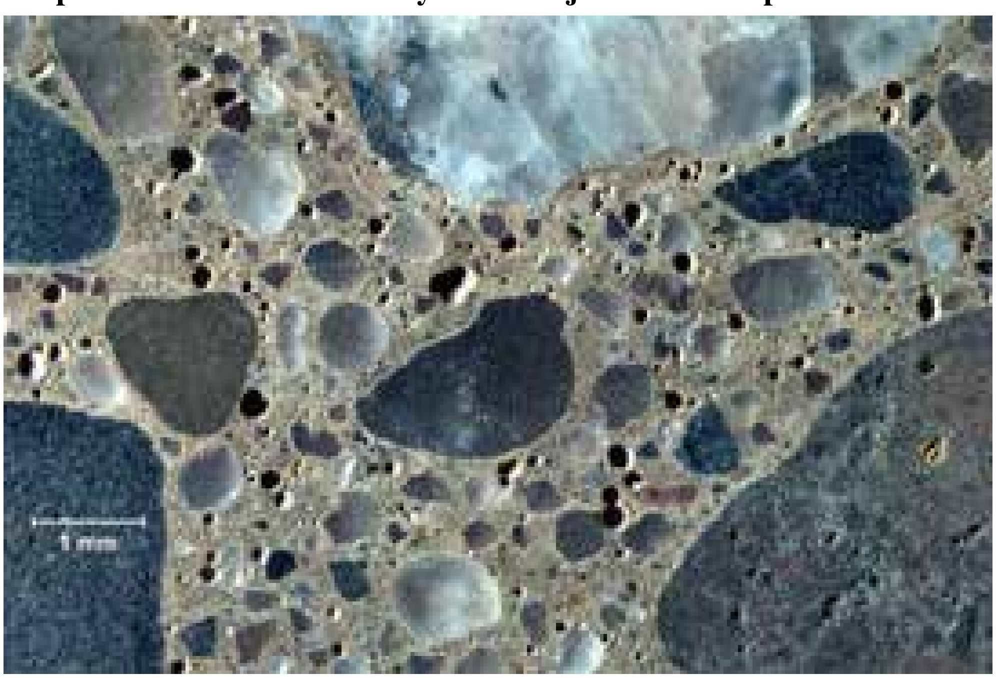
Test Data: By ASTM C:457

Air Void Content %	5.3
Entrained, % < 0.040”(1mm)	4.0
Entrapped, %> 0.040”(1mm)	1.3
Air Voids/inch	10.0
Specific Surface, in^2/in^3	750
Spacing Factor, inches	0.007
Paste Content, % calculated	29.8
Magnification	75x
Traverse Length, inches	90
Test Date	10/3/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

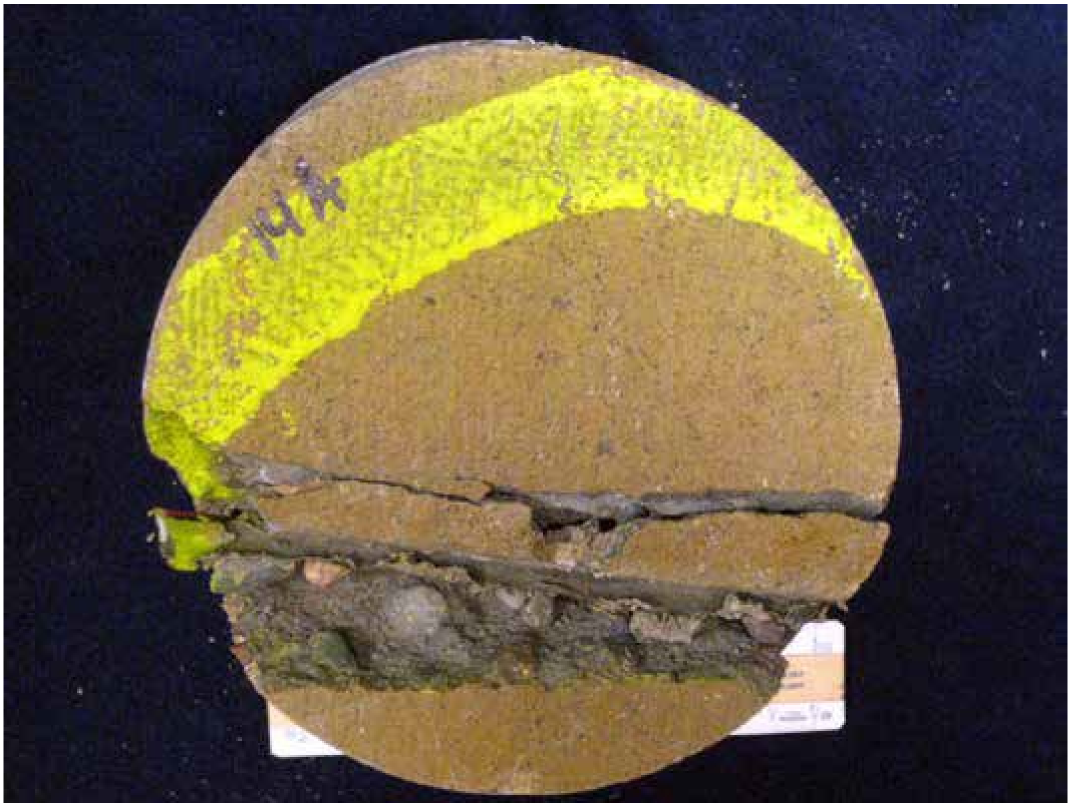
Magnification: 15x

Description: Hardened air void system@ adjacent tothe top surface of the core.

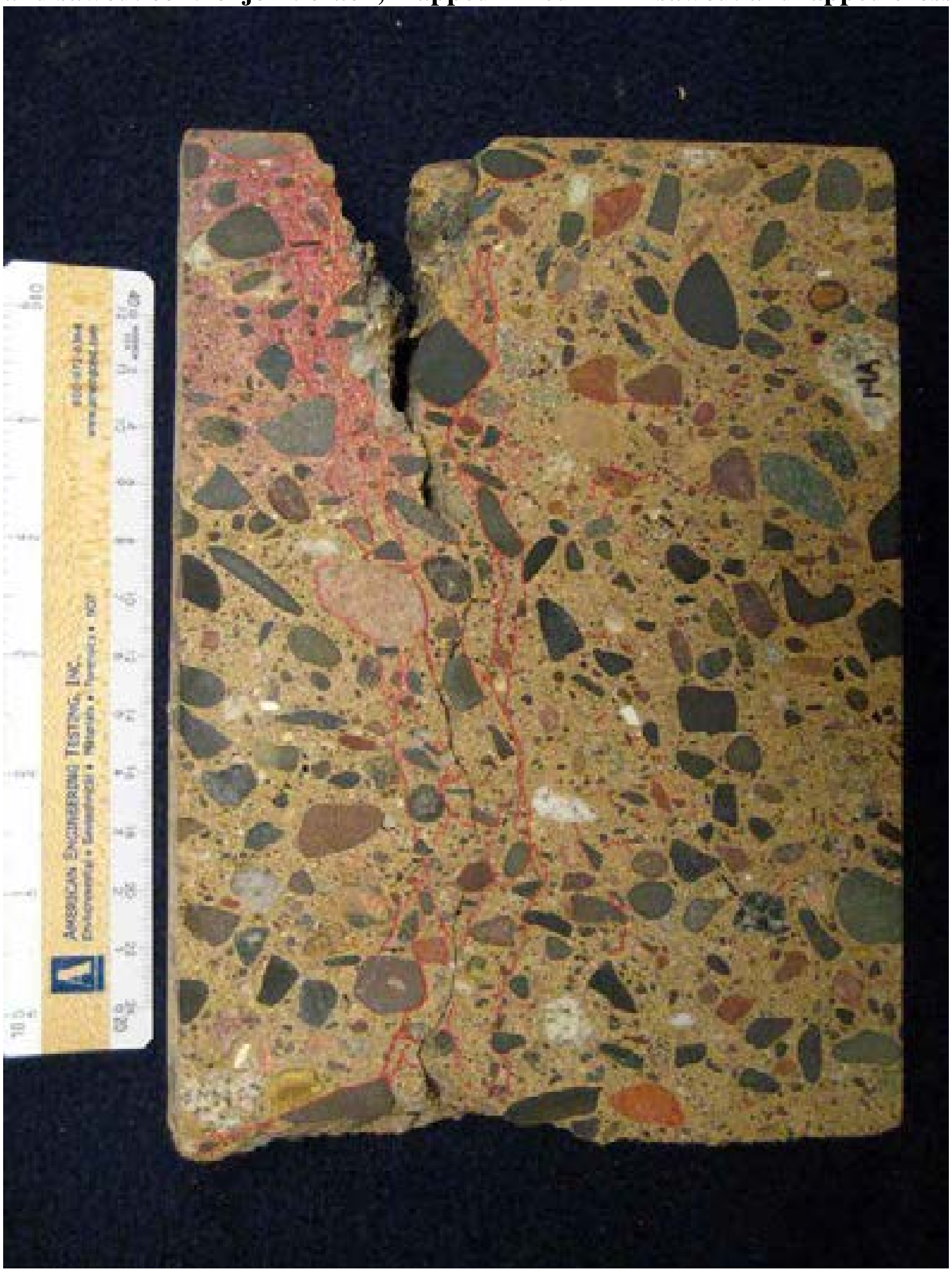


14A DESCRIPTION: Core sample as received. Top surface is right.

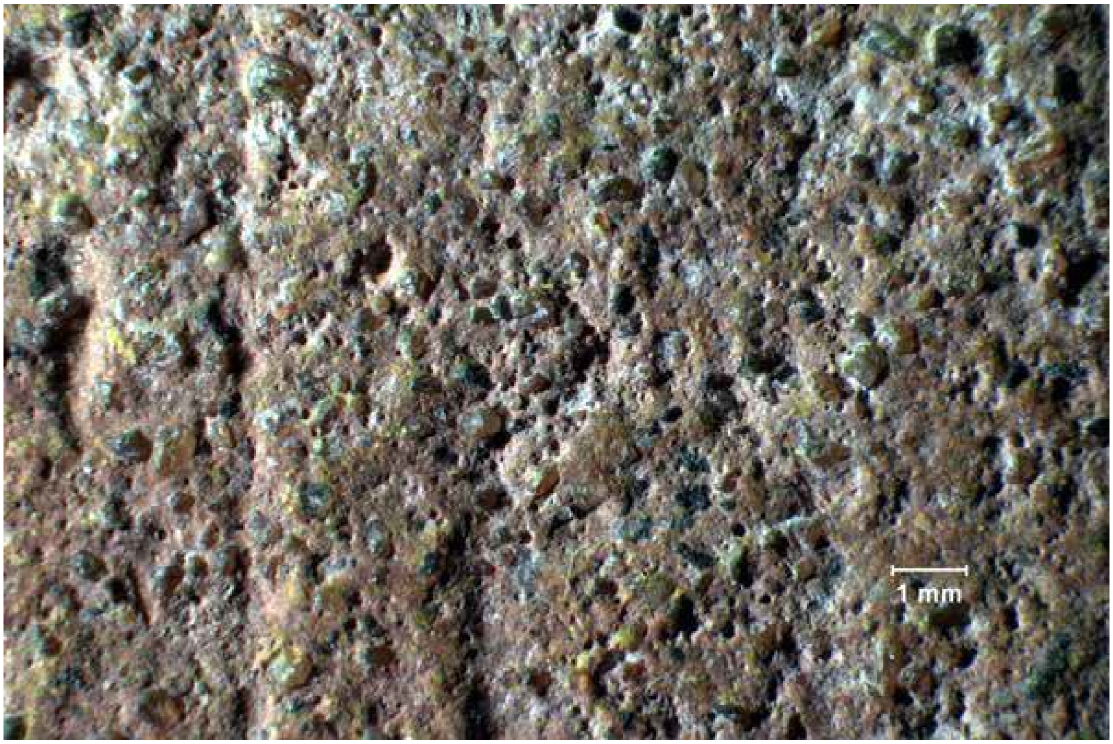
14A DESCRIPTION: Top surface of the core sample, with sliver spalled joint, as received.



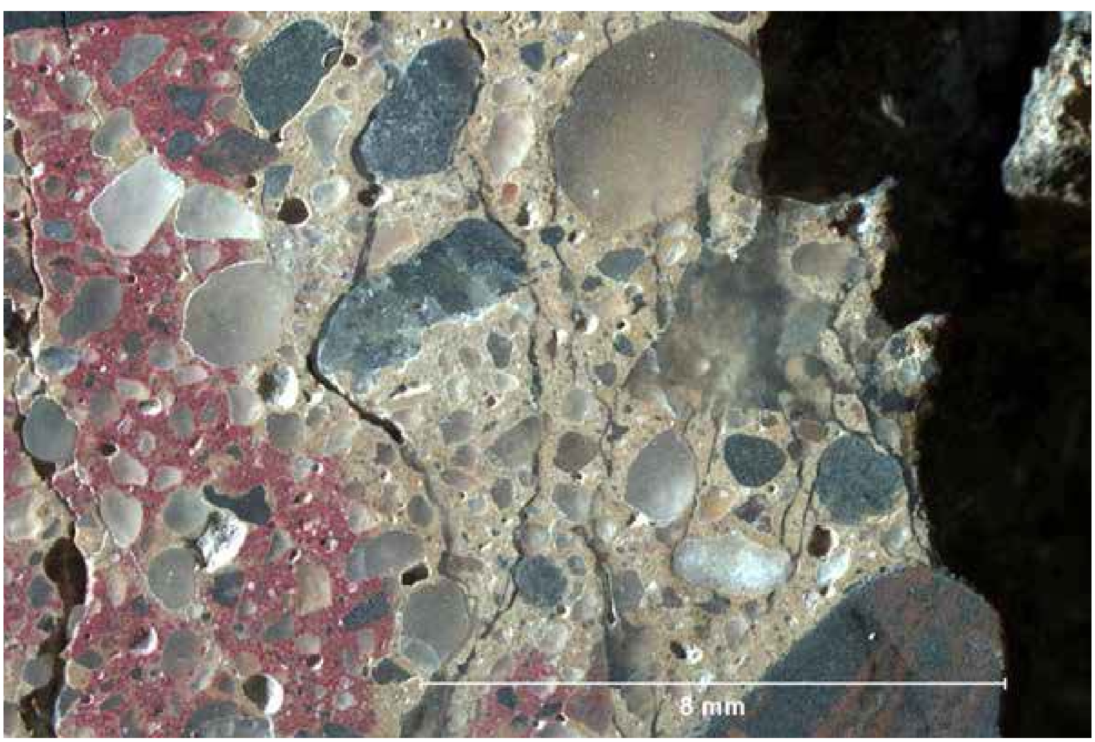
14A DESCRIPTION: Sliver spalling and severe incipient distress (sub-vertical micro and macro cracking) in the concrete paste directly adjacent to the "activated", tooled and sawcut control joint crack; mapped in red ink in sawcut and lapped cross sectcore.



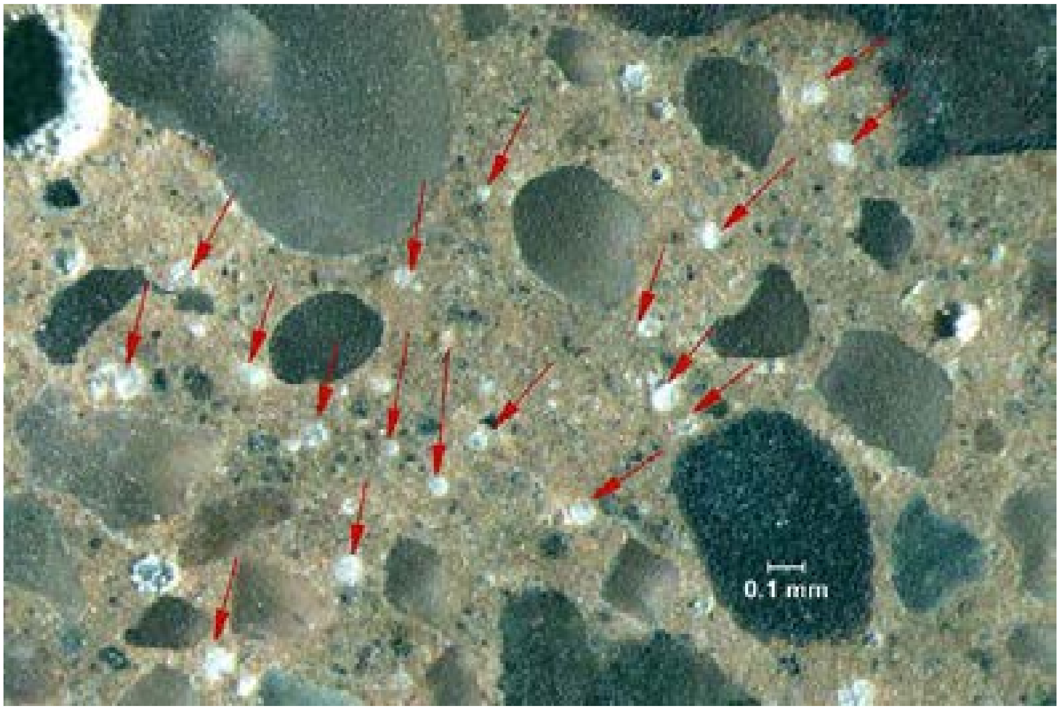
14A DESCRIPTION: Close up. MAG: 5x



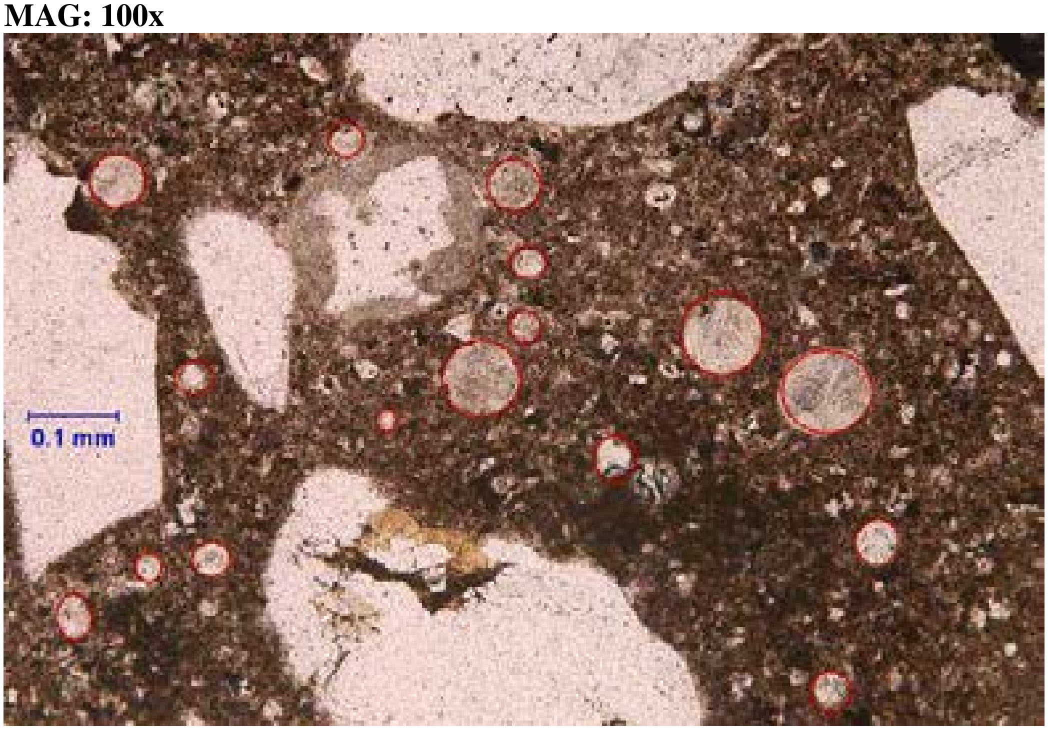
14A DESCRIPTION: Severely microcracked paste adjacent to the distressed joint plane. Microcracking is filled with epoxy required for preparation of the sawcut and lapped cross section. Note lack of open air entrainment. MAG: 10x



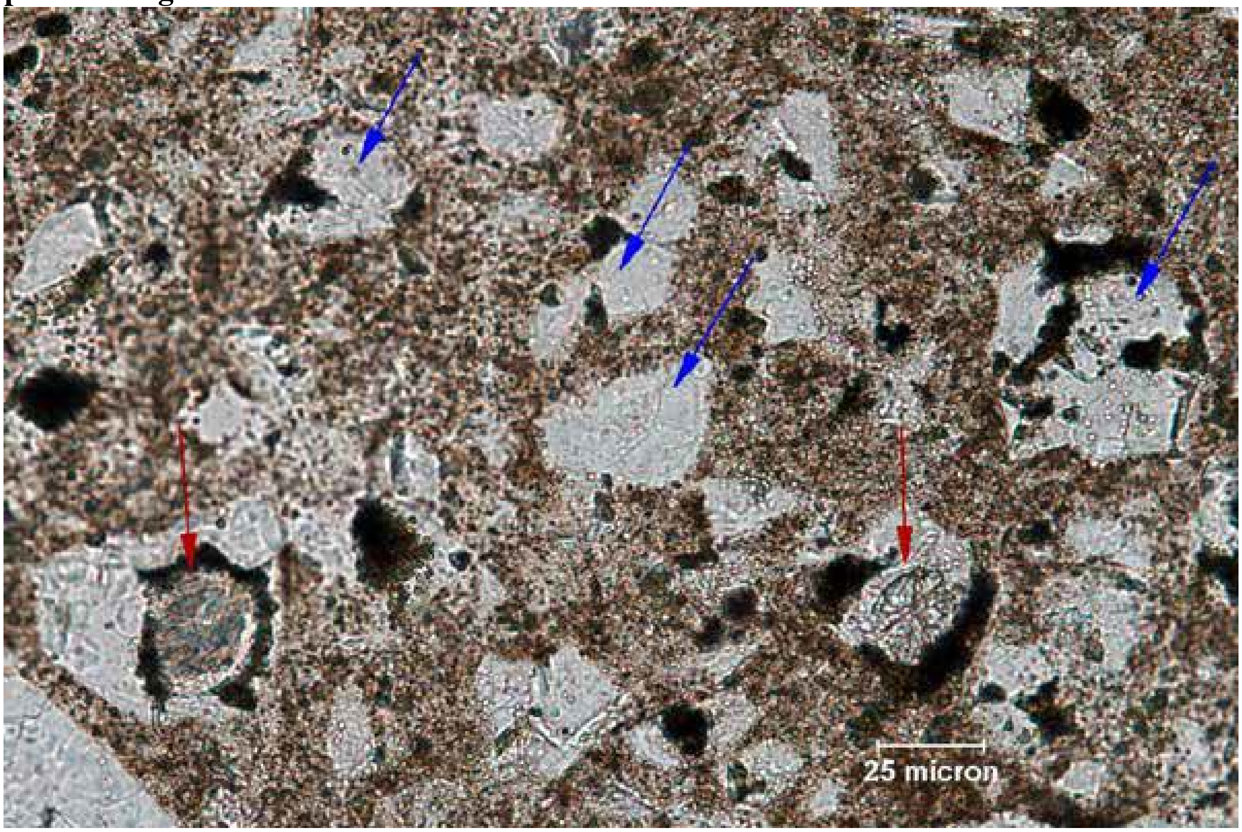
14A DESCRIPTION: Ettringite-filled air voids at 130mm depth from the top surface andat least 3mm depth from the distressed joint plane. MAG: 50x



14A DESCRIPTION: Ettringite-filled entrained sized air voidspaces in the pigmented paste (outlined in red); in thin section of concrete under plane polarized light. MAG: 100x



14A DESCRIPTION: Fully hydrated alite portland cement clinker relicts (blue arrows) and well hydrated belite particles (red) in thin section of concrete paste under plane polarized light. MAG: 400x



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

Project No.	24-00469	Date:	October 9, 2012
Sample ID:	14C	Performed by:	D. Hunt, G. Moulzolf

I. & General Observations

1. &Sample Dimensions: Our analysis was performed on one lapped side of a 210mm (8 1/4") x 151mm (6") x 38mm (1 1/2") thick section and one 76mm (3") x 52mm (2") wide thin section that were sawcut and prepared from the original 151mm (6") diameter x 210mm (8 1/4") long core The thin section was located at between 0mm and 47mm depth in the core from the top surface.

2. &Surface Conditions:
Top: Fairly smooth textured and traffic worn surface; exposing many fine aggregate surfaces. Bottom:Rough, irregular, formed surface; placed on a crushed bituminous-rich base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The lightly textured top surface of the core has undergone minor traffic wear exposing many fine aggregate surfaces. Several, fine, sub-vertical drying shrinkage microcracks proceed up to 15mm maximum depth from the top surface. Carbonation ranges from <1mm up to 6mm depth; "spiking" along the drying shrinkage microcracking. The coarse aggregate appeared hard, sound, and durable. No evidence of ASR associated with the coarse aggregate was observed.

The concrete was fairly well consolidated, with a few scattered consolidation voids measuring up to 12mm. The concrete was purposefully air entrained and contains a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Air void parameters include a 5.1% entrained-sized void volume and a 0.003" spacing factor. Secondary ettringite lines most voidspaces and fills many of the smallest entrained-sized voidspaces below approx. 20mm depth from the top surface. The concrete contains a finely disseminated red pigment.

II. &Aggregate

1. &Coarse: 19mm (3/4") nominal sized, superior lobe glacial gravel consisting predominately of basalt, rhyolite, graywacke, and granite with smaller amounts of sandstone, carbonate, and iron oxide. The coarse aggregate appeared well graded and exhibited good overall distribution.

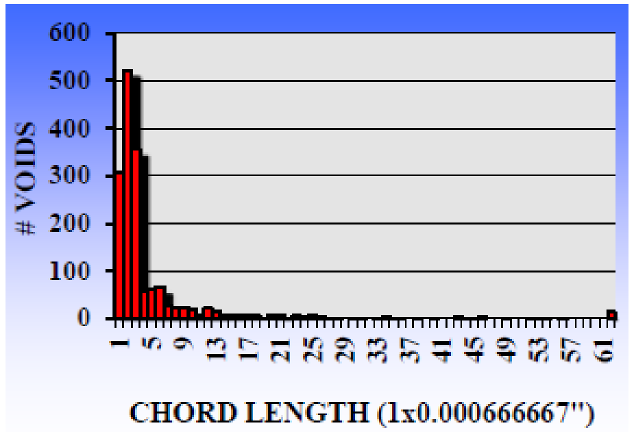
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, siltstone and shale.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 6.1% total.
2. &Depth of carbonation: Ranged from <1mm up to 6mm depth from the top surface of the core; proceeding deepest along sub-vertical drying shrinkage microcracking.
3. &Pozzolan presence: None observed.
4. &Paste aggregate bond: Fair.
5. &Paste color:Pigmented with color similar to Pale Reddish Brown (Munsell® 10R 5/4). Sub-vitreous.
6. &Paste hardness: Moderately hard (Moh's 3)
7. &Microcracking: Several, very fine, sub-vertical drying shrinkage microcracks proceed up to 15mm depth from the top surface of the core. A few, fine, shrinkage microcracks were observed scattered in the paste at various depths and orientations in the core.
8. &Secondary deposits:Secondary ettringite partially fills to fills many of the smaller entrained sized voidspaces.
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 fully.

Sample ID: 14C (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Core

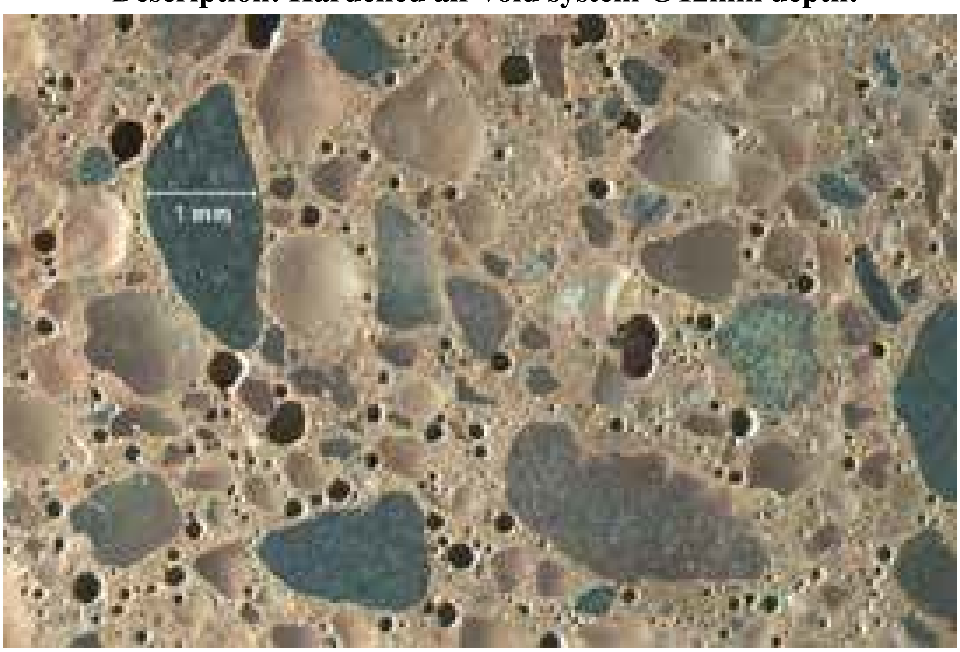
Dimensions: 151mm (6") diameter by 205mm (8") long

Test Data: By ASTM C:457

Air Void Content %	6.1
Entrained, % < 0.040"(1mm)	5.1
Entrapped, %> 0.040"(1mm)	1.0
Air Voids/inch	17.6
Specific Surface, in^2/in^3	1150
Spacing Factor, inches	0.003
Paste Content, % calculated	23.6
Magnification	75x
Traverse Length, inches	92
Test Date	10/3/2012

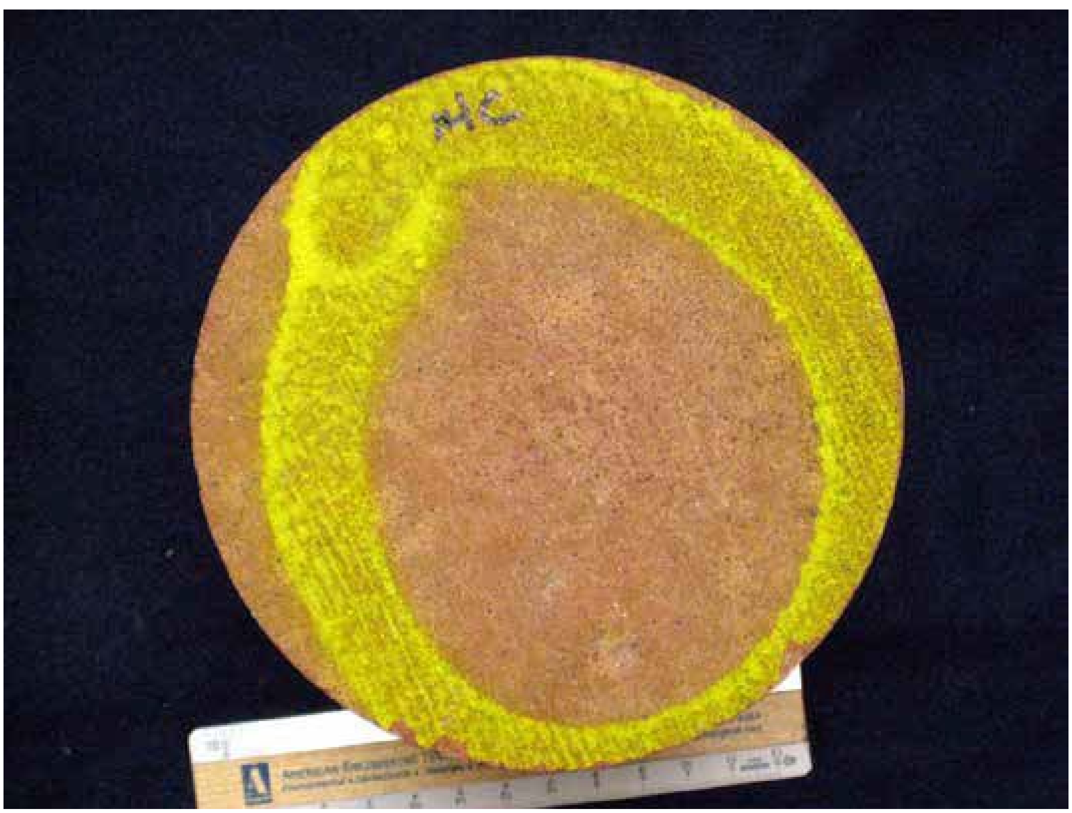
Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x
Description: Hardened air void system @12mm depth.

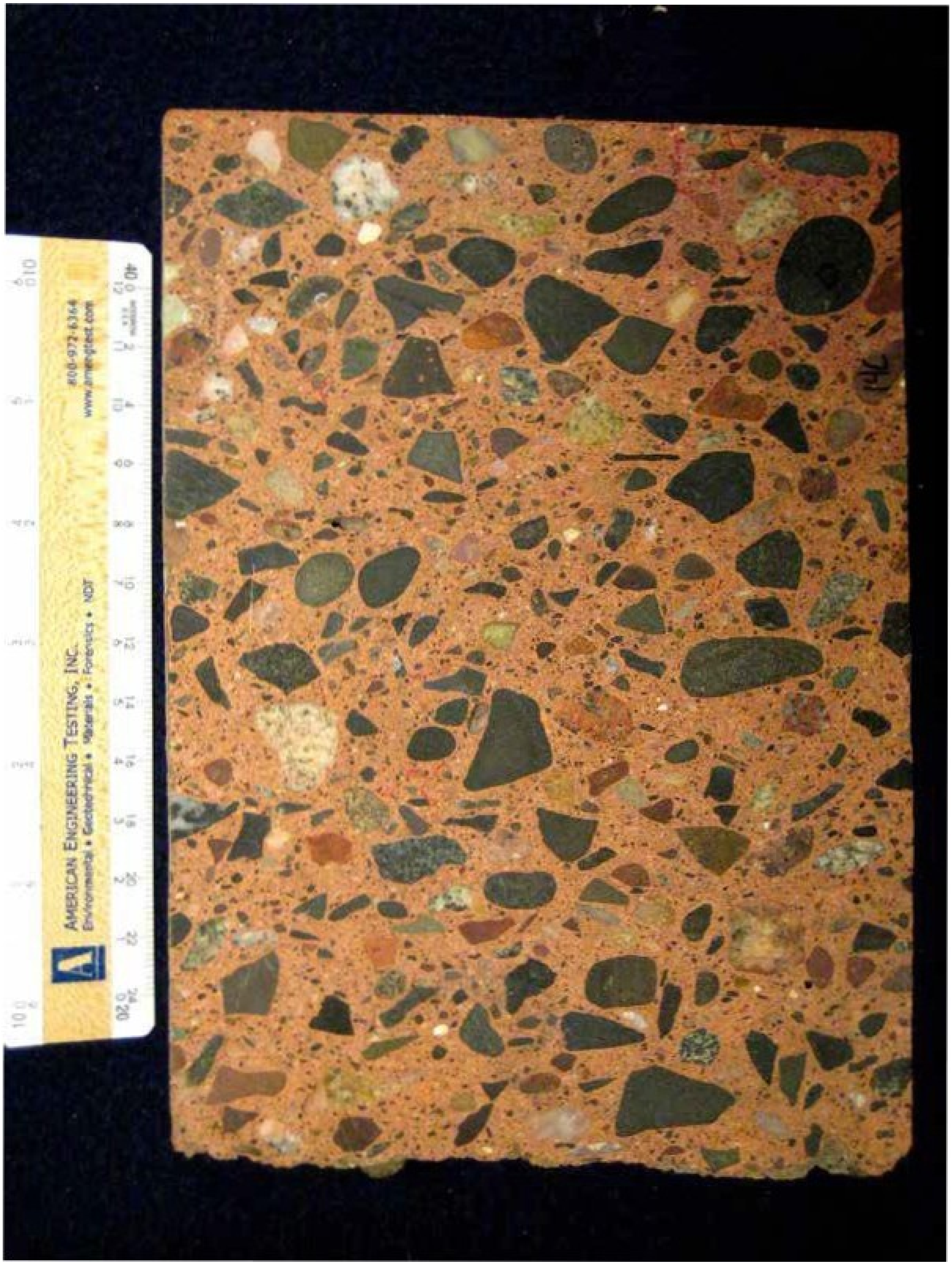


14C DESCRIPTION: Core sample as received. Top surface is right.

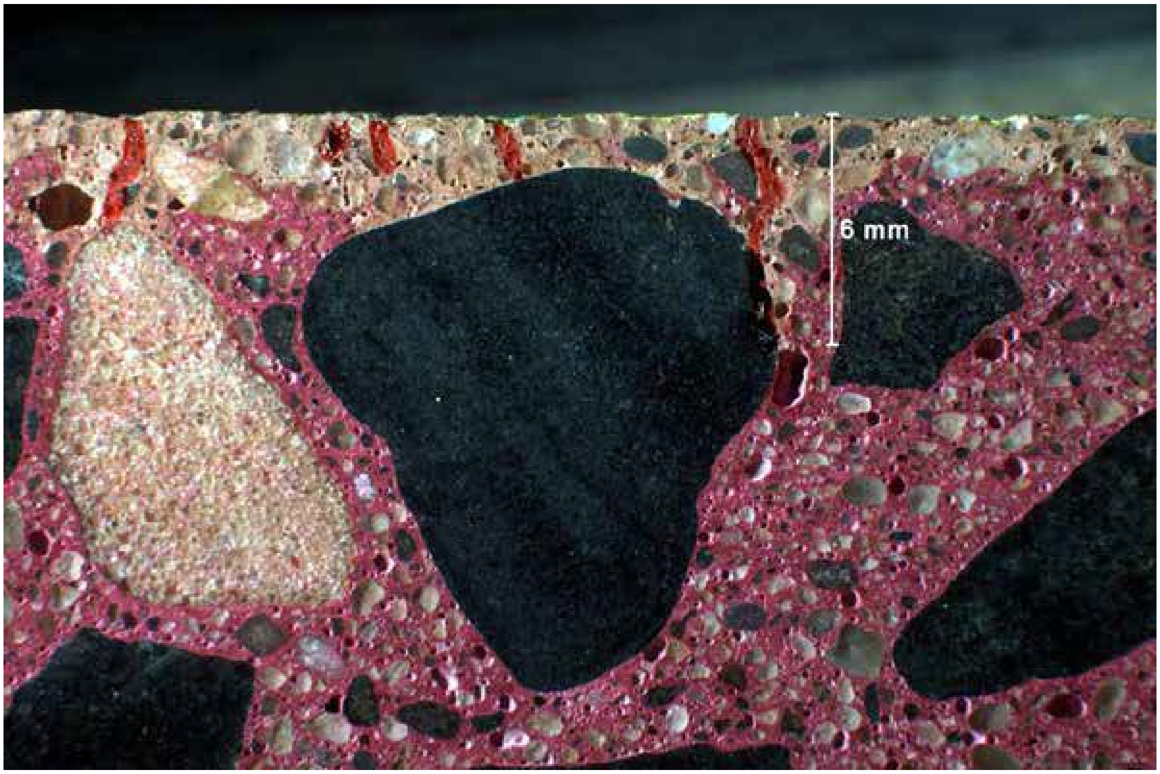
14C DESCRIPTION: Lightly textured and mortar eroded top surface of the core sample as received.



14C DESCRIPTION: Sawcut and lapped cross section of un-distressed concrete core.

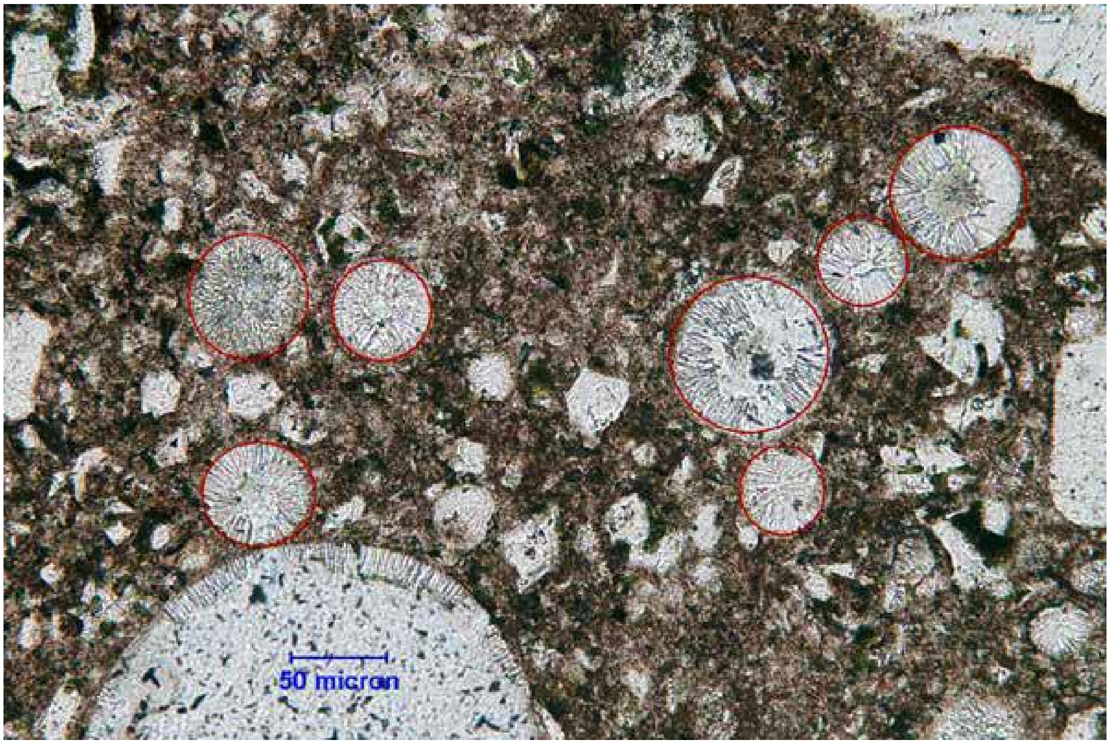


14C DESCRIPTION: Carbonation (unstained) ranged from lmm up to 6mm depth from the top surface along sub-vertical drying shrinkage microcracks mapped in red ink. MAG: 5x

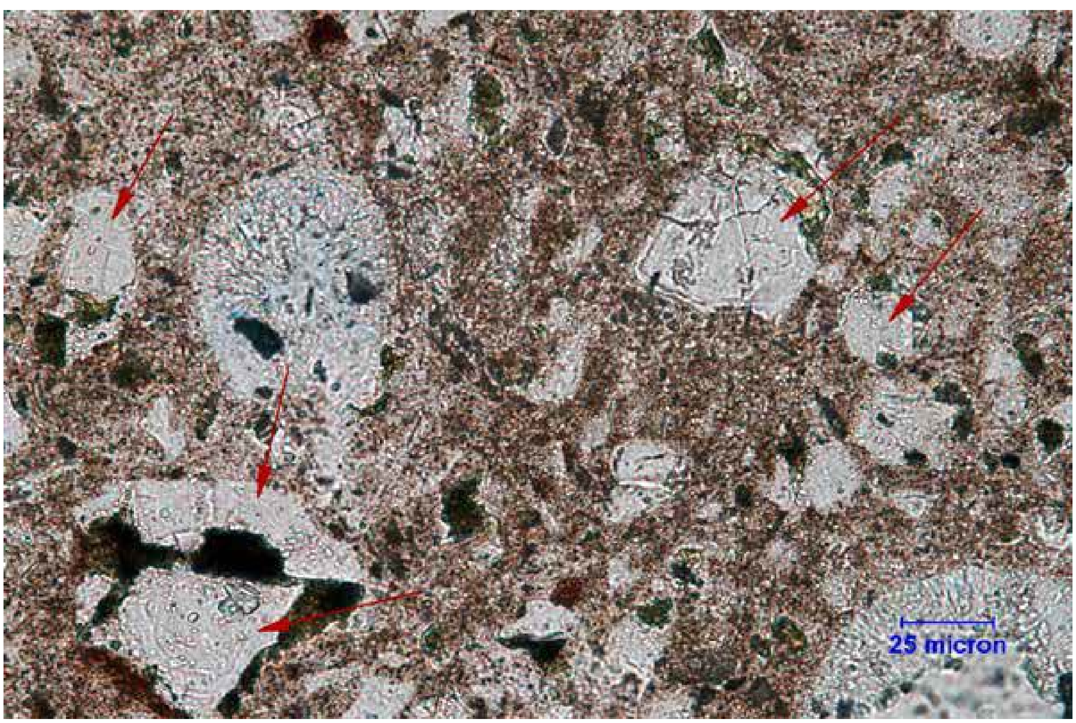


14C DESCRIPTION: Brightly colored (orange), carbonated paste in thin (cross) section of concrete paste at the top surface under plane polarized light. MAG: 40x

14C DESCRIPTION: Ettringite-filled or lined entrained sized air voidspaces in the pigmented paste (outlined in red); in thinsection of concrete under plane polarized light. MAG: 200x



14C DESCRIPTION: Fully hydrated alite portland cement clinker relicts (arrows) in thin section of concrete paste under plane polarized light. MAG: 400x



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

Project No.	24-00469	Date:	October 9, 2012
Sample ID:	14E	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. & Sample Dimensions: Our analysis was performed on one lapped side of a 194mm (7 5/8") x 145mm (5 3/4") x 43mm (1 5/8") thick section (in two pieces) and two 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 151mm (6") diameter x 194mm (7 5/8") long core taken directly through a distressed tooled and sawcut joint. The thin sections were located at between approx. 10mm and 86mm depth and 95mm and 170mm depth in the core from the top surface.

2. & Surface Conditions:
Top: Fairly smooth traffic worn surface; exposing fine aggregate surfaces. Bottom: Rough, irregular, formed surface; placed on a crushed bituminous-rich base.

3. & Reinforcement: None observed.

4. & General Physical Conditions: The core was taken directly through a distressed tooled and sawcut pavement joint. The joint is characterized by an originally rounded - tooled penetration; diamond sawcut (scored) to approximately 38mm depth. The resulting joint crack proceeds the depth of the core at a low angle from vertical. One side of the top surface of the core at the joint has vertically scaled/spalled away while the other side of the joint is relatively intact; exhibiting evidence of the tooling and sawcut. The joint surface has a dark gray colored, "dirty" appearance proceeding to approximately 40mm depth from the top surface into the joint crack. At 40mm the joint plane is lined with light gray colored dirt and debris to approximately 100mm depth. Below 100mm depth, the joint crack plane exhibits a somewhat fresh appearance and is partly lined with white secondary ettringite. Concentrated sub-vertical microcracks (incipient scaling/spalling) occur generally on both sides of the joint crack and within 20mm of the joint plane. The microcracking occurs mostly in the paste but does bisect a few coarse aggregates. Below 150mm depth the concentration of microcracks increases and incorporates up to 80mm of total concrete paste between the two sides of the joint crack. The core exhibits tight residual interlock between the two slabs along the joint crack. The joint plane proceeds around coarse aggregate particles. Several, fine, sub-vertical drying shrinkage microcracks proceed up to 9mm maximum depth from the top surface. Carbonation ranged from <1mm up to 3mm depth from the top surface; "spiking" along the drying shrinkage microcracking. Carbonation, along the joint plane, ranged from, 1mm up to 9mm from the joint crack. The coarse aggregate appeared hard, sound, and durable. No evidence of ASR associated with the coarse aggregate was observed.

   The concrete was fairly well consolidated, with a few scattered consolidation voids measuring up to 10mm. The concrete was purposefully air entrained and contains a well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Air void parameters include a 4.5% entrained-sized void volume and a 0.005" spacing factor. Secondary ettringite lines most voidspaces and fills many of the smallest entrained-sized voidspaces below approx. 20mm depth from the top surface. Void fillings of secondary ettringite increase below 140mm depth and decrease with depth from the plane of the joint. The concrete within approx. 20mm of the joint plane appears to have very limited freeze-thaw resistance.

II. & Aggregate

1. & Coarse:19mm (3/4") nominal sized, superior lobe glacial gravel consisting predominately of basalt, rhyolite, graywacke, and granite with smaller amounts of sandstone, carbonate, and iron oxide. The coarse aggregate appeared well graded and exhibited good overall distribution.

2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, siltstone and shale.) 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: 5.4% total.
2. &Depth of carbonation: Ranged from <1mm up to 3mm depth from the top surface of the core; proceeding deepest along sub-vertical drying shrinkage microcracking. Ranged from <1mm up to 9mm depth from the joint crack: proceeding the deepest near the bottom of the tooled and sawcut joint.
3. &Pozzolan presence: None observed.
4. &Paste aggregate bond: Poor.
5. & Paste color: Pigmented with color similar to Moderate Yellowish Brown (Munsell® 10YR 5/4). Sub- vitreous.
6. &Paste hardness: Moderately hard (>Moh's 3)
7. & Microcracking: Several, very fine, sub-vertical drying shrinkage microcracks proceed up to 9mm depth from the top surface of the core. A few, other, fine, shrinkage microcracks were observed scattered in the paste at various depths and orientations in the core. "Severe", concentrated sub-vertical microcracking (incipient spalling/scaling) occurs generally within 20mm of the joint crack. However, the cracking splays at a moderate angle away from the joint to 55mm distance within 25mm (1") of the bottom surface. The cracking bisects a few typically sound coarse aggregate particles it encounters.
8. &Secondary deposits: Secondary ettringite lines most voidspaces and fills many of the smallest entrained-sized voidspaces below approx. 20mm depth from the top surface. Void fillings of secondary ettringite increase below 140mm depth and decrease with depth from the plane of the joint.
9. &w/cm: Estimated at between 0.44 and 0.50 with approximately 7 to 9% residual portland cement clinker particles.
10. Cement hydration: Alites: Fully. Belites: Mostly fully.

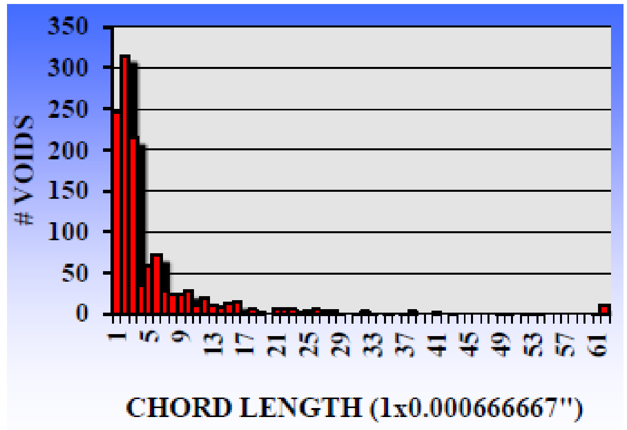
Sample ID: 14E (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Core

Dimensions: 151mm (6") diameter by 194mm (7 5/8") long

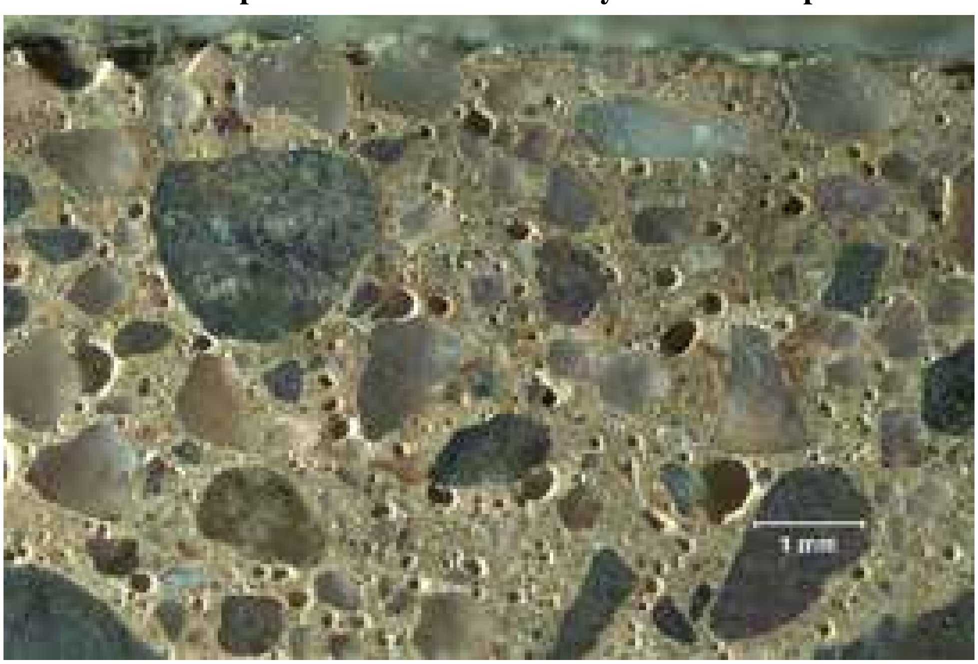


Test Data: By ASTM C:457

Air Void Content %	5.4
Entrained, % < 0.040”(1mm)	4.5
Entrapped, %> 0.040”(1mm)	0.9
Air Voids/inch	13.2
Specific Surface, in^2/in^3	980
Spacing Factor, inches	0.005
Paste Content, % calculated	24.4
Magnification	75x
Traverse Length, inches	90
Test Date &	10/3/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x
Description: Hardened air void system @ the top surface.

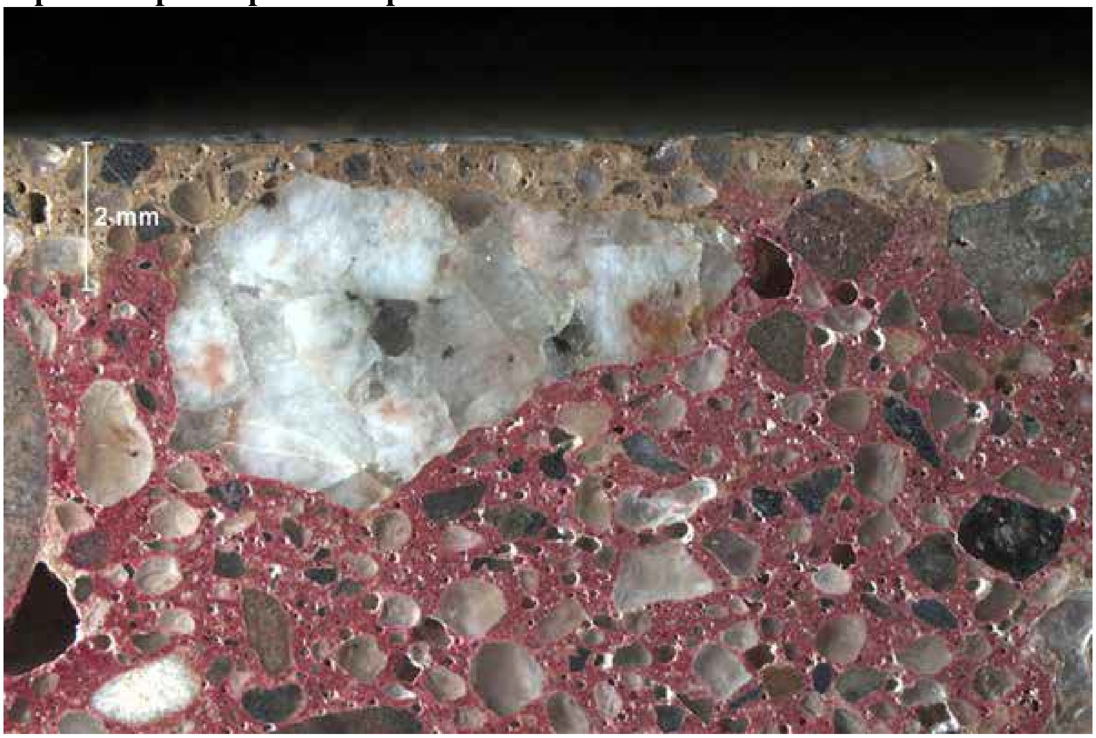


14E DESCRIPTION: Core sample as received. Top surface is right. Note raveled joint and "activated" joint.

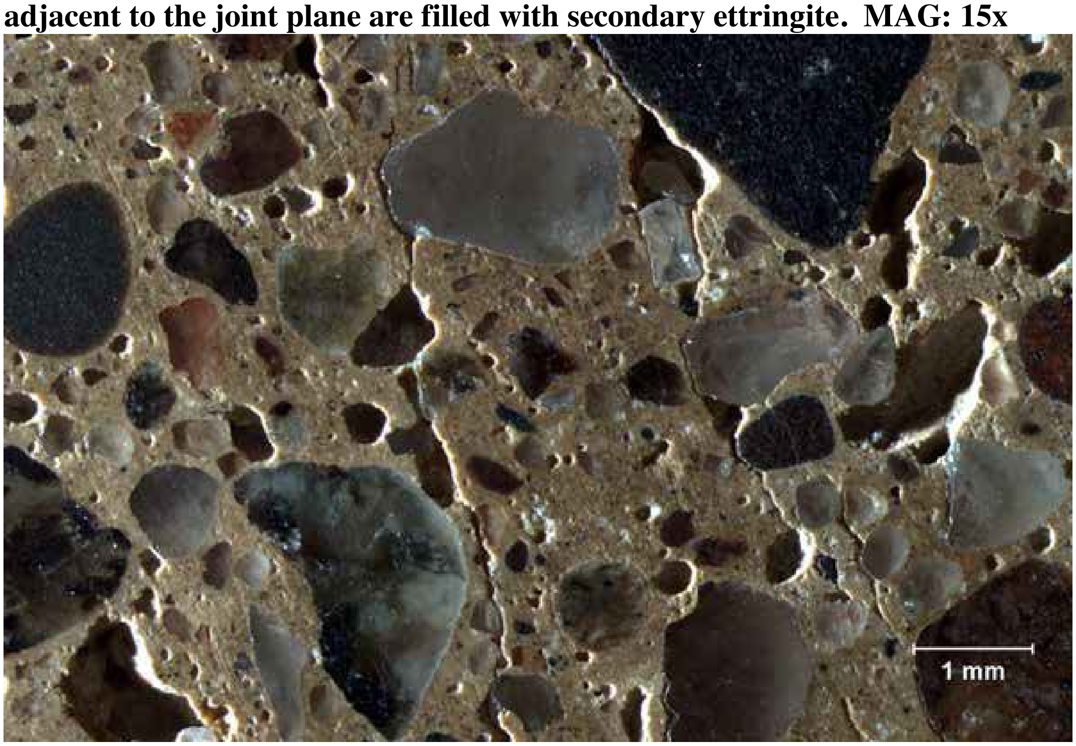
14E DESCRIPTION: Top surface of the core sample as received. Note spalled joint.

14E DESCRIPTION: Sliver spalling and severe incipient distress (sub-vertical micro and macro cracking) in the concrete paste directly adjacent to the "activated", tooled and sawcut oint in red ink in sawcut and cross section of core.

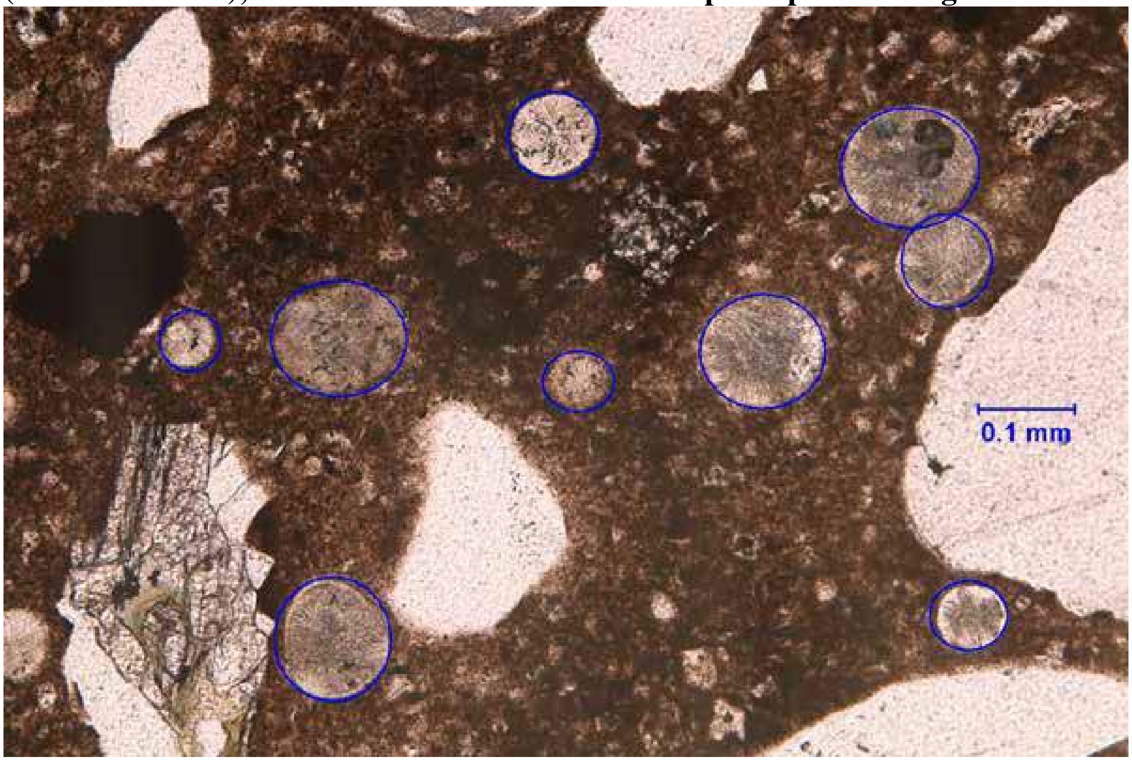
14E DESCRIPTION: Carbonation (unstained paste) proceeds up to 2mm depth from the traffic-worn top surface of the core. In freshly sawcut and lapped cross section of core exposed to phenolphthalein pH indicator. MAG: 10x



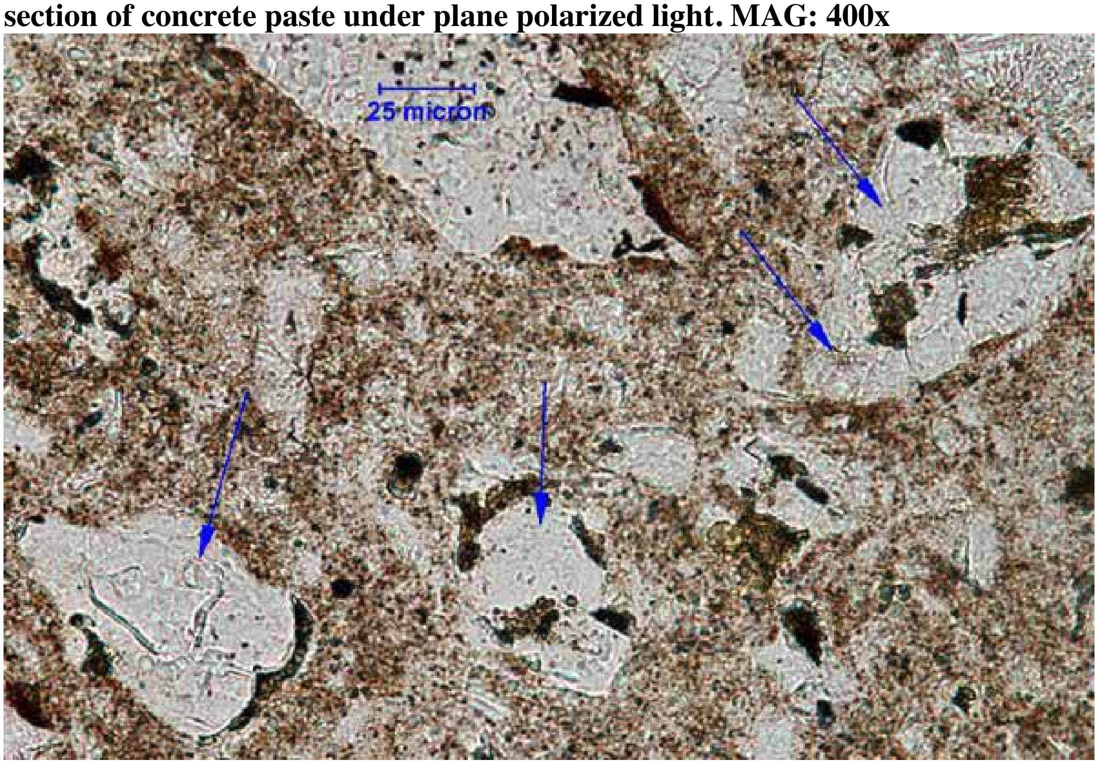
14E DESCRIPTION: Most fine entrained-sized air void spaces within the distressed paste adjacent to the joint plane are filled with secondary ettringite. MAG: 15x



14E DESCRIPTION: Ettringite-filled entrained sized air voidspaces in the pigmented paste (outlined in blue); in thin section of concrete under plane polarized light. MAG: 10x



14E DESCRIPTION: Fully hydrated alite portland cement clinker relicts (arrows) in thin section of concrete paste under plane polarized light. MAG: 400x



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

Project No.	24-00469	Date:	October 10, 2012
Sample ID:	96A	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. & Sample Dimensions: Our analysis was performed on one lapped side of a 240mm (9 1/2") x 145mm (5 3/4") x 35mm (1 3/8") thick section and two 76mm (3") x 52mm (2") wide thin sections that were sawcut perpendicular to the distressed joint plane and prepared from the original 151mm (6") diameter x 240mm (9 1/2") long core taken directly through a distressed sawcut joint. The thin sections were located at between 0mm and 75mm depth and 130mm and 215mm depth in the core from the top surface; directly adjacent to the joint surface.

2. & Surface Conditions:
Top: Fairly smooth, originally lightly textured, and traffic worn surface; exposing many fine aggregate surfaces. Bottom:Rough, irregular, formed surface; placed on a recycled concrete and bituminous base.

3. & Reinforcement: None observed.

4. & General Physical Conditions: The concrete core was directly through a severely distressed pavement joint. No evidence of the original joint detailing remains. Some "interlock" remains at depth between the two slabs along the resulting joint crack. The distress is characterized by moderately-angled corner spalling to approx. 37mm (1 1/2") on each side of the joint and to approx. 52mm (2") depth into the joint and severe incipient spalling/scaling along the entire depth of the joint. The joint crack exhibits shallow, sub-vertical scaling/spalling below approx. 52mm depth and along the entire depth of the core. Several of the aggregate particles on the face of the joint crack appear to have fractured along the joint crack while a few relatively “clean” and un-distressed aggregate particles protrude from the cement paste along the joint crack. Concentrated, mostly sub-vertical microcracks (incipient scaling/spalling) were observed within 37mm (1 1/2") of the joint crack. The microcracking passes through several coarse aggregate particles. White secondary deposits or "mats" of ettringite and/or calcium carbonate line the joint plane. Portions of the outer up to 7mm of paste directly adjacent to the vertical distressed joint surface exhibit an "altered" appearance, with lighter coloration and much softer (portions carbonated and some portions free of calcium hydroxide or filled with an unidentified low relief, low birefringent material) paste filled with concentrated microcracking. The coarse aggregate appeared sound. No evidence of ASR associated with the coarse aggregate was observed. A few alkali-silica “reacted” shale fine aggregate particles were present in the core. The “reacted” shale particles exhibit internal cracking that propagates shallowly into the paste.

The fairly smooth top surface of the core exhibits minor traffic wear; topographic highs have been worn smooth; exposing fine aggregate surfaces. The concrete was fairly well consolidated, with a few, scattered, irregular-shaped consolidation voids observed to at least

12mm 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 3.4% entrained-sized void volume and a 0.004" spacing factor. Secondary ettringite fills most finer entrained sized voidspaces throughout the sample and has compromised the effectiveness of the air void system. Current air void parameters, outside of the top approx. 5mm of the core, and greater than 125mm depth from the top surface and 40mm distance from the distress, appear to offer no freeze-thaw resistance. The concrete paste contained a finely disseminated red pigment.

II. &Aggregate

1. &Coarse:19mm (3/4") nominal sized glacial gravel consisting predominately of rhyolite, granite, basalt, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.

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

III. Cementitious Properties

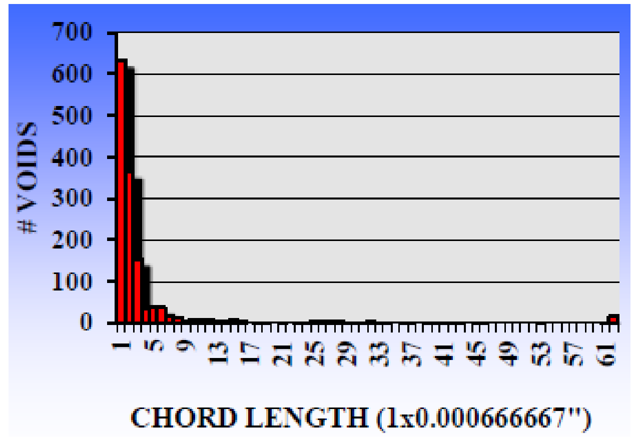
1. &Air Content: Original total: 4.9% total.
2. &Depth of carbonation: Ranged from negligible 4mm depth from the top surface of the core; spiking along fine sub- vertical drying shrinkage microcracking. Carbonation occurs along vertical microcracking (incipient spalling/scaling) up to 25mm depth from the distressed joint plane.
3. &Pozzolan presence:A purposeful addition of flyash was observed.
4. &Paste/aggregate bond: Fair to poor.
5. &Paste color: Pigmented with a color similar to Moderate Red (Munsell® 5R 5/4). Lighter coloration in the altered outer up to 7mm of paste adjacent to the distressed joint surface.
6. & Paste hardness: Relatively hard (Moh's 4). Soft (<Moh s 2) in portions of the outer up to 7mm of paste directly adjacent to the distressed joint.
7. &Microcracking: A few, fine, sub-vertical drying shrinkage microcracks proceed to 8mm depth from the top surface of the core. Numerous microcracks (incipient scaling/spalling) were observed oriented sub-parallel to and generally within 37mm (1 1/2") of the distressed joint face. The microcracking appeared highly concentrated in the outer approx. 15mm. The cracking proceeded through several coarse aggregates.
8. &Secondary deposits:Secondary ettringite fills numerous entrained sized voidspaces throughout the sample. However, air voids within the top approx. 4mm of the core exhibits little ettringite. Ettringite also partly fills sub-vertical microcracking, generally within 15mm of the distress plane. Portland is also common within voidspaces in the outer approx. 8mm of the distressed concrete paste. ASR gel lines a few, scattered voidspaces proximate to reactive shale fine aggregates. Abundant calcite occurs within microcracking in the outer approx. 7mm of the distressed concrete at the joint plane.
9. &w/cm: Estimated at between 0.42 and 0.47 with approximately 7 to 9% residual portland cement clinker particles, an amount of flyash visually consistent with a 5 to 15%

replacement of flyash, and a trace of residual slag cement.

10. Cement hydration: Alites: Fully. Belites: Well to fully. Slag: Mostly fully.

Sample ID: 96A (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Core

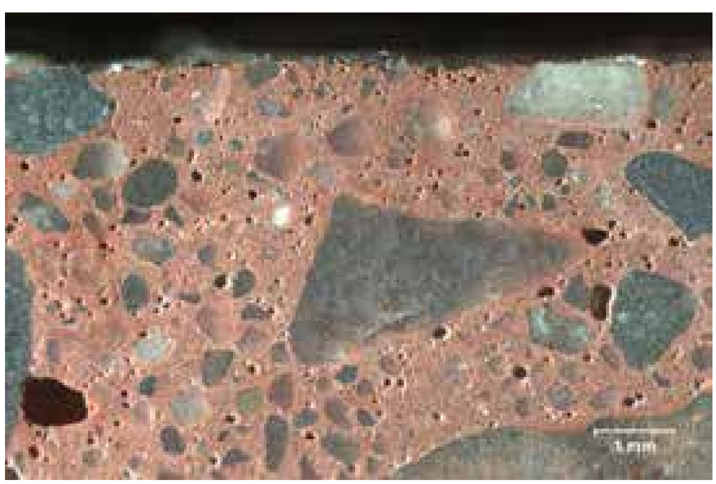
Dimensions: 151mm (6") diameter by 240mm (9 1/2") long

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	15.2
Specific Surface, in^2/in^3	1250
Spacing Factor, inches	0.004
Paste Content, % calculated	30.9
Magnification	75x
Traverse Length, inches	92
Test Date	9/27/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x
Description: Hardened air void system @ the top surface.

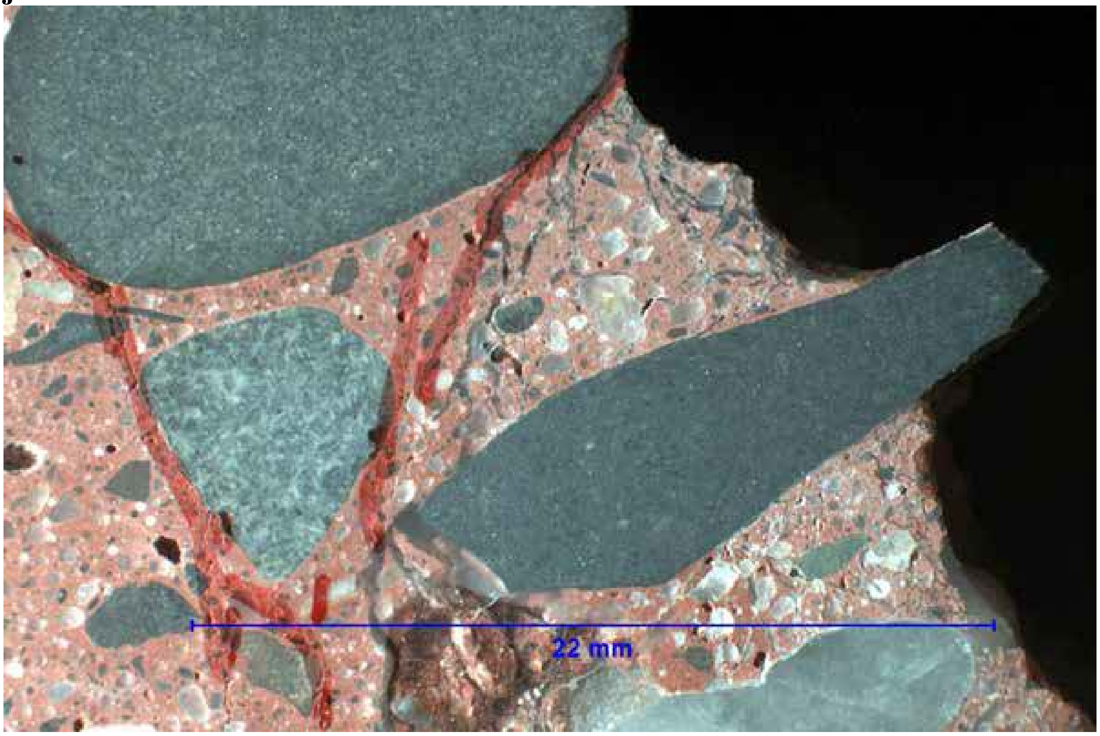


96A DESCRIPTION: Core sample as received. Top surface is right. Note severely distressed joint.

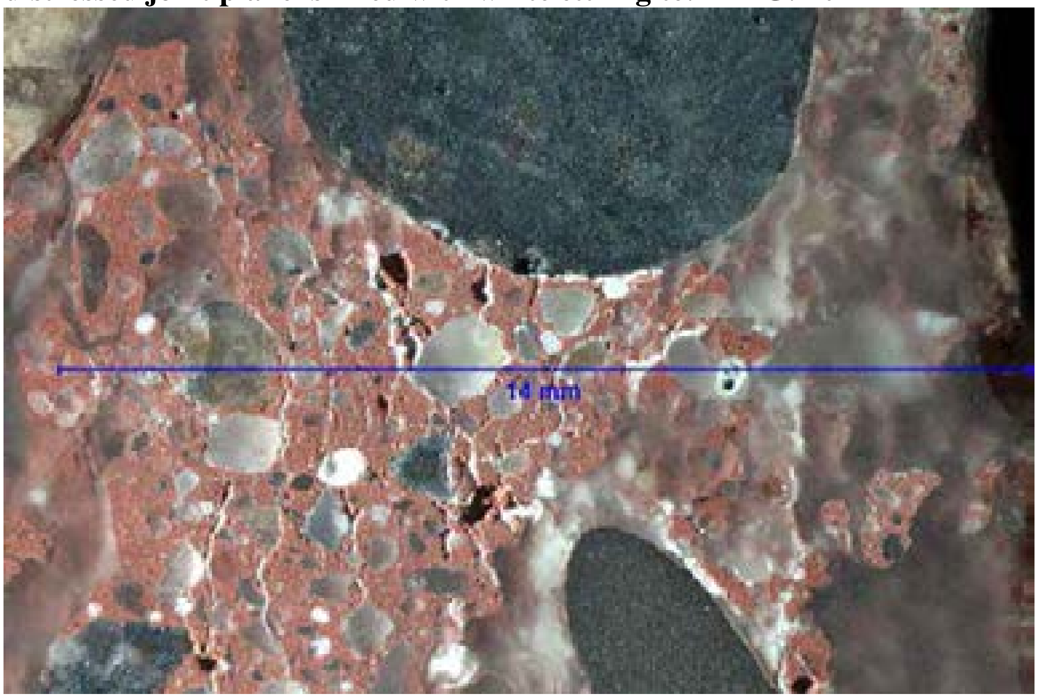
96A DESCRIPTION: Top surface of the core sample as received. Note severely distressed joint.

96A DESCRIPTION: Spalling and severe incipient distress (sub-vertical micro and macro cracking) in the concrete paste directly adjacent to the "activated" control joint crack. Micro and macrocracking is mapped in red ink in the sawcut and lapped cross section of core.

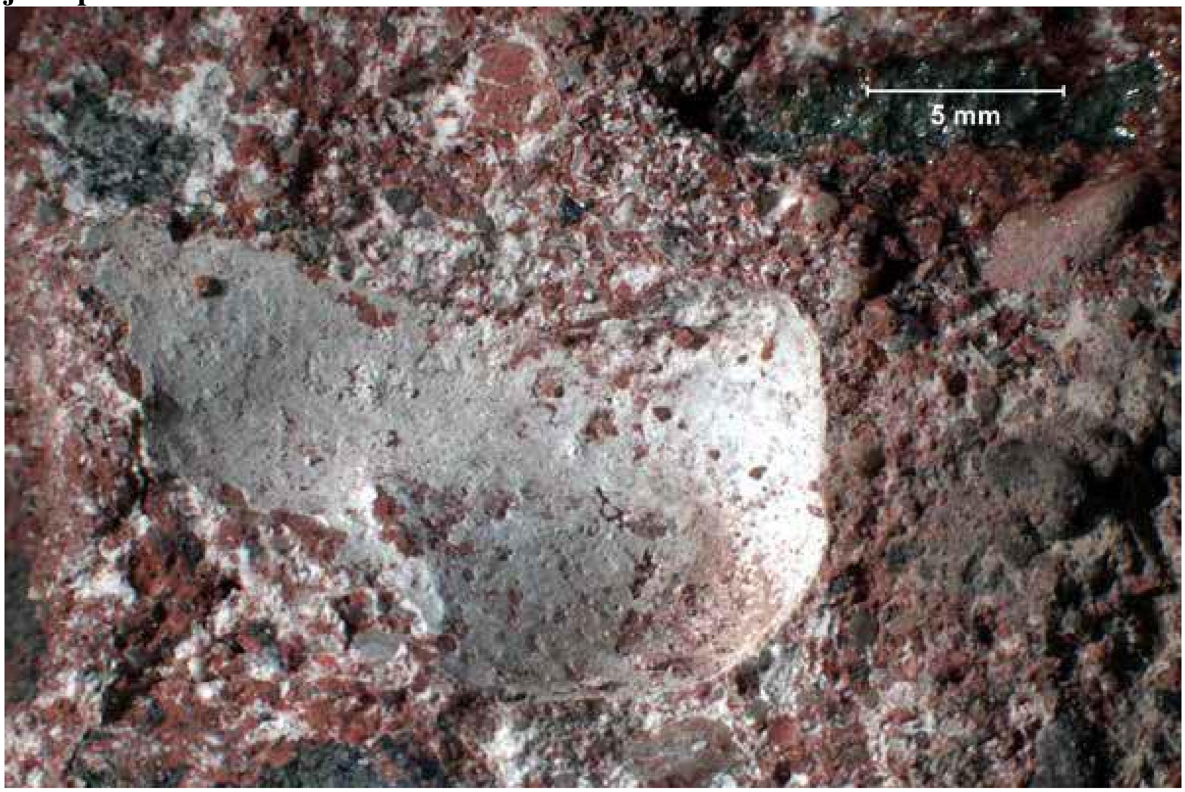
96A DESCRIPTION: Highly distressed paste occurs within 22mm of the spalled corner of the joint. Some microcracking is mapped in red ink. Concentrated fine microcracking filled with epoxy is present between the mapped microcracking and the spalled corner of the joint. MAG: 5x



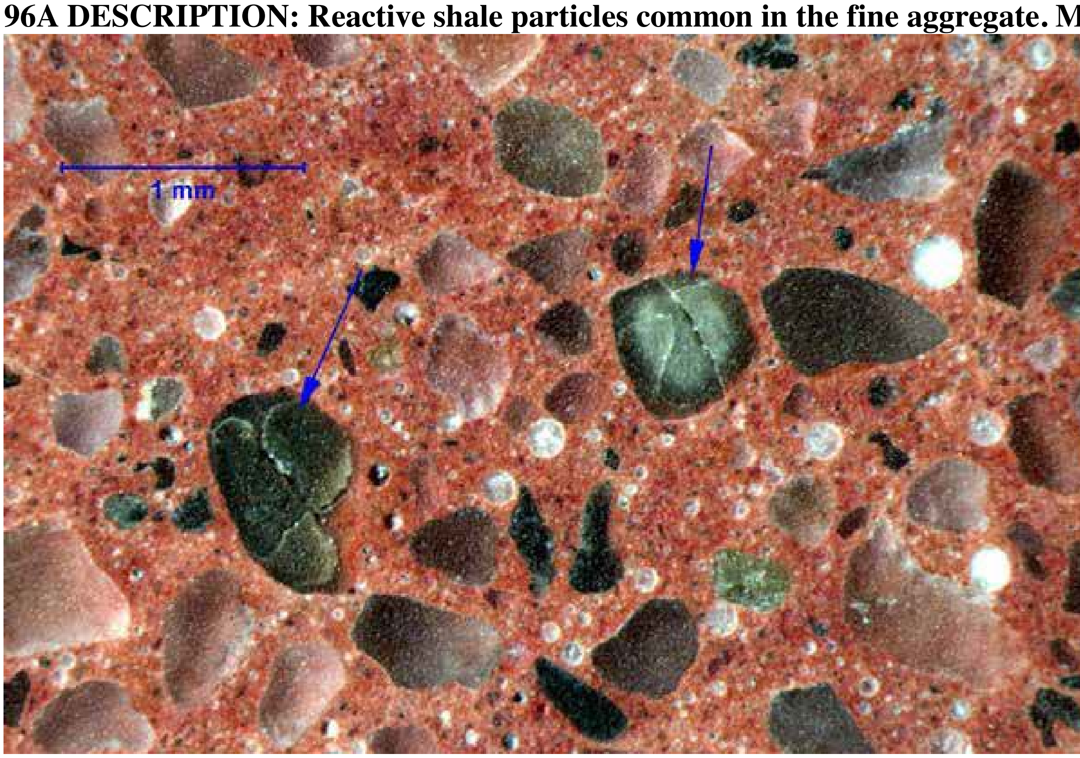
96A DESCRIPTION: Concentrated, sub-vertical microcracking within 14mm of the distressed joint plane is filled with white ettringite. MAG: 10x



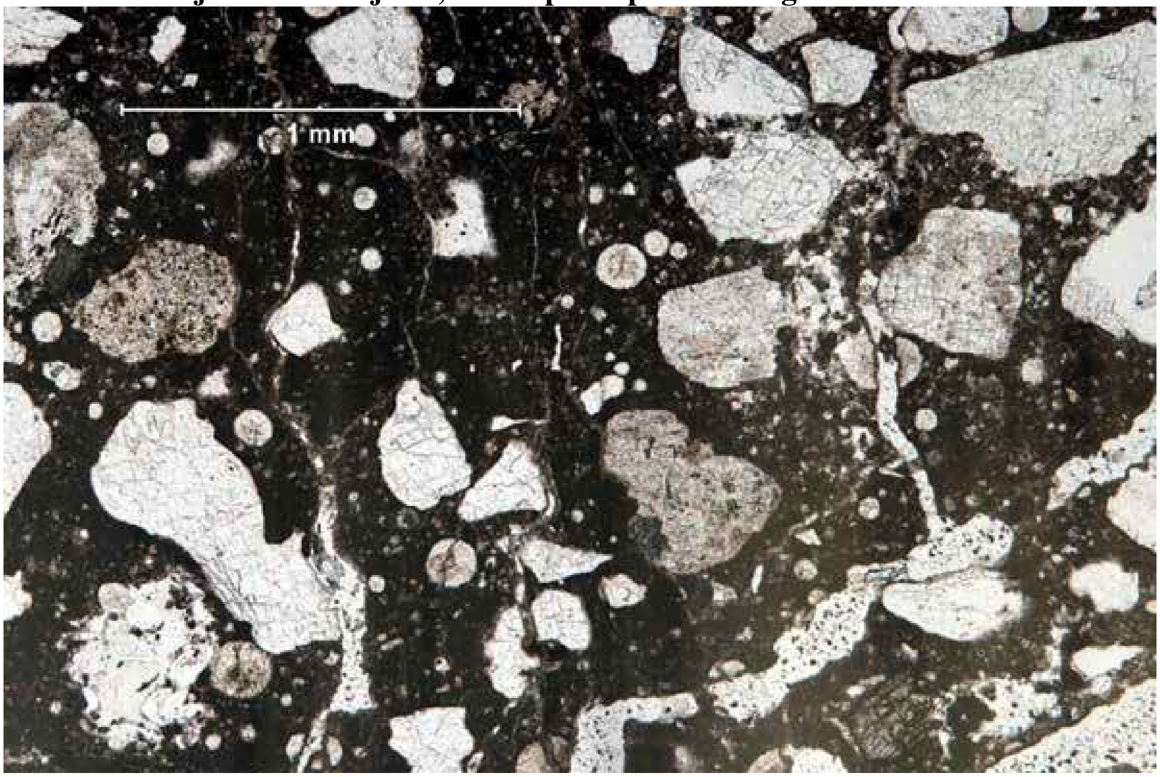
96A DESCRIPTION: White mats of ettringite partly cover the spalled inner surface of the joint plane. MAG: 5x



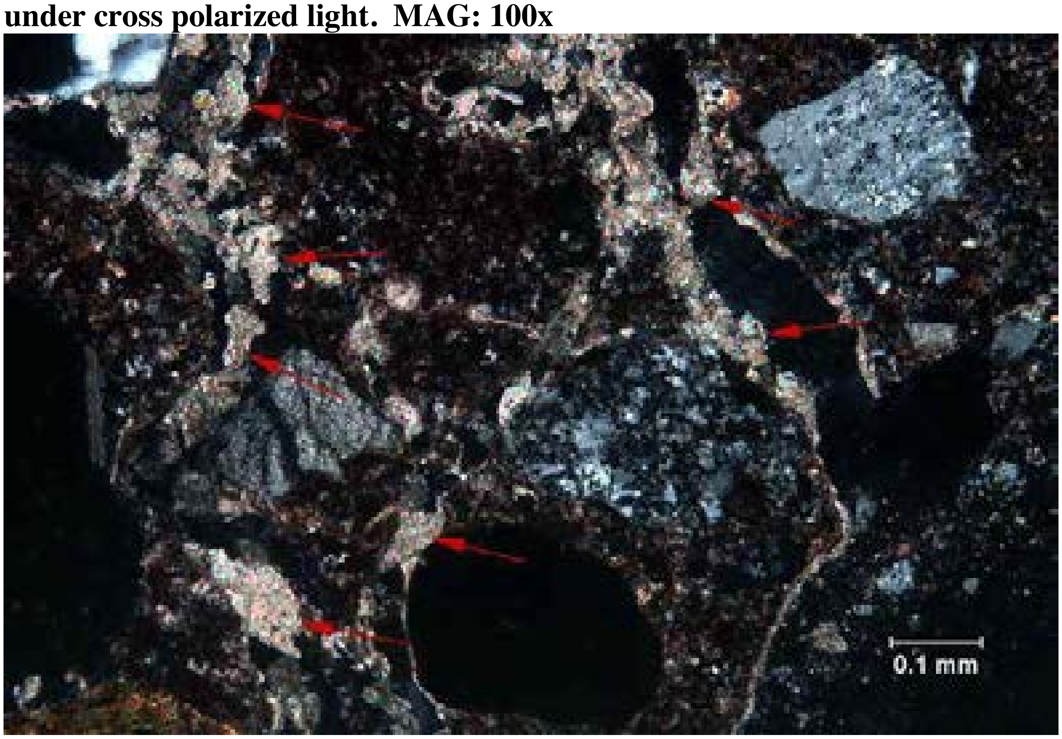
96A DESCRIPTION: Reactive shale particles common in the fine aggregate. MAG: 30x



96A DESCRIPTION: Fine sub-vertical microcracking in the paste, in thin section of concrete adjacent to the joint; under plane polarized light. MAG: 40x

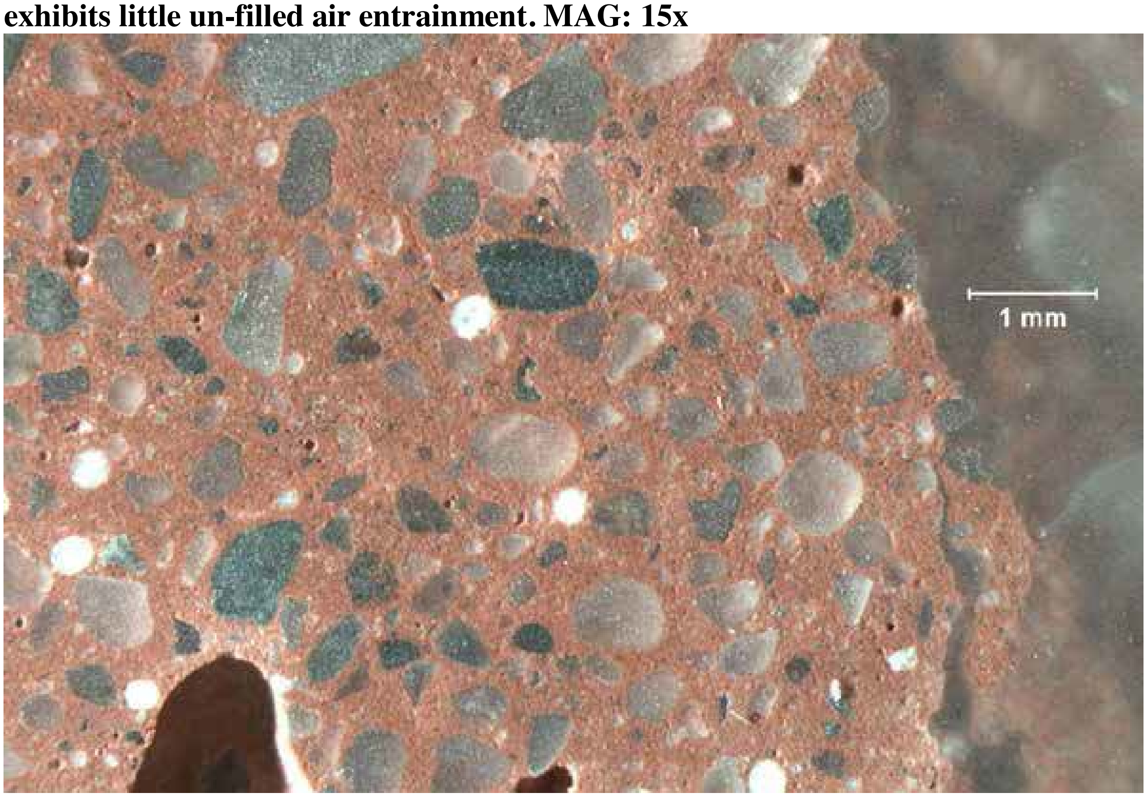


96A DESCRIPTION: Brightly colored secondary calcite in microcracking within the outer
7mm of the concrete directly adjacent to the distressed joint plane; in thin section under cross polarized light. MAG: 100x



96A DESCRIPTION: The entrained air void system adjacent to the top surface of the core is free of secondary ettringite fillings. MAG: 15x

96A DESCRIPTION: The concrete at +165mm depth and directly adjacent to the joint exhibits little un-filled air entrainment. MAG: 15x



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

Project No.	24-00469	Date:	October 8, 2012
Sample ID:	96C	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on one lapped side of a 210mm (8 1/4") x 145mm (5 3/4") x 38mm (1 1/2") thick section and two 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 145mm (5 ¾") diameter x 210mm (8 1/4") long core.

2. &Surface Conditions:
Top: Somewhat rough textured and mortar eroded surface; with many exposed fine aggregate surfaces. Bottom:Rough, irregular, formed surface; placed on a recycled concrete and bituminous base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The somewhat rough textured top surface of the core exhibits mortar erosion; exposing fine particles. The concrete was fairly well consolidated, with a few, scattered, irregular shaped consolidation voids measuring up to 15mm. The concrete was purposefully air entrained and originally contained a relatively fine, well- distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air void parameters include a 3.4% entrained-sized void volume and a 0.004" spacing factor. The concrete contains a finely disseminated red pigment. Secondary ettringite fills many of the finest entrained sized voidspaces throughout the sample, with the greatest concentration of fillings occurring below 5mm and 55mm depth from the top surface and within 50mm of the formed bottom surface. The fillings have likely compromised the effectiveness of the air void system in these locations. The coarse aggregate appeared hard, sound and durable. No evidence of alkali-silica reaction (ASR) associated with the coarse aggregate was observed. A few alkali-silica "reacted" shale fine aggregate particles were scattered in the core.

II. &Aggregate

1. &Coarse:19mm (¾") nominal sized superior lobe glacial gravel consisting predominately of rhyolite, granite, basalt, graywacke, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.

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

III. Cementitious Properties

1. &Air Content: Original total: 5.1%
2. &Depth of carbonation:Ranged from negligible up to 12mm depth, intermittently, from the top surface of the core; spiking to 5mm depth along a sub-vertical microcrack.
3. &Pozzolan presence: Flyash was observed.
4. &Paste/aggregate bond: Poor.
5. &Paste color:Pigmented with a color similar to Moderate Red (Munsell® 5R 5/4). Vitreous to sub-vitreous.
6. &Paste hardness: Relatively hard (Moh's 4)
7. &Microcracking: Several, fine, sub-vertically oriented, drying shrinkage microcracks proceed up to 15mm maximum depth from the top surface of the core. "Reacted" shale particles exhibit internal cracking that shallowly propagates into the paste.
8. & Secondary deposits: Secondary ettringite fills most of the finest entrained sized voidspaces throughout the sample below approx. 5mm depth from the top surface; and lines most other voids. ASR gel lines few voidspaces directly adjacent to reacted shale fine aggregate particles.
9. & w/cm: Estimated at between 0.42 and 0.47 with approximately 8 to 10% residual portland cement clinker particles, 0% residual slag cement particles, and an amount of flyash visually consistent with a 5 to 15% replacement of portland cement.
10. Cement hydration: Alites: Mostly fully. Belites: Fully. Slag: Fully.

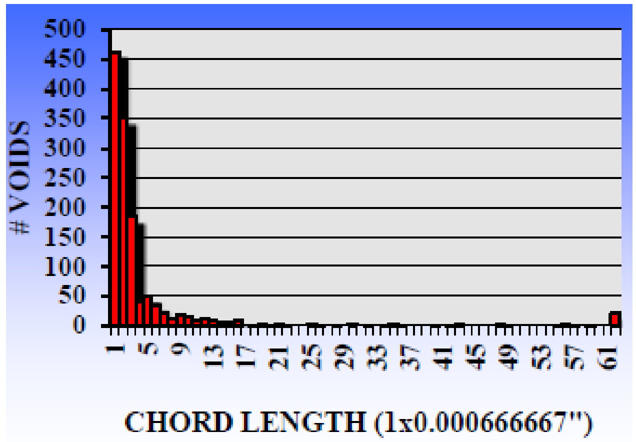
Sample ID: 96C (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Core

Dimensions: 151mm (6") diameter by 210mm (8 1/4") long



Test Data: By ASTM C:457

Air Void Content %	5.1
Entrained, % < 0.040"(1mm)	3.4
Entrapped, %> 0.040"(1mm)	1.7
Air Voids/inch	14.0
Specific Surface, in^2/in^3	1110
Spacing Factor, inches	0.004
Paste Content, % calculated	22.3
Magnification	75x
Traverse Length, inches	92
Test Date	9/13/2012

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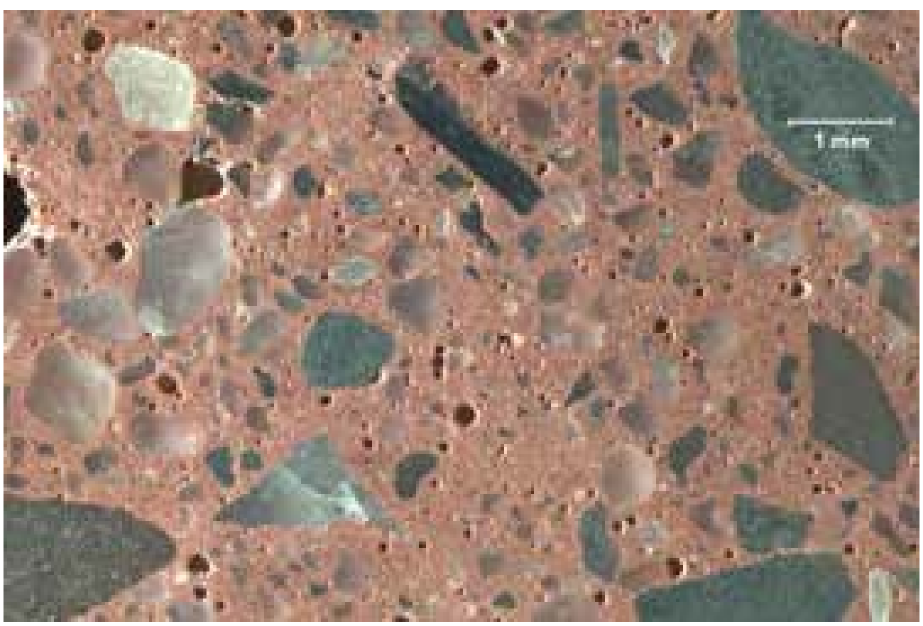
Magnification: 15x

Description: Hardened air void system @ 12mm depth from the top surface.

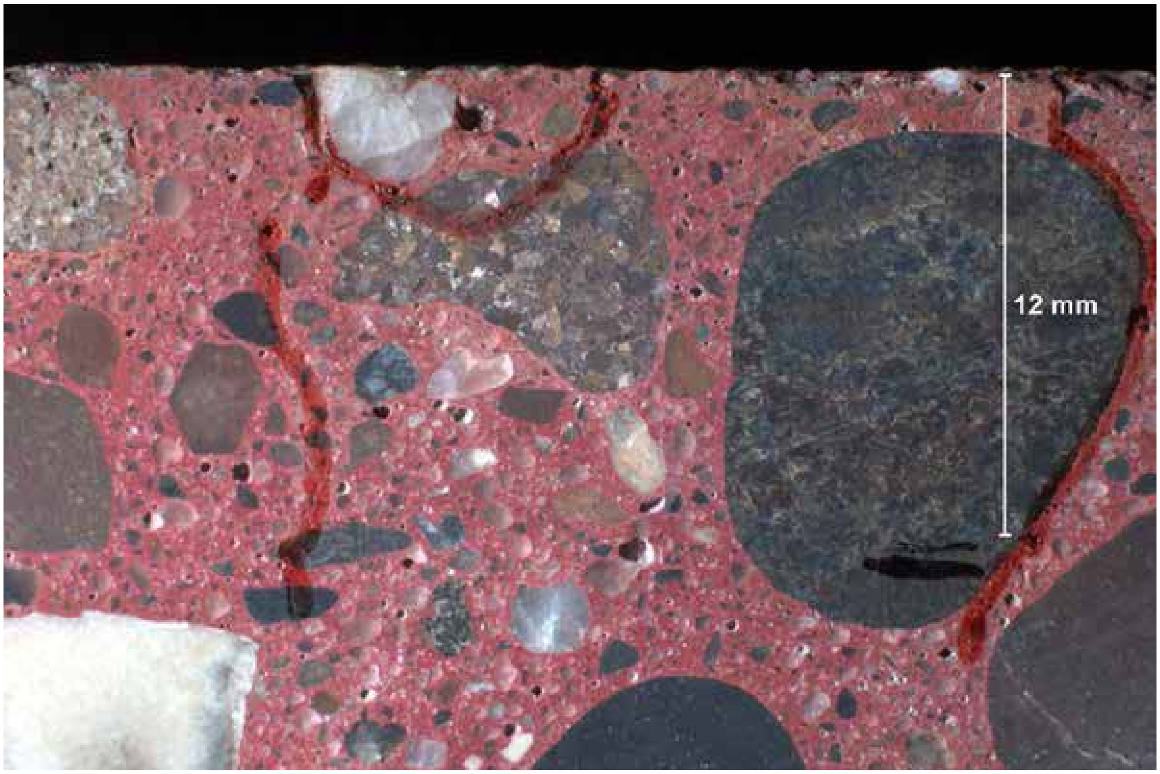


96C DESCRIPTION: Core sample as received. Top surface is right.

96C DESCRIPTION: Lightly textured and mortar eroded top surface of the core sample as received.

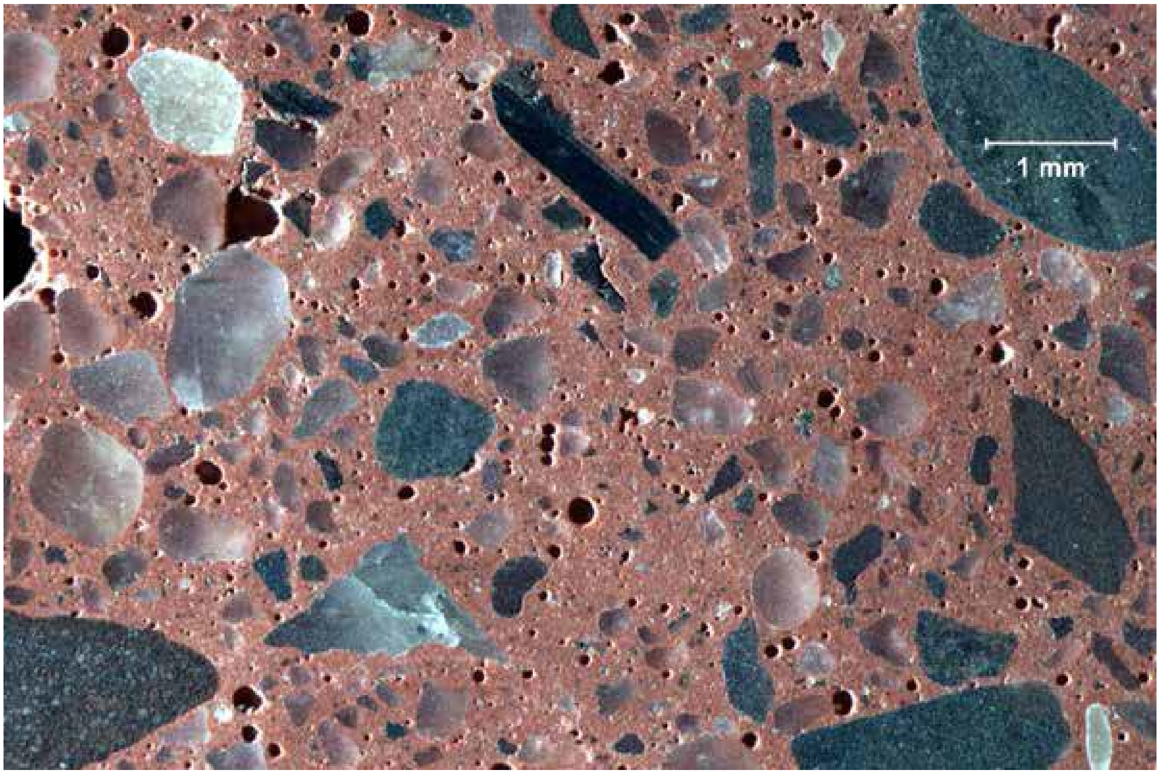
96C DESCRIPTION: Sawcut and lapped cross section of 151mm diameter, un-distressed,
mid-panel concrete core.

96C DESCRIPTION: Carbonation ranged from negligible up to 12mm depth, intermittently, along sub-vertical drying shrinkage microcracks mapped in red ink. MAG: 5x

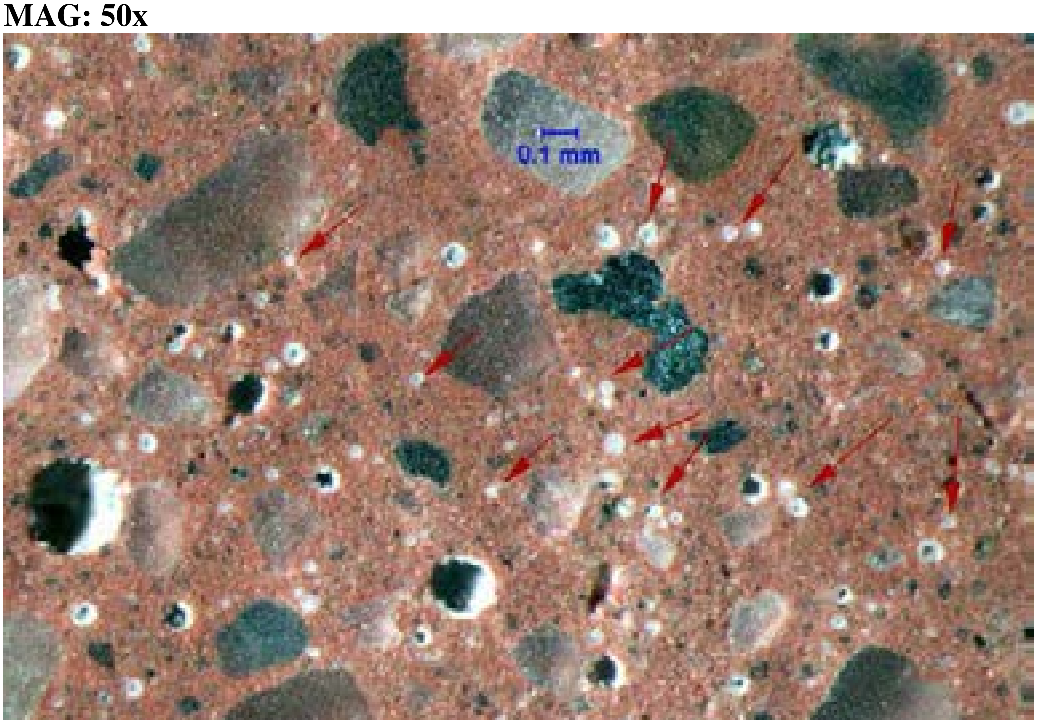


96C DESCRIPTION: The top surface of the concrete exhibits mortar erosion exposing many fine aggregates. MAG: 5x

96C DESCRIPTION: Overall hardened air content proximate to the top surface of the core. MAG: 15x



96C DESCRIPTION: Ettringite-filled voidspaces below 17mm depth in the core. MAG: 50x



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

Project No.	24-00469	Date:	October 8, 2012
Sample ID:	96D	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on one lapped side of a 200mm (7 3/4") x 145mm (5 3/4") x 38mm (1 ") thick section and two 76mm (3") x 52mm (2") wide thin sections that were sawcut and prepared from the original 151mm (6") diameter x 200mm (7 3/4") long core taken adjacent to a distressed sawcut joint. The thin sections were located at between 0mm and 45mm depth and 47mm and 130mm depth in the core from the top surface; directly adjacent to the joint surface.

2. &Surface Conditions:
Top: Fairly smooth, traffic worn surface; exposing many fine aggregate surfaces. Approx. 10% scaled away. Bottom: Rough, irregular, formed surface; placed on a recycled concrete and bituminous base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The concrete core was apparently taken directly adjacent to a distressed, sawcut pavement joint. The joint is characterized by evidence of a sawcut, locatable only by a single, vertically-truncated, sawcut aggregate particle protruding from the distressed cement paste, to 12mm (1/2") depth from the top surface plane. The remaining evidence of the sawcut joint was vertically scaled/spalled away; with the subsequent distressed joint plane comprising a vertical face along the entire depth of the core. Up to approximately 19mm (3/4") of the total core diameter has vertically scaled/spalled off along the joint crack. Several of the aggregate particles on the face of the joint crack appear to have fractured along the joint crack while a few relatively “clean” and un-distressed aggregate particles protrude from the cement paste along the joint crack. Numerous sub-vertical microcracks (incipient scaling/spalling) were observed within 25mm of the joint crack. The microcracks pass through several coarse aggregate particles. The top approximately 20mm of the joint plane is characterized by a light brownish gray, somewhat “dirty” surface with some debris lining the joint plane. Below 20mm depth the joint plane appears clean with some white secondary deposits or "mats" of ettringite lining the joint plane to a depth of 170mm. The coarse aggregate appeared sound. No evidence of ASR associated with the coarse aggregate was observed. A few alkali-silica “reacted” shale fine aggregate particles were present in the core. The “reacted” shale particles exhibit internal cracking that propagates shallowly into the paste.

   The fairly smooth top surface of the core exhibits significant traffic wear; topographic highs have been worn smooth with exposed fine particles exhibiting worn surfaces. Approx. 10% of the top surface area was scaled away along a cored edge of the top surface. The scaling was not contemporaneous with the distressed joint plane. The concrete was fairly well consolidated, with a few, scattered, irregular-shaped consolidation voids measuring up to

15mm. 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 2.7% entrained-sized void volume and a 0.007" spacing factor. Secondary ettringite fills numerous finer entrained sized voidspaces throughout the sample and has compromised the effectiveness of the air void system. Current air void parameters, excluding ettringite filled voids, are characterized by a 1.1% entrained-sized void volume and a 0.019" spacing factor. The concrete paste contained a finely disseminated red pigment. Distinct, darker colored, denser paste of lower w/cm was observed in many concave coarse aggregate notches; suggesting multiple additions of water during batching.

II. &Aggregate

1. &Coarse: 19mm (3/4") nominal sized glacial gravel consisting predominately of rhyolite, granite, basalt, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.

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

III. Cementitious Properties

1. &Air Content: Original total: 4.3% Current total: 2.3%
2. &Depth of carbonation: Ranges from 1mm up to 2mm depth from the top surface of the core; spiking to 5mm depth along fine sub-vertical drying shrinkage microcracking.
3. &Pozzolan presence: None observed.
4. &Paste/aggregate bond: Fair to poor.
5. &Paste color: Pigmented with a color similar to Moderate Red (Munsell® 5R 5/4)
6. &Paste hardness: Relatively hard (Moh's 4)
7. &Microcracking: Several, fine, sub-vertical drying shrinkage microcracks proceed to 8mm depth from the top surface of the core. Numerous microcracks (incipient scaling/spalling) were observed oriented sub-parallel to and generally within 25mm of the distressed joint face. The cracking proceeded through several coarse aggregates.
8. &Secondary deposits: Secondary ettringite fills numerous entrained sized voidspaces throughout the sample. However, the top approx. 5mm of the core exhibits little ettringite.
9. &w/cm: Estimated at between 0.42 and 0.47 with approximately 7 to 9% residual portland cement clinker particles and a trace of residual slag cement.
10. Cement hydration: Alites: Mostly fully. Belites: Well to fully. Slag: Mostly fully.

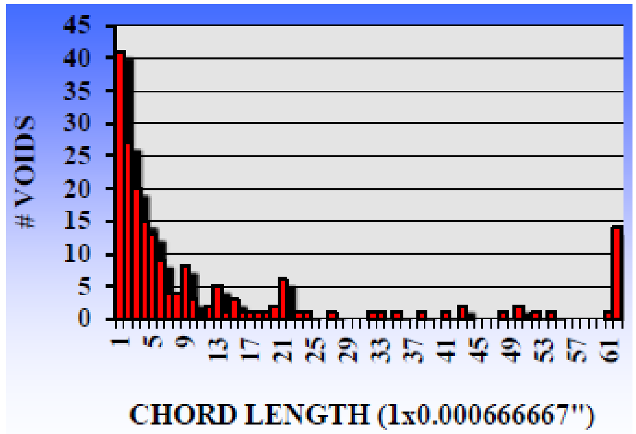
Sample ID: 96D (unfilled air)

Conformance: The concrete core 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: 151mm (6") diameter by 210mm (8 1/4") long



Test Data:	By ASTM C:457
Air Void Content %	2.3
Entrained, % < 0.040"(1mm)	1.1
Entrapped, %> 0.040"(1mm)	1.2
Air Voids/inch	2.1
Specific Surface, in^2/in^3	370
Spacing Factor, inches	0.019
Paste Content, % calculated	29.6
Magnification	75x
Traverse Length, inches	92
Test Date	9/13/2012

Report Prepared By:
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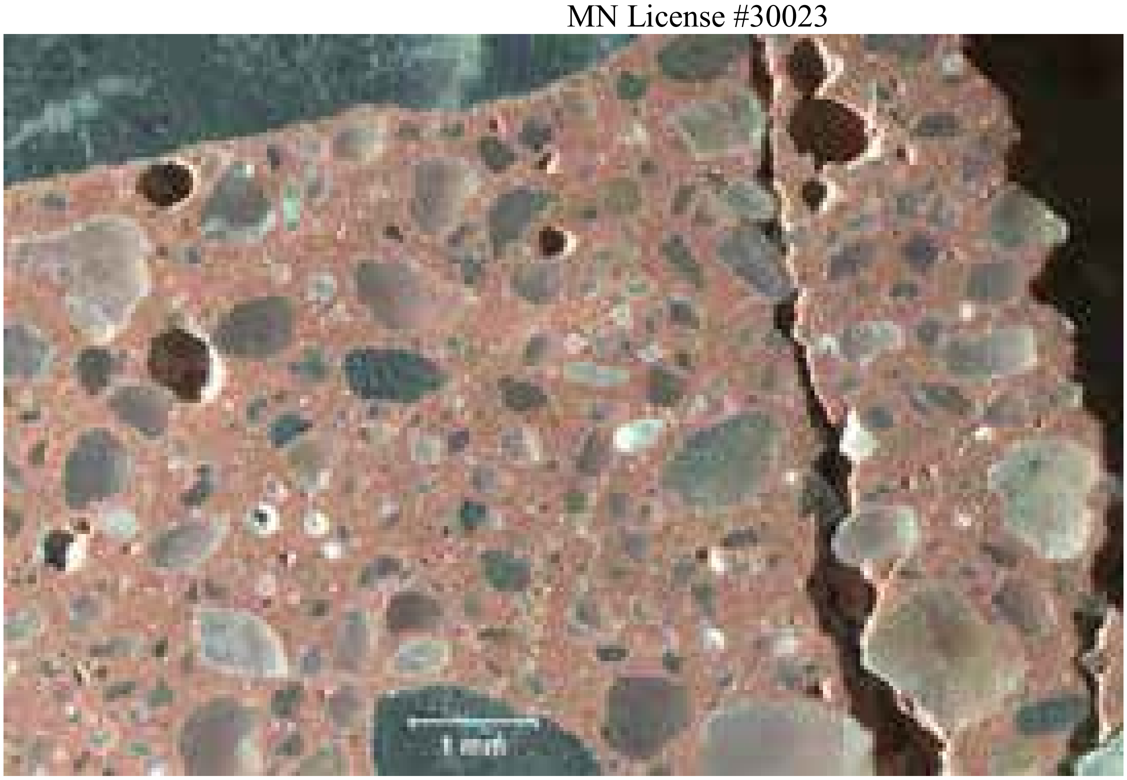
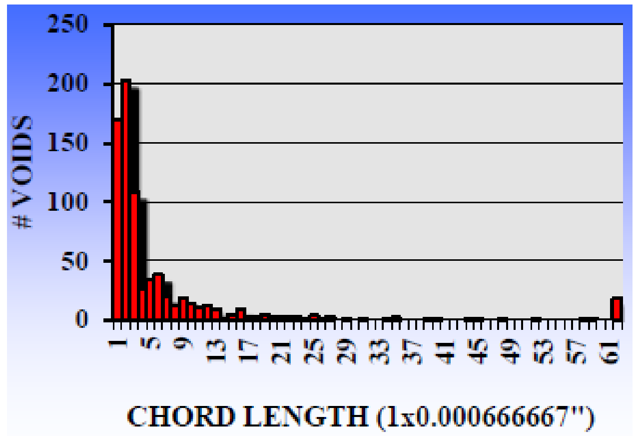
Vice President/Principal Petrographer
MN License #30023



Magnification: 15x

Description: Hardened air void system @ 65mm depth from the top surface at the distress.

Sample ID: 96D (all voids)
Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Core
Dimensions: 151mm (6") diameter by 200mm (7 3/4") long

Test Data: By ASTM C:457

Air Void Content %	4.3
Entrained, % < 0.040"(1mm)	2.7
Entrapped, %> 0.040"(1mm)	1.6
Air Voids/inch	8.1
Specific Surface, in^2/in^3	760
Spacing Factor, inches	0.007
Paste Content, % calculated	29.6
Magnification	75x
Traverse Length, inches	92
Test Date	9/12/2012

Report Prepared By:
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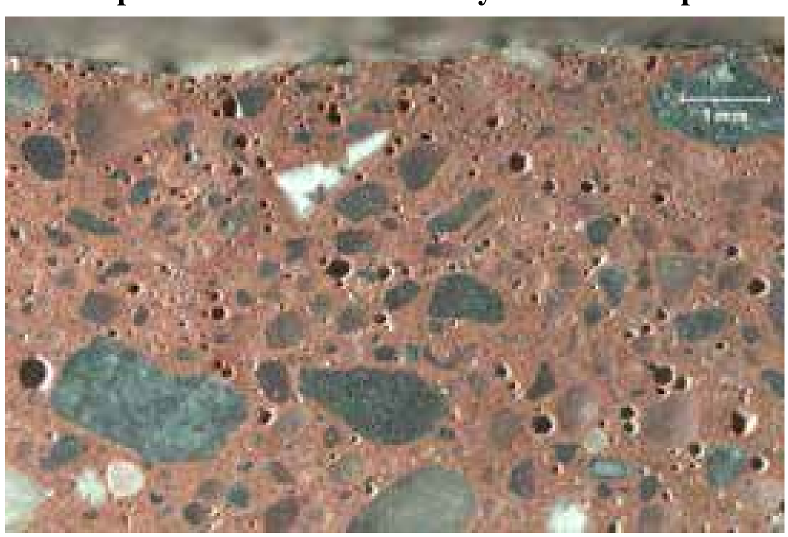
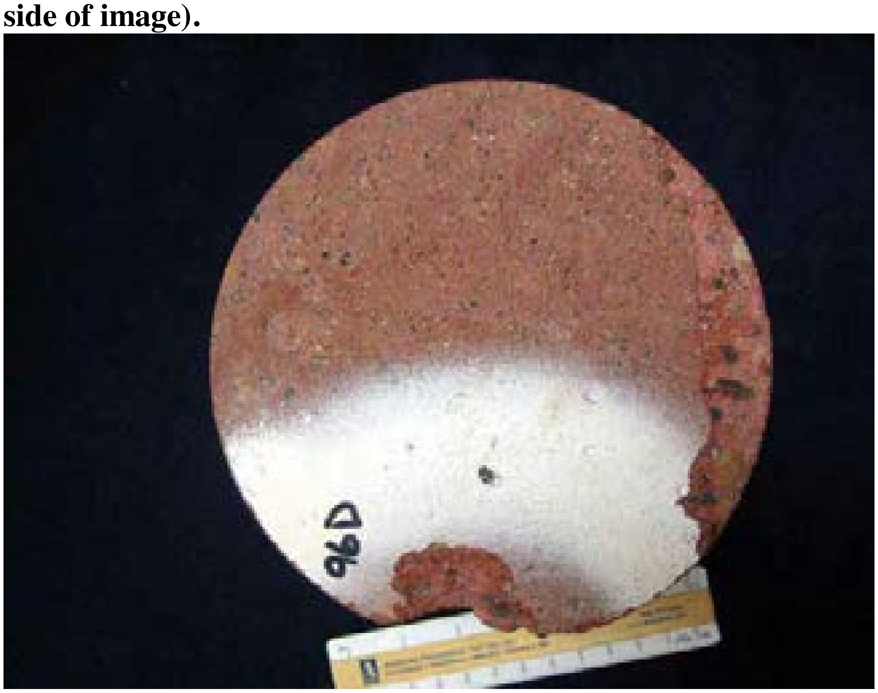
Magnification: 15x
Description: Hardened air void system @ the top surface.

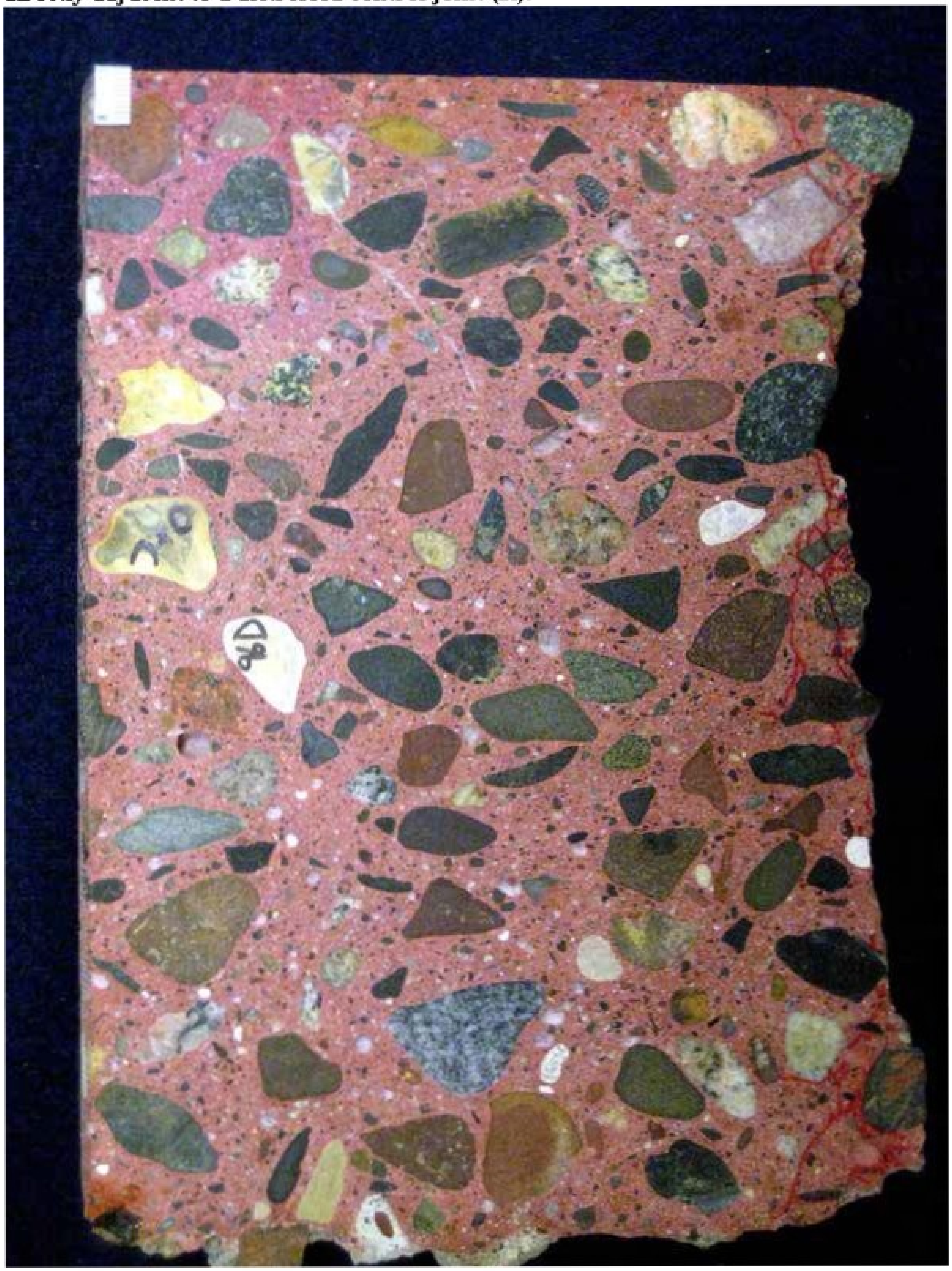


96D DESCRIPTION: Core sample as received. Top surface is right. Note distressed joint profile.

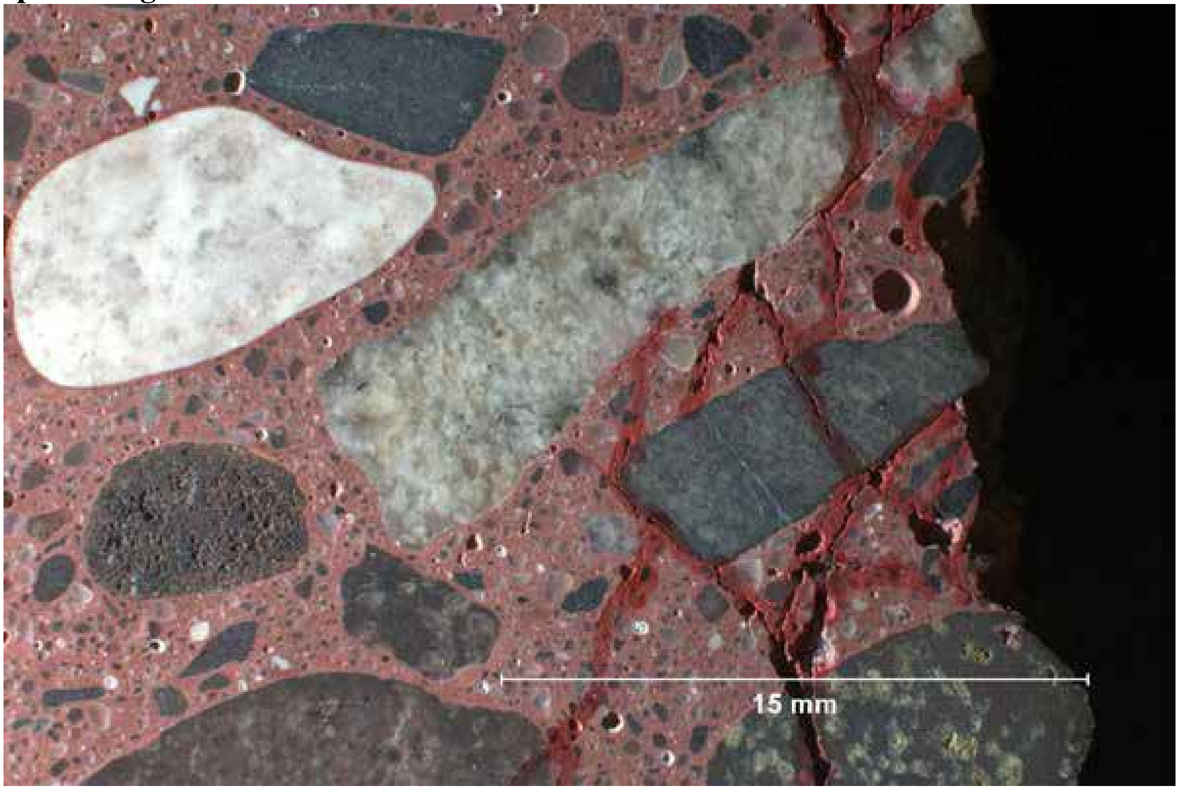
96D DESCRIPTION: Lightly textured and traffic worn/mortar eroded top surface of the core sample as received. Note raveled joint edge (bottom) and shallowly scaled area (right side of image).



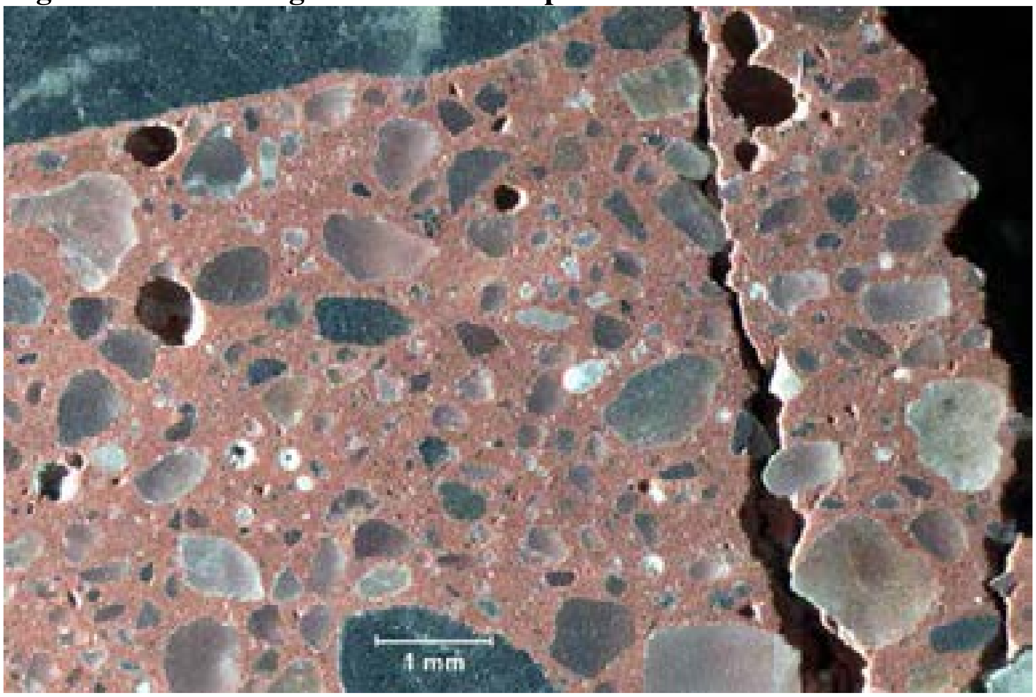
96D DESCRIPTION: Saw cut and lapped cross section of200mm long concrete core taken **directly adj**acent to a distressed control ¸oint **(R).**



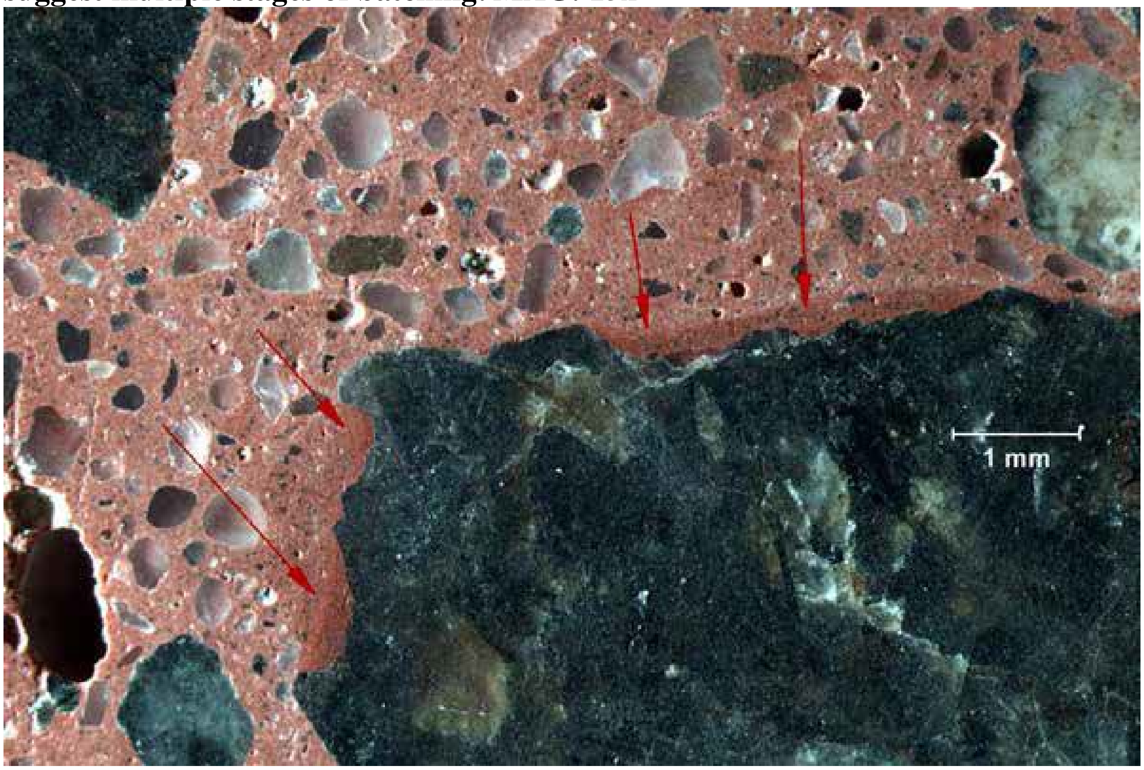
96D DESCRIPTION: Incipient spalling (microcracking mapped in red ink) adjacent to the spalled edge of the core. MAG: 5x



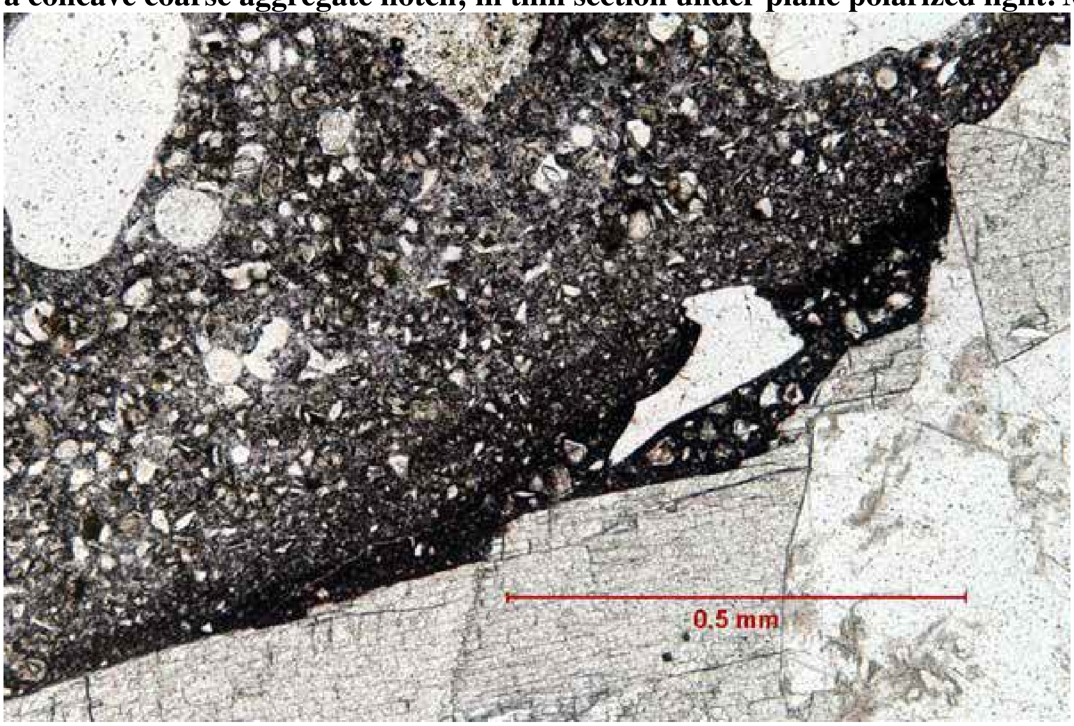
96D DESCRIPTION: The concrete contains little un-filled air voids adjacent to the spalled edge of the core. Image from 165mm depth in the core. MAG: 15x



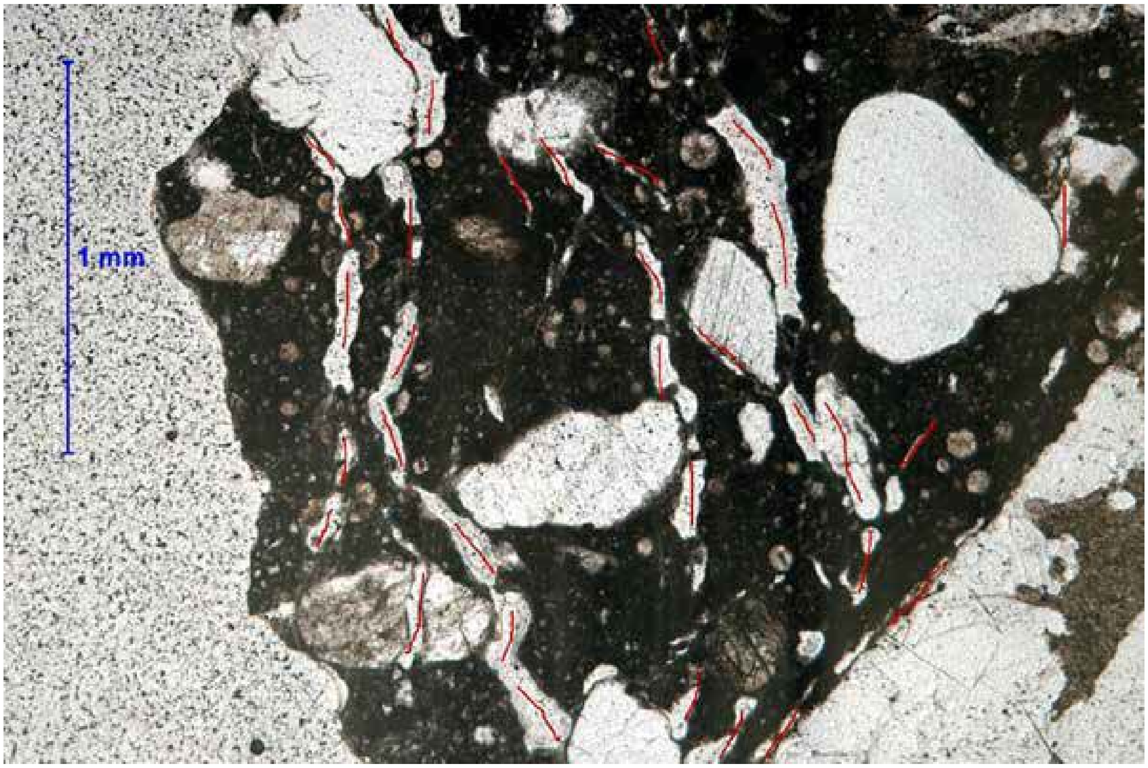
96D DESCRIPTION: Darker colored areas of paste in concave coarse aggregate notches suggest multiple stages of batching. MAG: 15x



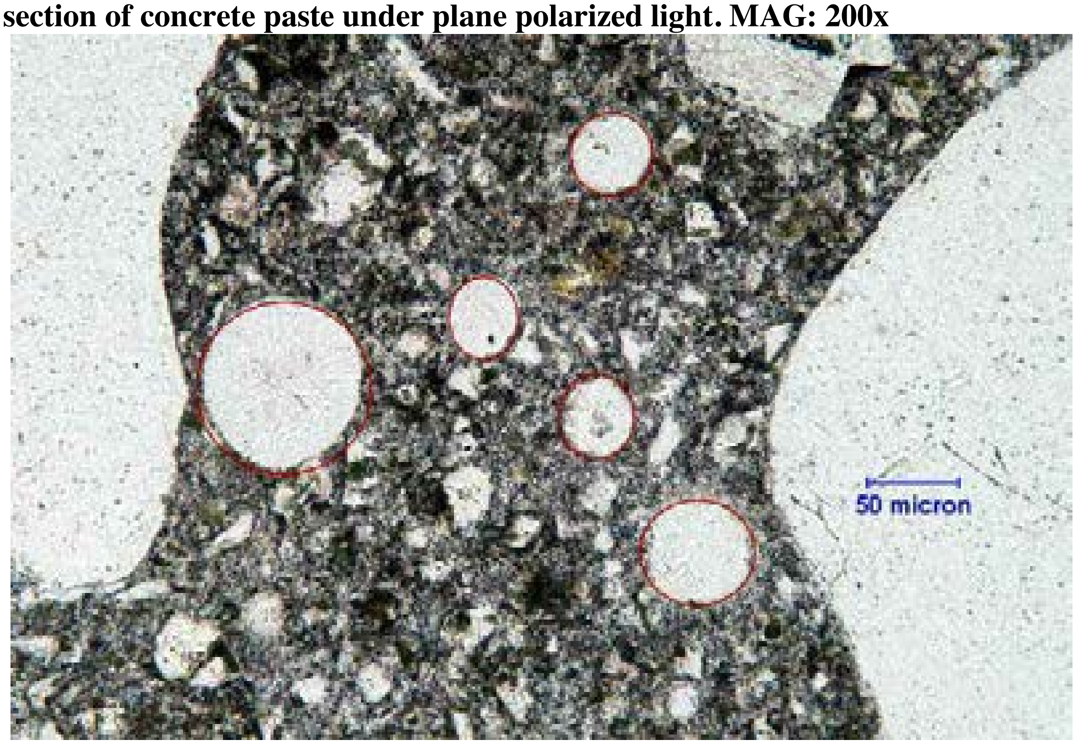
96D DESCRIPTION: A concentration of pigment and lessor hydrated Portland cement in a concave coarse aggregate notch; in thin section under plane polarized light. MAG: 100x



96D DESCRIPTION: Highly concentrated microcracks in the paste at 15mm depth into the distressed joint; mapped in red dashed line, in thin section under plane polarized light. MAG: 40x



96D DESCRIPTION: Ettringite-filled entrained sized air voids (outlined in red) in thin section of concrete paste under plane polarized light. MAG: 200x



00 LAB 001 Petrographic Examination of Hardened Concrete

ASTM: C-856

Project No.	24-00469	Date:	October 18, 2012
Sample ID:	L F A	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on both lapped sides of a 215mm (8 1/2") x 152mm (6") x 48mm (1 7/8") thick section (in two pieces) and a 76mm (3") x 52mm (2") wide thin section; that were sawcut and prepared from the original 152mm (6") diameter x 215mm (8 1/2") long core.

2. &Surface Conditions:
   Top: Fairly smooth, traffic worn surface; with many exposed fine aggregate surfaces and several "mortar flakes" over coarse aggregate particles proximate to the top surface.
   Bottom: Rough, irregular, formed surface; placed on a crushed gravel base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The core was taken directly through a distressed sawcut pavement joint. The joint is characterized by an approx. 3mm wide diamond pilot sawcut to approximately 57mm depth. A second approx. 9mm wide reservoir cut proceeds up to 35mm depth maximum from the top surface. The joint was sealed with a gray foam backer rod and an at least 9mm thick silicone sealant (not including meniscus). The sealant appears to have had limited bond with the sawcut joint surfaces. The resulting joint crack proceeds the depth of the core in near vertical orientation. Both sides of the top surface of the core at the joint have thinly to deeply spalled away with little intact sealant bond remaining with the remaining intact sawcut surface. The joint crack surface exhibits mass lost from vertical spalling/scaling along its depth. The greatest loss of mass (43mm total width) occurs between the top surface and 40mm depth from the top surface. Concentrated sub-vertical microcracks (incipient scaling/spalling) occur generally on both sides of the joint crack and within 15mm of the present distressed joint surfaces. The microcracking generally occurs within the paste; but bisects several carbonate aggregates. Below 165mm depth, the microcracking becomes nearly horizontal. The core exhibits limited residual interlock between the two slabs along the joint crack. Several, fine, sub-vertical drying shrinkage microcracks proceed up to 6mm maximum depth from the top surface. Carbonation ranged from 1mm up to 7mm depth from the top surface; "spiking" along the drying shrinkage microcracking. Apparent carbonation, along the spalled joint plane, proceeded up to 10mm from the joint crack. Portions of the outer up to 10mm of paste directly adjacent to the vertical distressed joint surface exhibit an "altered" appearance, with lighter coloration and much softer paste. Portions of which are carbonated with some portions free of calcium hydroxide paste filled with concentrated microcracking. The microcracking is often lined/filled with secondary calcite. Several coarse and fine chert aggregate particles appeared to exhibit evidence of very mild ASR.

   The concrete was fairly well consolidated, with few, scattered, irregular shaped consolidation voids measuring over 6mm. The concrete was purposefully air entrained and originally contained a relatively fine, well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Air void parameters include a 6.8% entrained-sized void volume and a 0.002" spacing factor. The concrete contains a finely disseminated red pigment.

II. &Aggregate

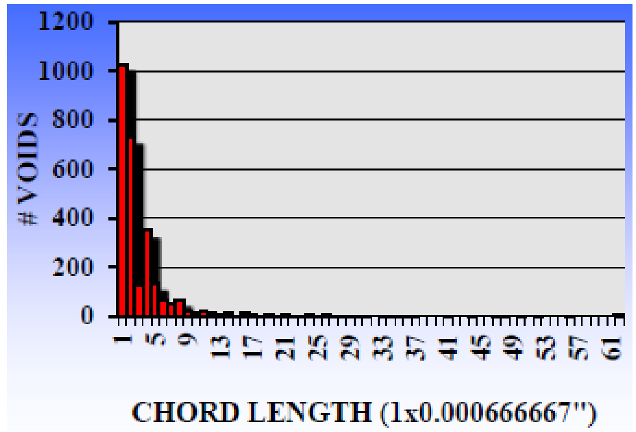
1. &Coarse: 19mm (3/4") nominal sized superior lobe glacial gravel consisting predominately of rhyolite, granite, basalt, graywacke, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, and rhyolite.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 7.5% total.
2. &Depth of carbonation:Ranged from 1.5mm up to 7mm depth from the top surface and apparently up to 10mm depth from the joint crack plane.
3. &Pozzolan presence: None observed.
4. &Paste/aggregate bond: Fair.
5. Paste color: Pigmented with a color similar to Moderate Reddish orange (Munsell® 10R 6/6). Vitreous to sub-vitreous.
6. &Paste hardness: Relatively hard (Moh's 4). Soft (Moh's 2) in portions of the 10mm of carbonated paste directly adjacent to the distressed joint plane at depth in the joint.
7. &Microcracking: Several, sub-vertically oriented drying shrinkage microcracks proceed up to 6mm depth from the top surface of the core. Several mildly ASR "reacted" coarse and fine chert aggregate particles exhibit very fine internal cracking propagating shallowly into the paste. Concentrated sub-vertical microcracks (incipient scaling/spalling) occur generally on both sides of the joint crack and within 15mm of the present distressed joint surfaces. The microcracking generally occurs within the paste; but bisects several carbonate aggregates. Below 165mm depth, the microcracking becomes nearly horizontal.
8. Secondary deposits: Secondary ettringite thinly lines or filling many of the finest entrained sized voidspaces throughout the sample below approx. 4mm depth from the top surface; and lines most other voids. Secondary calcite lines microcracks and fills voids in the altered outer 100mm of paste adjacent to the distressed joint plane.
9. & w/cm: Estimated at between 0.40 and 0.45 with approximately 8 to 10% residual portland cement clinker particles.
10. Cement hydration: Alites: Fully. Belites: Mostly fully.

Sample ID: L&F A (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Core

Dimensions: 151mm (6") diameter by 215mm (8 1/2") long

Test Data: By ASTM C:457

Air Void Content %	7.5
Entrained, % < 0.040"(1mm)	6.8
Entrapped, %> 0.040"(1mm)	0.7
Air Voids/inch	30.2
Specific Surface, in^2/in^3	1630
Spacing Factor, inches	0.002
Paste Content, % calculated	26.0
Magnification	75x
Traverse Length, inches	90
Test Date	10/16/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x
Description: Hardened air void system.

L&F A DESCRIPTION: Core sample as received. Top surface is left.

L&F A DESCRIPTION: Top surface of the core sample as received. Note sealed and raveled joint.

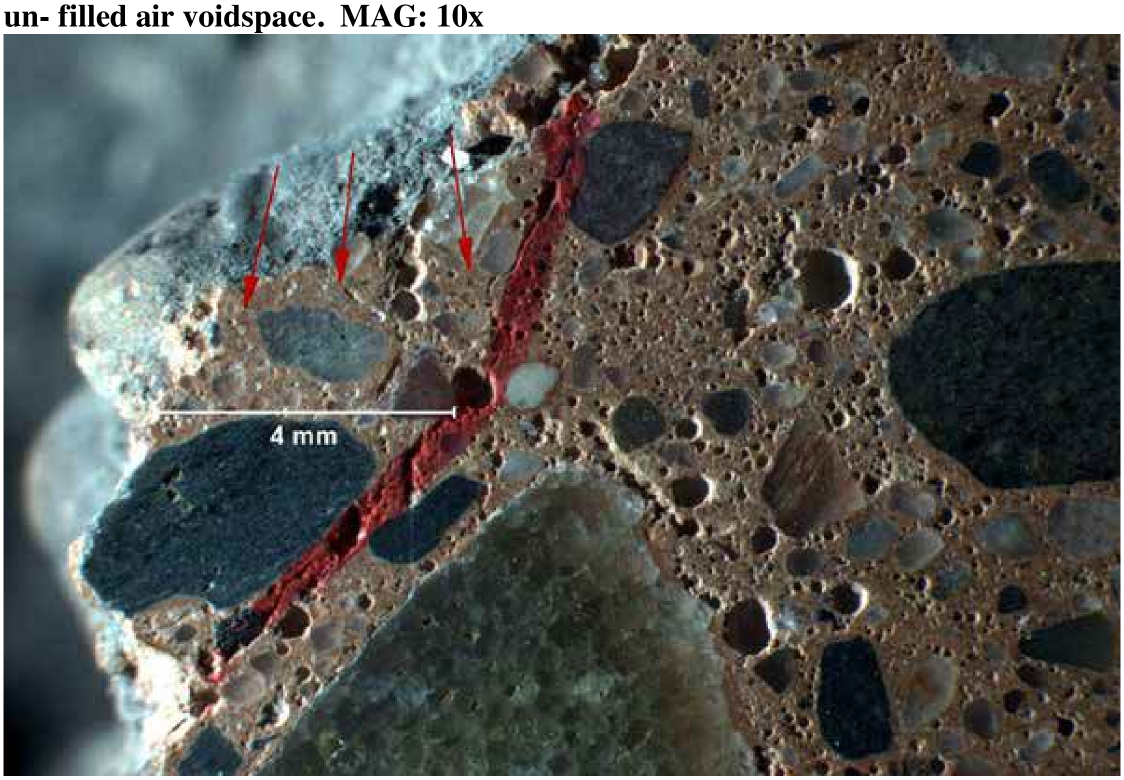
L&F A DESCRIPTION: Carbonation (unstained paste) proceeds up to 10mm depth from

L& F A DESCRIPTION: Spalling and severe incipient distress (sub-vertical micro andmacro cracking) in the concrete paste directly adjacent to the"activated" control joint crack. Cracking is mostly sub-horizontally oriented below 165mm depth in the core. Micro and in red ink in the sawcut and ed cross section of core.

L&F A DESCRIPTION: Carbonation (unstained paste) proceeds up to lOmm depth from

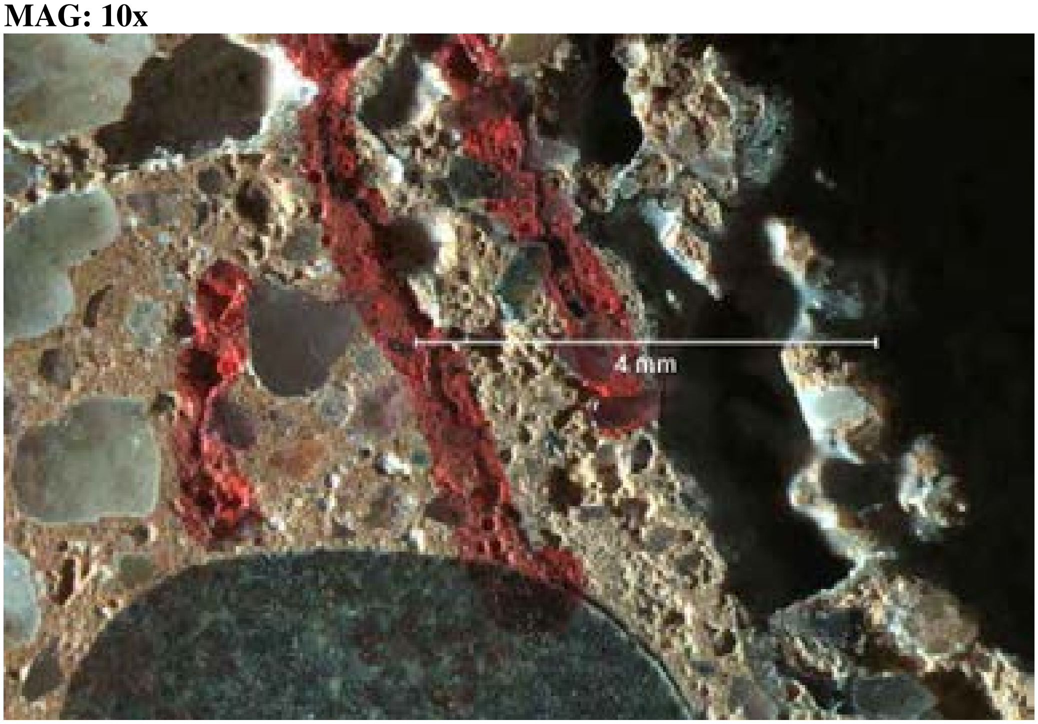
the joint crack plane (R). MAG: 5x

L&F A DESCRIPTION: The distressed outer 4mm of the concrete paste contain little un- filled air voidspace. MAG: 10x



L&F A DESCRIPTION: Portions of the outer up to 10mm of paste directly adjacent to the distressed joint crack plane (R) are relatively soft. MAG: 10x

L&F A DESCRIPTION: Softer paste characterizing the outer 4mm of distressed concrete directly adjacent to the spalled joint surface at 15mm depth from the top surface plane. MAG: 10x



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

Project No.	24-00469	Date:	October 15, 2012
Sample ID:	L F B	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on one lapped side of a 222mm (8 3/4") x 148mm (5 7/8") x 41mm (1 5/8") thick section and a 76mm (3") x 52mm (2") wide thin section; that were sawcut and prepared from the original 152mm (6") diameter x 222mm (8 3/4") long core.

2. &Surface Conditions:
Top: Rough, traffic worn surface; with many exposed fine and coarse aggregate surfaces.
Bottom:Rough, irregular, formed surface; placed on a crushed gravel base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The rough top surface of the core exhibits significant traffic wear; exposing many fine and coarse aggregate particles. The concrete was fairly well consolidated, with a few, scattered, irregular shaped consolidation voids measuring up to 12mm. The concrete was purposefully air entrained and originally contained a relatively fine, well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Air void parameters include a 6.4% entrained-sized void volume and a 0.003" spacing factor. The concrete contains a finely disseminated red pigment. Secondary ettringite was observed lightly lining to filling a few of the finest entrained sized voidspaces throughout the sample, with the greatest concentration of fillings occurring within 5mm of the formed bottom surface. The secondary ettringite fillings have not affected the freeze-thaw durability of the air void system. Evidence of alkali-silica reaction (ASR) was observed associated with coarse and fine aggregate particles. Some granite, chert, rhyolite, sandstone, siltstone, and greywacke particles exhibited internal microcracking propagating into the paste and proceeding through adjacent reactive coarse and fine aggregate particles. The cracking occurs generally in an sub-horizontal orientation and between 7mm and 60mm depth in the core. Clear to white ASR gel was observed partially lining to filling voidspaces and microcracks adjacent to the reactive particles and bisected by the microcracking. A sub-vertical micro/macrocrack proceeding to 125mm (5") total depth from the top surface intersects reactive chert and granite particles between 25mm and 40mm depth. ASR gel fills to partially fills the microcrack and voidspaces between 20mm and 40mm depth from the top surface.

II. &Aggregate

1. &Coarse:19mm (¾") nominal sized superior lobe glacial gravel consisting predominately of rhyolite, granite, basalt, graywacke, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, and

rhyolite.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 7.2% total
2. &Depth of carbonation:Ranged continuously from <1mm to 10mm depth from the top surface; but "spiking",
   intermittently up to 25mm depth along sub-vertical microcracking.
3. &Pozzolan presence: None observed.
4. &Paste/aggregate bond: Fair.
5. &Paste color: Pigmented with a color similar to Moderate Reddish orange (Munsell® 10R 6/6). Vitreous to
   sub-vitreous.
6. &Paste hardness: Relatively hard (Moh's 4).
7. &Microcracking: Several, sub-vertically oriented microcracks proceed up to 25mm depth from the top surface of the core; one proceeds up to 125mm depth. ASR "reacted" coarse and fine particles exhibit internal cracking propagating into the paste as fine sub-horizontal swarms generally proceeding through the next adjacent reactive aggregate. The ASR induced microcracking is generally confined to between 7mm and 60mm depth in the core from the top surface.
8. Secondary deposits: Secondary ettringite thinly lining to filling a few of the finest entrained sized voidspaces throughout the sample below approx. 5mm depth from the top surface; and lines most other voids. Clear to white ASR gel lines or fills voidspaces and microcracks adjacent to and proceeding through reacted aggregate particles.
9. &w/cm: Estimated at between 0.40 and 0.45 with approximately 9 to 11% residual portland cement clinker particles.
10. Cement hydration: Alites: Well to mostly fully. Belites: Well to fully.

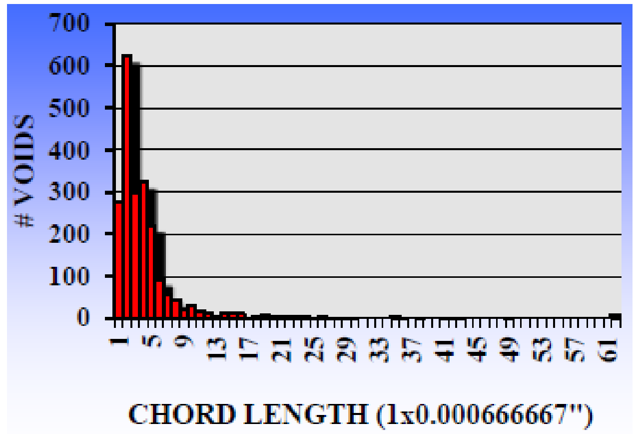
Sample ID: L&F B (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.

Sample Data

Description: Hardened Concrete Core

Dimensions: 151mm (6") diameter by 222mm (8 3/4") long

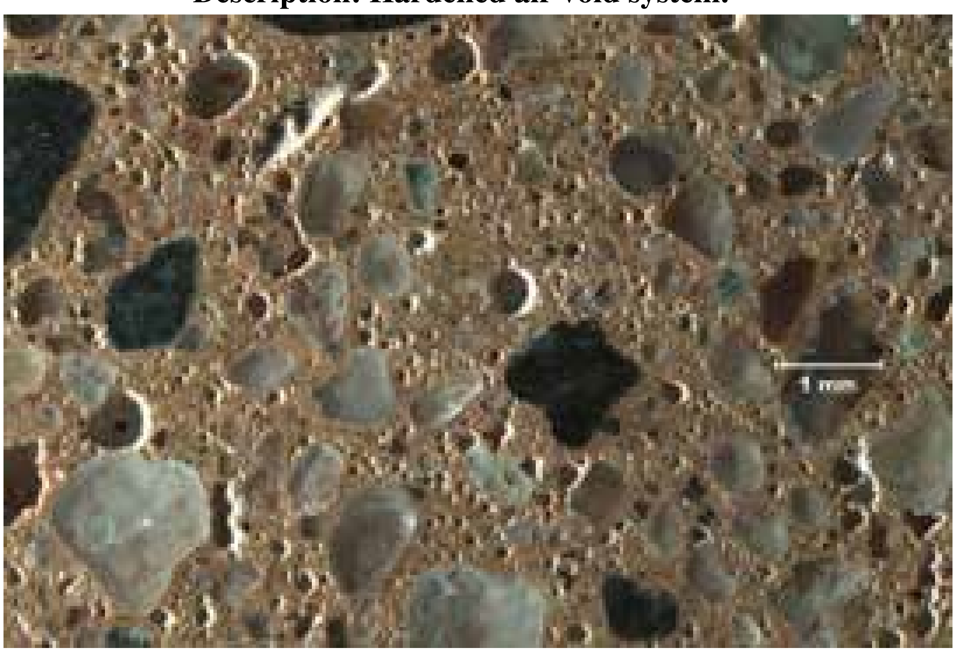


Test Data: By ASTM C:457

Air Void Content %	7.2
Entrained, % < 0.040"(1mm)	6.4
Entrapped, %> 0.040"(1mm)	0.8
Air Voids/inch	23.0
Specific Surface, in^2/in^3	1280
Spacing Factor, inches	0.003
Paste Content, % calculated	23.3
Magnification	75x
Traverse Length, inches	92
Test Date	10/12/2012

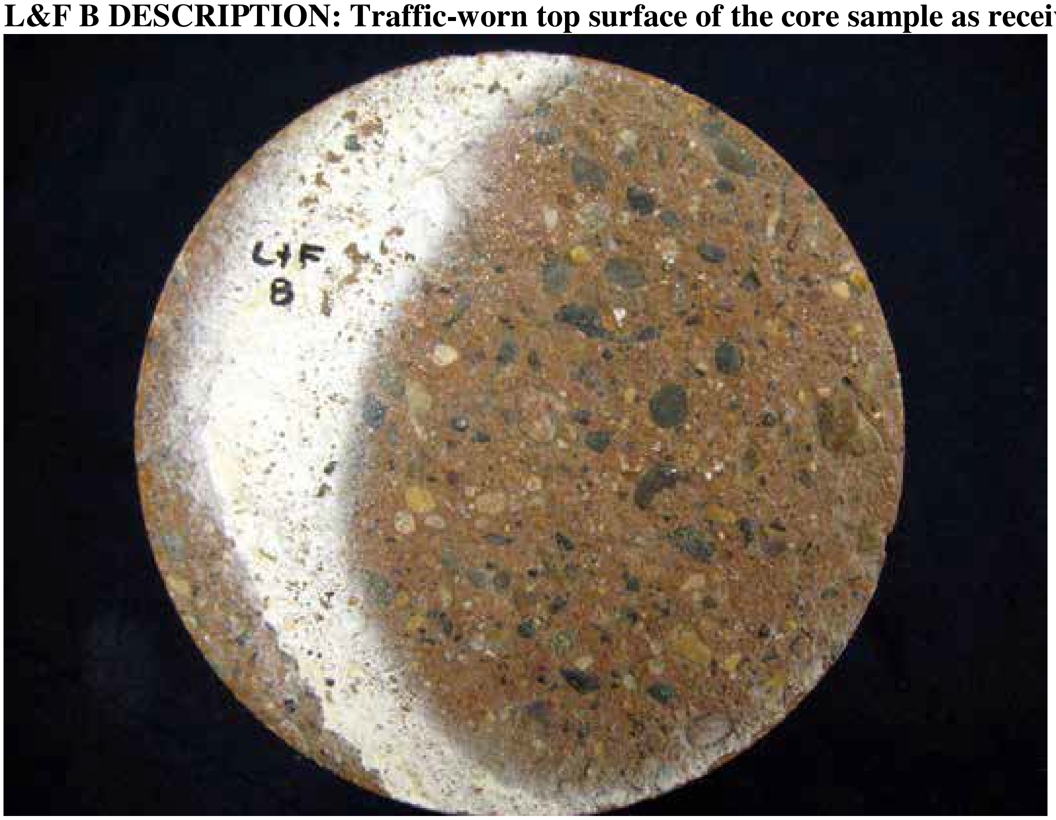
Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x
Description: Hardened air void system.



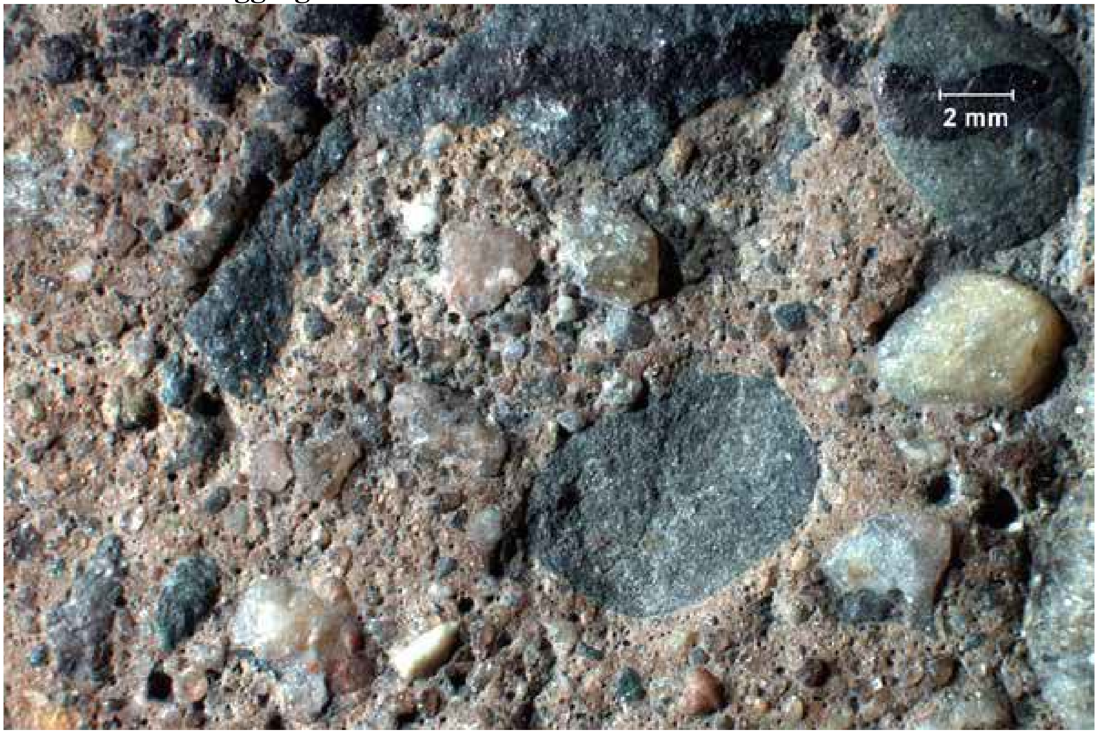
L&F B DESCRIPTION: Core sample as received. Top surface is left.

L&F B DESCRIPTION: Traffic-worn top surface of the core sample as received.

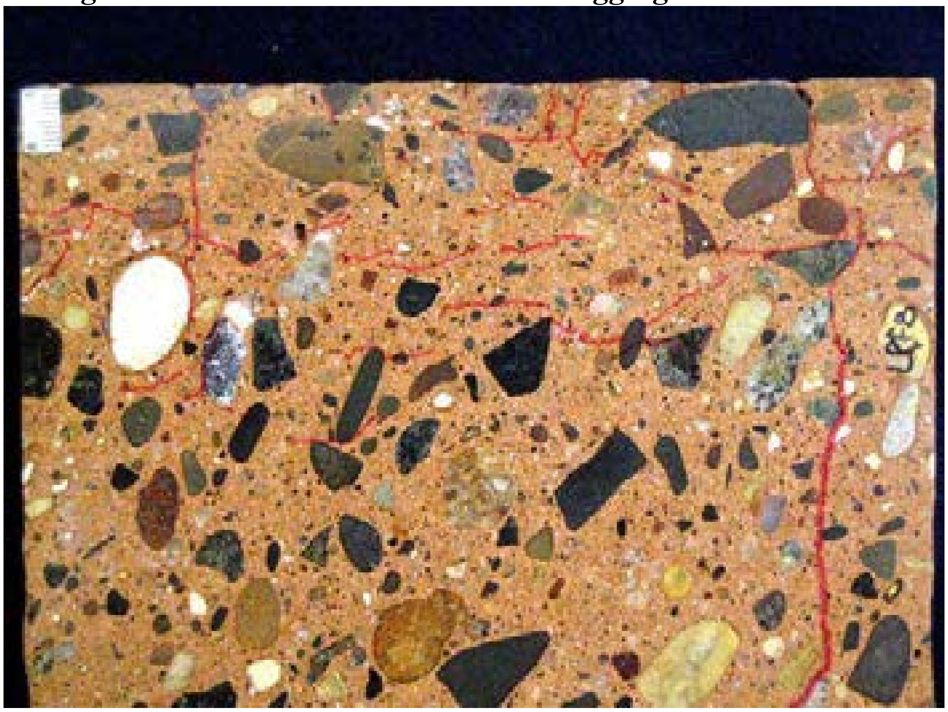


L&F B DESCRIPTION: Sawcut and lapped cross section of 151mm diameter concrete core. Note abundant subhorizontal microcracking in the top approx. 60mm of the core.

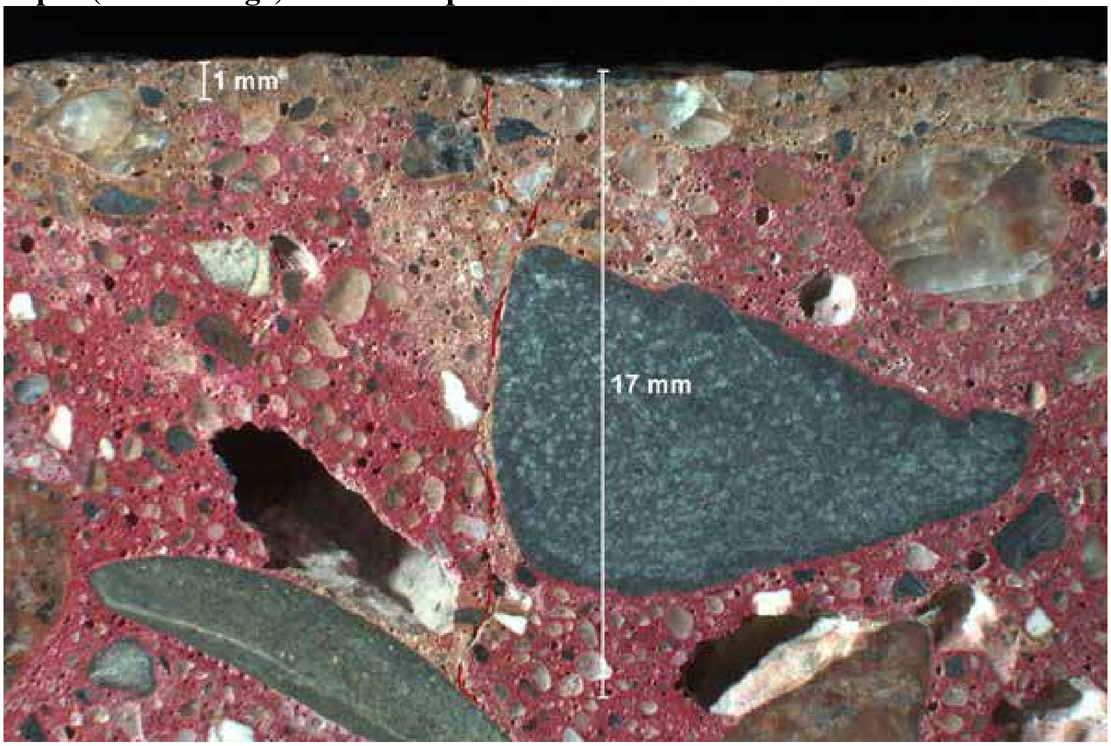
L&F B DESCRIPTION: The traffic worn top surface of the concrete core exhibits exposed coarse and fine aggregates. MAG: 5x



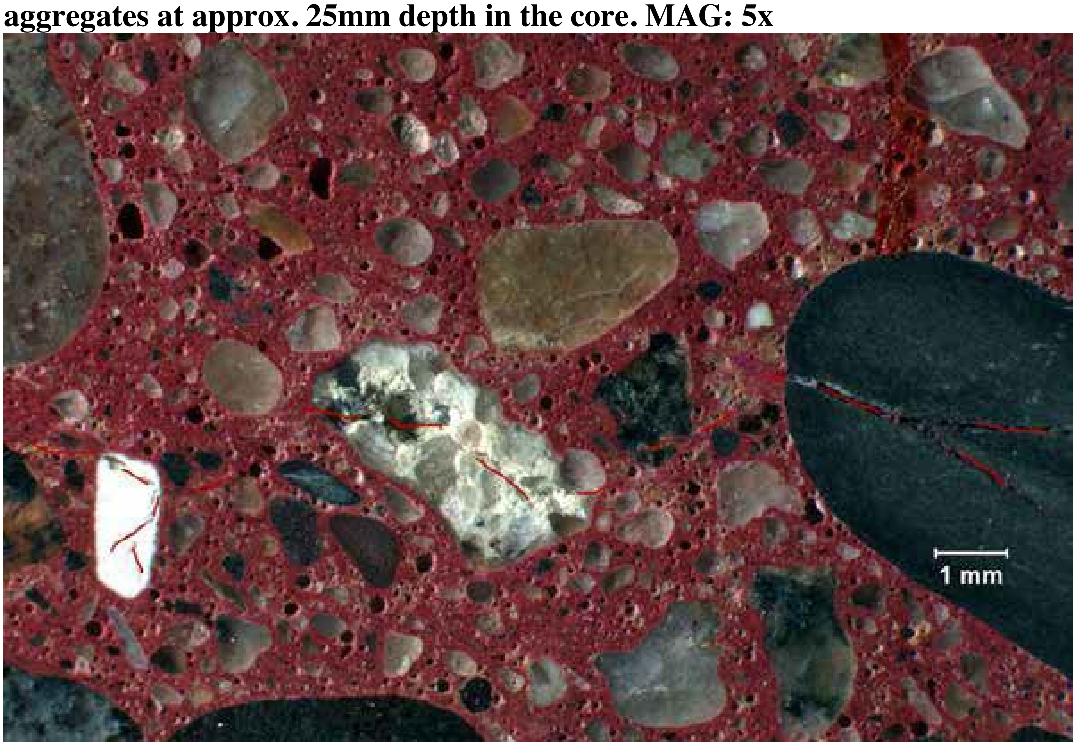
L&F B DESCRIPTION: Alkali-silica reaction (ASR) induced microcracking is mapped in red ink. The subhorizontally oriented cracking is confined to the top 60mm and proceeds through several coarse and dozens of fine aggregates.



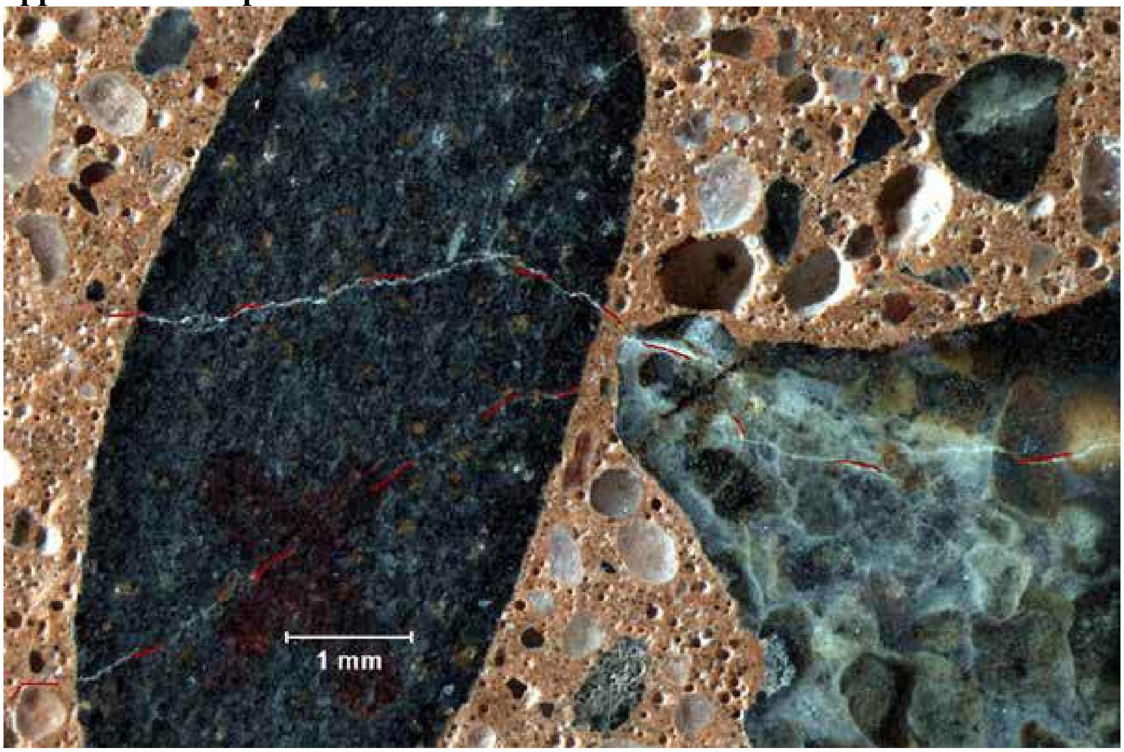
L&F B DESCRIPTION: Carbonation (unstained paste) ranged from 1mm up to 17mm depth (in this image) from the top surface of the concrete. MAG: 5x



L&F B DESCRIPTION: Alkali-silica reaction (ASR) induced sub-horizontal microcracking (mapped in red dashed line) proceeds through three coarse and fine aggregates at approx. 25mm depth in the core. MAG: 5x



L&F B DESCRIPTION: Alkali-silica reaction (ASR) induced sub-horizontal microcracking (mapped in red dashed line) proceeds through two coarse aggregates at approx. 40mm depth in the core. MAG: 15x



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

Project No.	24-00469	Date:	October 16, 2012
Sample ID:	L F C	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on both lapped sides of a 207mm (8 1/8") x 148mm (5 7/8") x 45mm (1 3/4") thick section and a 76mm (3") x 52mm (2") wide thin section; that were sawcut and prepared from the original 152mm (6") diameter x 207mm (8 1/8") long core.

2. &Surface Conditions:
Top: Fairly smooth, traffic worn surface; with many exposed fine aggregate surfaces. Bottom:Rough, irregular, formed surface; placed on a crushed gravel base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The fairly smooth top surface of the core exhibits minor traffic wear; exposing many fine aggregate surfaces. The concrete was fairly well consolidated, with few, scattered, irregular shaped consolidation voids measuring up to 13mm. The concrete was purposefully air entrained and originally contained a relatively fine, well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Air void parameters include a 7.1% entrained-sized void volume and a 0.002" spacing factor. The concrete contains a finely disseminated red pigment. Secondary ettringite was observed thinly lining to filling a few of the finest entrained sized voidspaces throughout the sample, with the greatest concentration of fillings occurring within 20mm of the formed bottom surface. The secondary ettringite fillings have not affected the freeze-thaw durability of the air void system. Evidence of alkali-silica reaction (ASR) was observed associated with coarse and fine aggregate particles. Some granite, chert, rhyolite, sandstone, siltstone, and greywacke particles exhibited internal microcracking propagating into the paste and proceeding through adjacent reactive coarse and fine aggregate particles. The cracking occurs generally in a sub-horizontal orientation and between approx. 6mm and 50mm depth in the core. Clear to white ASR gel was observed partially lining to filling voidspaces and microcracks adjacent to the reactive particles and bisected by the microcracking. A sub-horizontal macrocrack proceeds through the entire diameter of the core between approx. 15mm and 35mm depth from the top surface. The cracking bisects a few reactive chert particles. ASR gel intermittently lines the crack plane adjacent to reactive particles. Random sub-vertical macrocracking, observed concentrated on one side of the top surface of the core, intersects the sub-horizontal macrocrack to a 35mm maximum depth.

II. &Aggregate

1. &Coarse: 19mm (¾") nominal sized superior lobe glacial gravel consisting predominately of rhyolite, granite, basalt, graywacke, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.

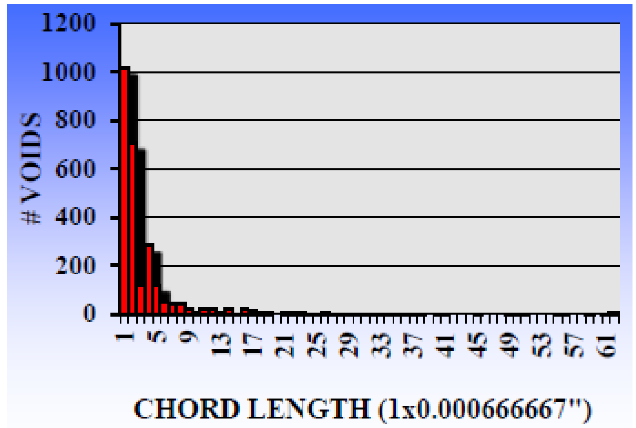
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, and rhyolite.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 7.8% total
2. &Depth of carbonation:Ranged continuously from <1mm to 6mm depth from the top surface. Carbonation proceeded
up to 37mm depth, intermittently, along sub-vertical and sub-horizontal macrocracking.
3. &Pozzolan presence: None observed.
4. &Paste/aggregate bond: Fair.
5. &Paste color:Pigmented with a color similar to Moderate Reddish Orange (Munsell® 10R 6/6). Vitreous to sub-vitreous.
6. &Paste hardness: Relatively hard (Moh's 4).
7. &Microcracking: Several, sub-vertically oriented microcracks proceed up to 34mm depth from the top surface of the core; intersecting the sub-horizontal macrocracking. ASR "reacted" coarse and fine particles are bisected by fine sub-horizontal swarms generally proceeding through the next adjacent reactive aggregate. The ASR induced microcracking is generally confined to between 6mm and 50mm depth in the core from the top surface.
8. Secondary deposits: Secondary ettringite thinly lining to filling a few of the finest entrained sized voidspaces throughout the sample below approx. 5mm depth from the top surface; and lines most other voids. Clear to white ASR gel lines or fills voidspaces and microcracks adjacent to and proceeding through reacted coarse and fine aggregate particles.
9. & w/cm: Estimated at between 0.40 and 0.45 with approximately 9 to 11% residual Portland cement clinker particles.
10. Cement hydration: Alites: Well to fully. Belites: Well to fully.

Sample ID: L&F C (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description: Hardened Concrete Core

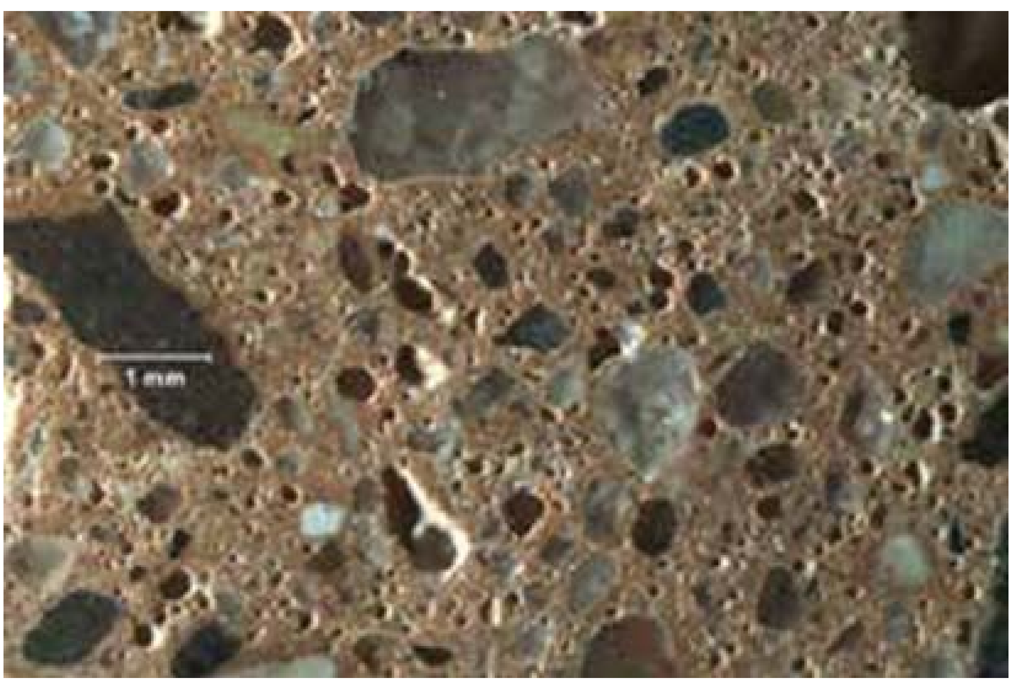
Dimensions: 151mm (6") diameter by 207mm (8 1/8") long

Test Data: By ASTM C:457

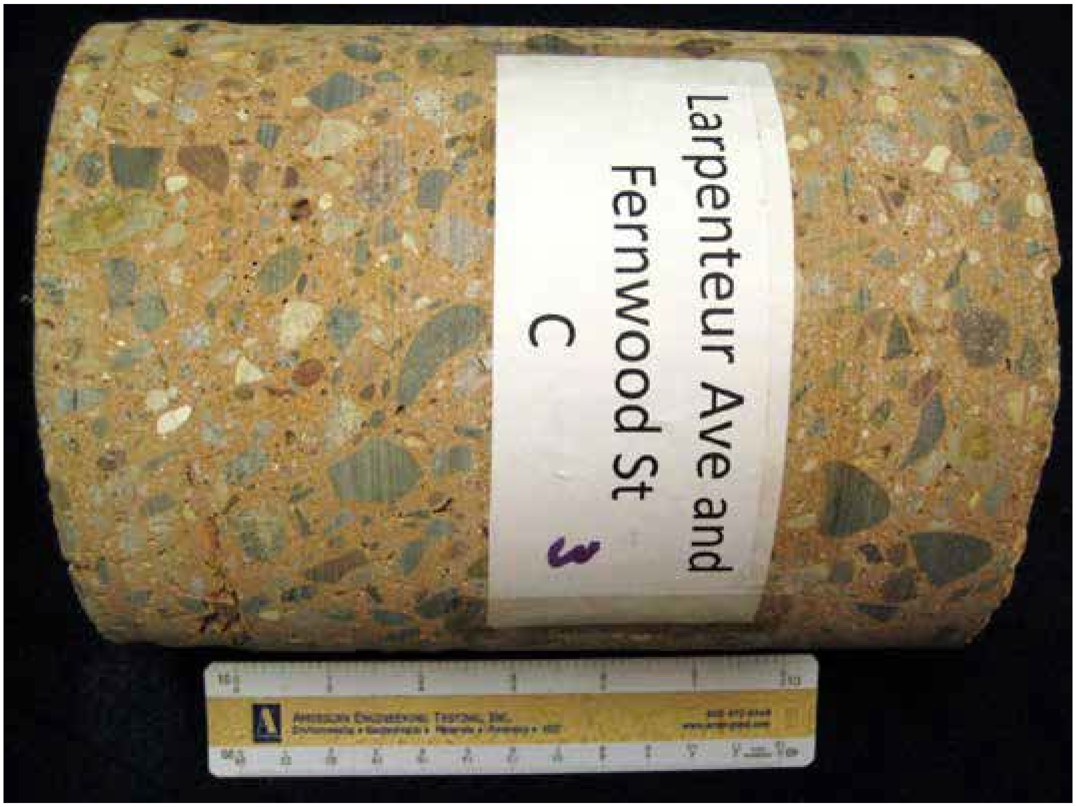
Air Void Content %	7.8
Entrained, % < 0.040"(1mm)	7.1
Entrapped, %> 0.040"(1mm)	0.7
Air Voids/inch	29.0
Specific Surface, in^2/in^3	1490
Spacing Factor, inches	0.002
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	90
Test Date	10/16/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x
Description: Hardened air void system.



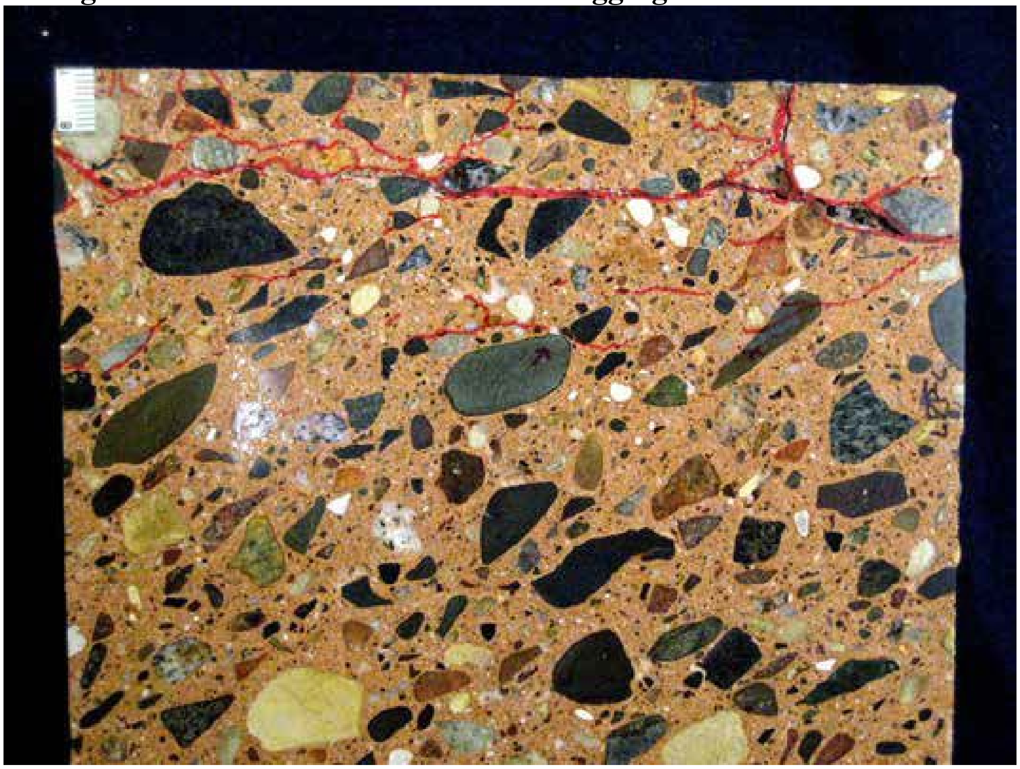
L&F C DESCRIPTION: Core sample as received. Top surface is left.



L&F C DESCRIPTION: Traffic-worn top surface of the core sample as received. Note cracking.

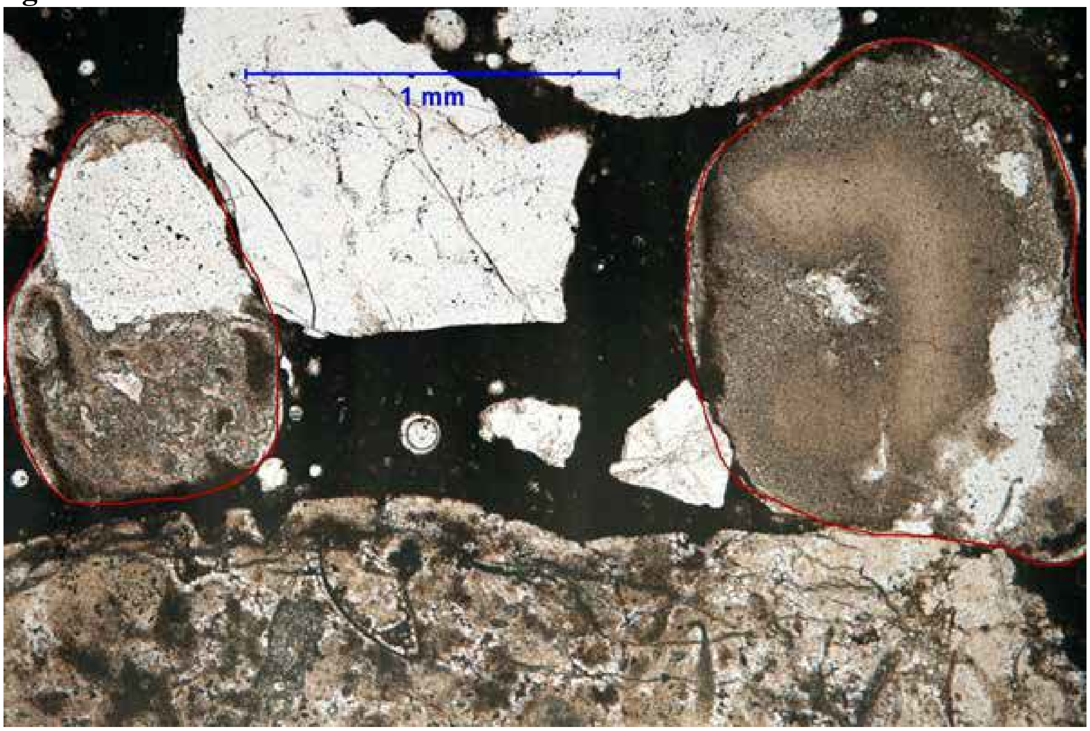
L&F C DESCRIPTION: Sawcut and lapped cross section of 15lmm diameter concrete core. Note abundant subhorizontal microcr _in the _ _ _rox. 50mm of the core.

L&F C DESCRIPTION: Alkali-silica reaction (ASR) induced microcracking is mapped in red ink. The sub-horizontally oriented cracking is confined to the top 50mm and proceeds through several coarse and dozens of fine aggregates.

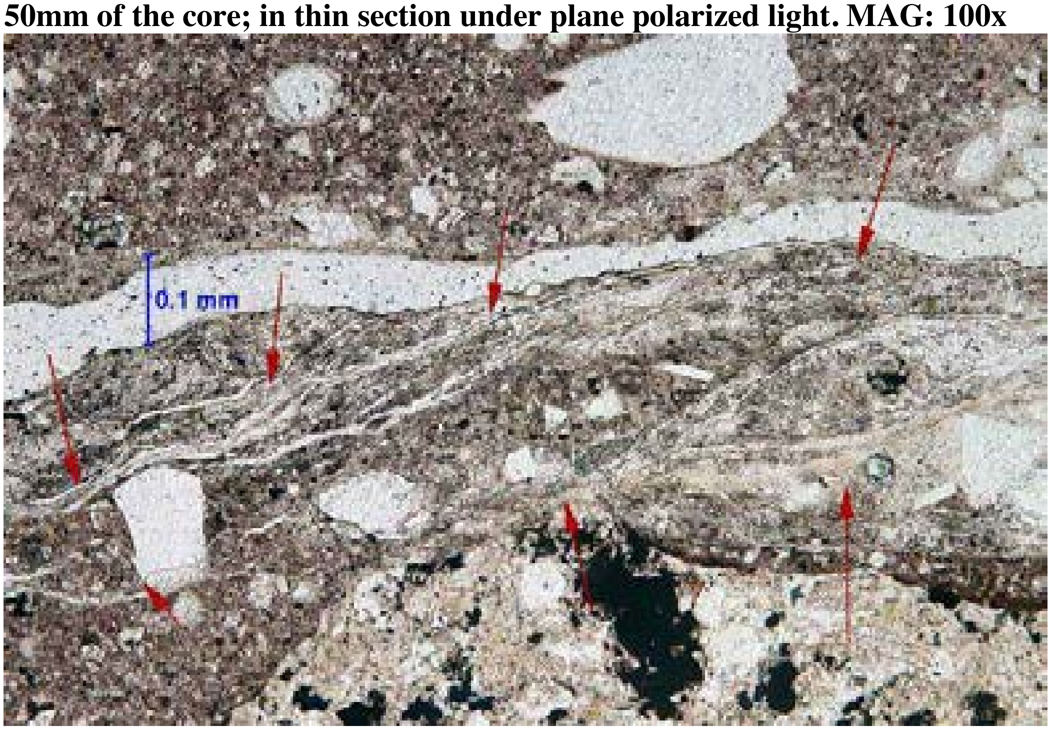


L&F C DESCRIPTION: Alkali-silica reaction (ASR) induced sub-horizontal microcracking (mapped in red dashed line) proceeds through coarse and fine aggregates within the top 50mm of the core. MAG: 10x

L&F C DESCRIPTION: ASR-gel filled voidspaces (outlined in red) directly adjacent to a reactive chert aggregate particle (bottom); in thin section of concrete under plane polarized light. MAG: 40x



L&F C DESCRIPTION: Clear ASR-gel product fills a swarm of sub-horizontal microcracking proceeding from an adjacent reactive aggregate particle within the top 50mm of the core; in thin section under plane polarized light. MAG: 100x



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

Project No.	24-00469	Date:	October 19, 2012
Sample ID:	LJEB A	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on both sides of a 216mm (8 1/2") x 151mm (6") x 45mm (1 3/4") thick section and a 76mm (3") x 52mm (2") wide thin section; that were sawcut and prepared from the original 152mm (6") diameter x 216mm (8 1/2") long core.

2. &Surface Conditions:
   Top: Fairly smooth, flat and planar, traffic worn surface. Corner spalling and mortar flaking occurred along a portion of both sides of the tooled control joint.
   Bottom:Rough, irregular, formed surface; placed on a crushed, bituminous-rich base.

3. &Reinforcement: None observed.

4. &General Physical Conditions: The core was taken directly through a tooled pavement joint with corner spalled and mortar flaked areas encompassing portions of both sides of the tooled joint. The joint is characterized by an originally rounded - tooled penetration to a depth of approximately 38mm depth from the top surface of the sample. The apparent semi-plastic concrete adjacent to the original tooled joint appeared to have slumped into and closed much of the depth of the joint off to a 17mm depth. The joint never "activated". However, a sub-vertical microcrack proceeds to approximately 60mm depth from the top surface.

   Approximately 70mm along the length of one side of the tooled joint has scaled/spalled away up to 45mm from the tooled joint, intersecting what appears to be a large consolidation void adjacent to the joint on the top surface that measures 20mm by 25mm wide and 18mm deep. Approximately 60mm along the length of the other side of the joint has shallowly scaled/spalled away up to 25mm from the joint surface, exposing several coarse aggregate surfaces. A consolidation void measuring approximately 10mm in diameter, surrounded by a scaled/spalled area measuring 15mm by 45mm, occurs on the top surface 35mm from the joint near the cored edge of the sample. Vertical scaling/spalling along the vertical joint face ranged from 5mm to the full depth of the joint adjacent to the surficially scaled/spalled areas. No scaling/spalling was observed along the vertical joint face away from the surficially affected areas. The joint never "activated". However, a sub-vertical microcrack proceeds to approximately 60mm depth from the top surface.

   The concrete was fairly well consolidated, with few, scattered, irregular shaped consolidation voids measuring up to 12mm in diameter. However, a few relatively large consolidation voids were observed within 25mm of the top surface of the core. The concrete was purposefully air entrained and originally contained a relatively fine, well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air void parameters include a 5.5% entrained-sized void volume and a 0.002" spacing factor. The concrete contains a finely disseminated red pigment. Secondary ettringite was observed partially filling to filling numerous entrained sized voidspaces below 5mm depth, with the greatest concentration of fillings occurring within approximately 20mm of the formed bottom surface. The ettringite fillings likely have compromised the future freeze-thaw resistance of the concrete. Evidence of alkali- silica reaction (ASR) was observed associated with coarse and fine aggregate particles. Some granite, chert, rhyolite, sandstone, siltstone, and greywacke particles exhibited internal microcracking propagating into the paste and proceeding through adjacent reactive coarse and fine aggregate particles. The cracking occurs generally in a sub- horizontal orientation and between 2mm and 76mm depth in the core; with the greatest concentration up to 40mm depth. Clear to white ASR gel was observed partially lining to filling voidspaces and microcracks adjacent to the reactive particles and bisected by the microcracking.

II. &Aggregate

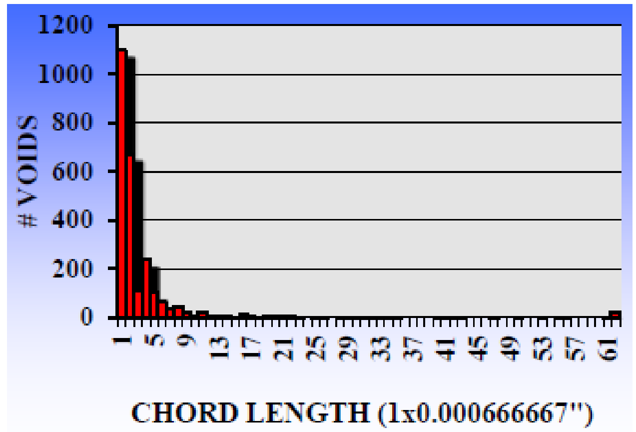
1. &Coarse:19mm (¾") nominal sized superior lobe glacial gravel consisting predominately of rhyolite, granite, basalt, greywacke, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall distribution.
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, and rhyolite.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 7.2% total.
2. &Depth of carbonation: Ranged continuously from <1mm to 5mm depth from the top surface; but "spiking" up to 9mm depth along sub-vertical microcracking.
3. &Pozzolan presence: Fly ash was observed.
4. &Paste/aggregate bond: Fair.
5. &Paste color:Pigmented with a color similar to Moderate Red (Munsell® 5R 4/6). Vitreous to sub-vitreous.
6. &Paste hardness: Relatively hard (Moh's 4).
7. Microcracking: Few, sub-vertically oriented microcracks proceed up to 8mm depth from the top surface of the core. ASR "reacted" coarse and fine particles exhibit internal cracking propagating into the paste as fine sub-horizontal swarms generally proceeding through the next adjacent reactive aggregate. The ASR induced microcracking is generally confined to between 7mm and 70mm depth in the core from the top surface. Several other fine microcracks were observed scattered in the paste at various depths and orientations in the concrete; in a shrinkage-type pattern.
8. Secondary deposits: Secondary ettringite partially fills to fills numerous entrained sized voidspaces throughout the sample below approx. 5mm depth from the top surface; and lines most other voids. Clear to white ASR gel lines or fills voidspaces and microcracks adjacent to and proceeding through reacted aggregate particles in the top 70mm of the core.
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 5% replacement of Portland cement.
10. Cement hydration: Alites: Mostly fully. Belites: Well to fully.

Sample ID: LJ EB A (all voids)

Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

Description:	Hardened Concrete Core
Dimensions:	151mm (6") diameter by 215mm (8 1/2") long

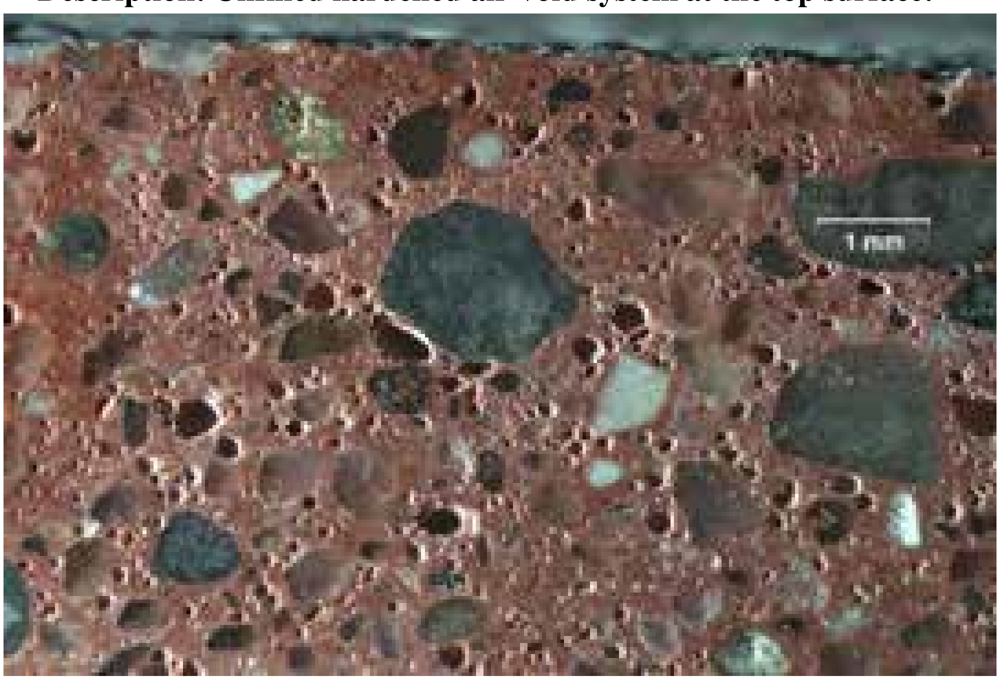
Test Data: By ASTM C:457

Air Void Content %	7.2
Entrained, % < 0.040"(1mm)	5.5
Entrapped, %> 0.040"(1mm)	1.7
Air Voids/inch	26.6
Specific Surface, in^2/in^3	1480
Spacing Factor, inches	0.002
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	95
Test Date	10/15/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

Magnification: 15x

Description: Unfilled hardened air-void system at the top surface.



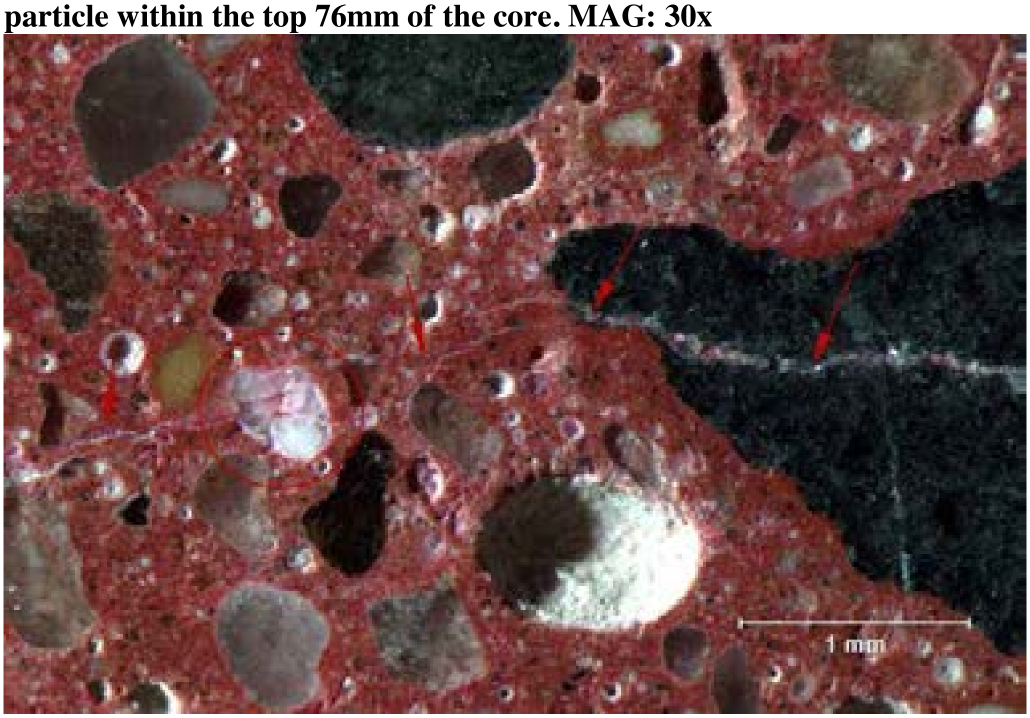
LJ EB A DESCRIPTION: Core sample as received. Top surface is left. Note un-activated joint.

LJ EB A DESCRIPTION: Traffic-worn top surface of the core sample as received. Note spalling adjacent to joint.

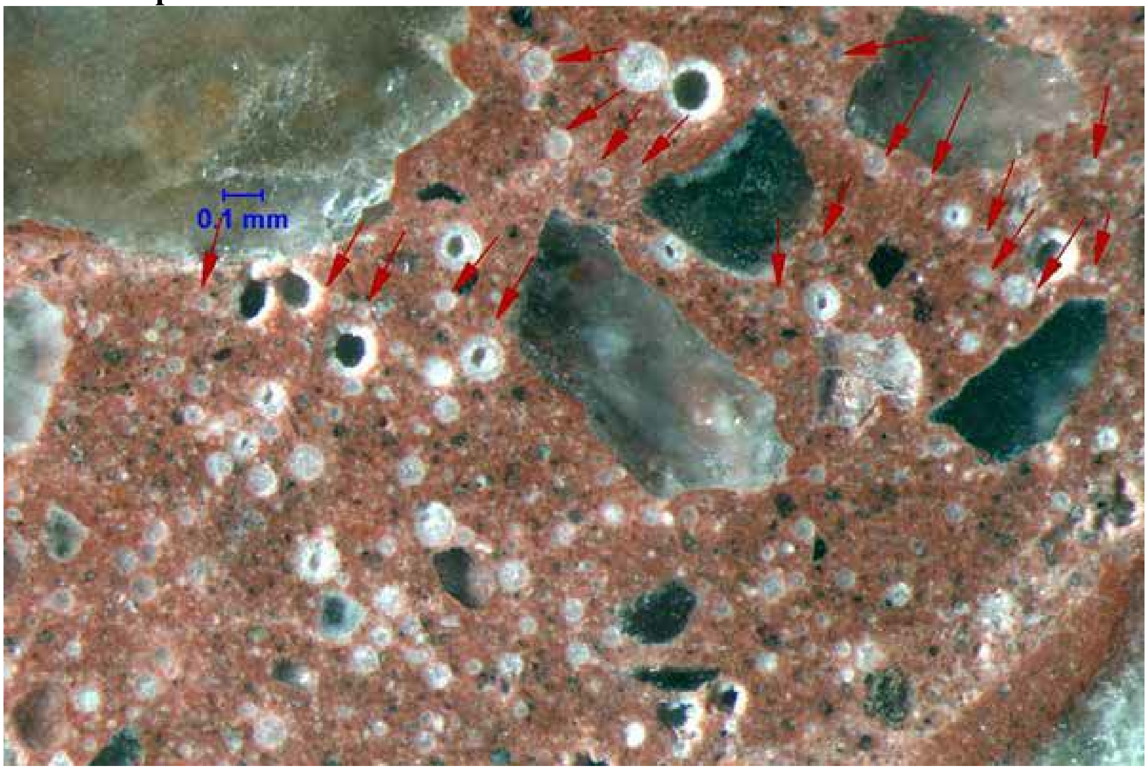
LJEB A DESCRIPTION: Saw cut and lapped cross section of 15lmm diameter concrete core. Note sub- horizontal microcr _ in the - -- 76mm of the core.

LJ EB A DESCRIPTION: ASR induced microcracking is mapped in red ink. The sub-horizontally oriented cracking is confined to the top 76mm and proceeds through several coarse and dozens of fine aggregates. Note un-activated, tooled, control joint.

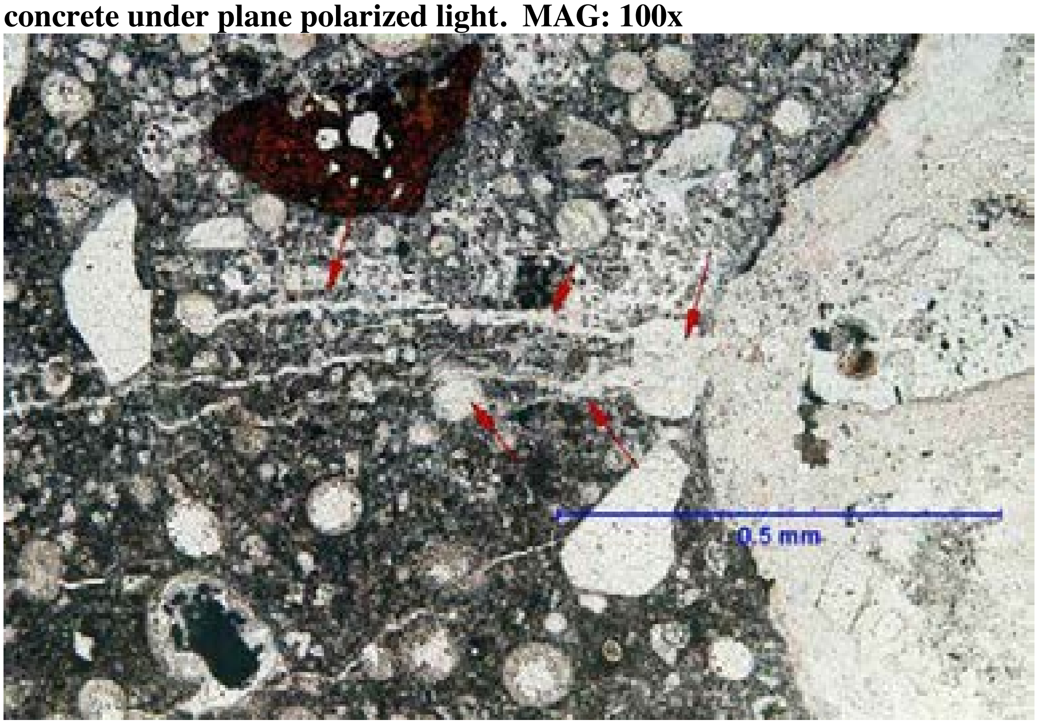
LJ EB A DESCRIPTION: Clear ASR-gel product fills a swarm of sub-horizontal microcracking within and proceeding from a reactive greywacke coarse aggregate particle within the top 76mm of the core. MAG: 30x



LJ EB A DESCRIPTION: Ettringite-filled entrained sized air voids in the concrete paste at60mm depth in the core. MAG: 50x



LJ EB A DESCRIPTION: Clear ASR-gel product fills a swarm of sub-horizontal microcracking proceeding from a reactive chert fine aggregate particle; in thin section of concrete under plane polarized light. MAG: 100x



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

Project No.	24-00469	Date:	October 18, 2012
Sample ID:	LJWB B	Performed by:	D. Hunt, G. Moulzolf

I. General Observations

1. &Sample Dimensions: Our analysis was performed on both sides of a 200mm (7 3/4") x 151mm (6") x 41mm (1 5/8") thick section and a 76mm (3") x 52mm (2") wide thin section; that were sawcut and prepared from the original 152mm (6") diameter x 200mm (7 3/4") long core.

2. &Surface Conditions:
Top: Fairly smooth, traffic worn surface; with many exposed fine aggregates.
Bottom:Rough, irregular, formed surface; placed on a crushed, bituminous-rich base.

3. &Reinforcement: None observed.

4. &General Physical Conditions:The core was taken directly through a tooled pavement joint. An approx. 30mm by 40mm scaled/corner spalled area encompasses portions of both sides of the tooled joint. The joint is characterized by an originally rounded - tooled penetration to an approximately 43mm maximum depth from the top surface of the sample. The apparent semi-plastic concrete adjacent to the original tooled joint appeared to have slumped into and closed much of the depth of the joint off to a 17mm depth. The joint never "activated". However, a sub-vertical microcrack proceeds along the penetration to approximately 50mm depth from the top surface.

Approximately 40mm along the length of one side of the tooled joint has scaled/spalled away up to 20mm from the joint at a relatively shallow angle intersecting the vertical face of the tooled joint at 15mm depth from the top surface. Approximately 20mm along the length of the other side of the joint has scaled/spalled away up to 5mm from the vertical joint surface at a relatively steep angle. Several sub-vertical microcracks (incipient spalling), observed within 12mm of the tooled joint, intersect the vertical face of the joint between 12mm and 19mm depth from the top surface. The cracking proceeds through a normally sound coarse aggregate particle; suggesting impacting.

The concrete was fairly well consolidated, with few, scattered, irregular shaped consolidation voids measuring over 7mm. The concrete was purposefully air entrained and originally contained a relatively fine, well-distributed air void system considered freeze-thaw resistant under severe exposure conditions. Original air void parameters include a 5.0% entrained-sized void volume and a 0.003" spacing factor. The concrete contains a finely disseminated red pigment. Secondary ettringite was observed partially filling to filling numerous entrained sized voidspaces below 5mm depth. Evidence of alkali-silica reaction (ASR) was observed associated with coarse and fine aggregate particles. Some granite, chert, rhyolite, sandstone, siltstone, and greywacke particles exhibited internal microcracking propagating into the paste and proceeding through adjacent reactive coarse and fine aggregate particles. The cracking occurs generally in a sub-horizontal orientation and between 10mm and 58mm depth in the core. Clear to white ASR gel was observed partially lining to filling voidspaces and microcracks adjacent to the reactive particles and bisected by the microcracking.

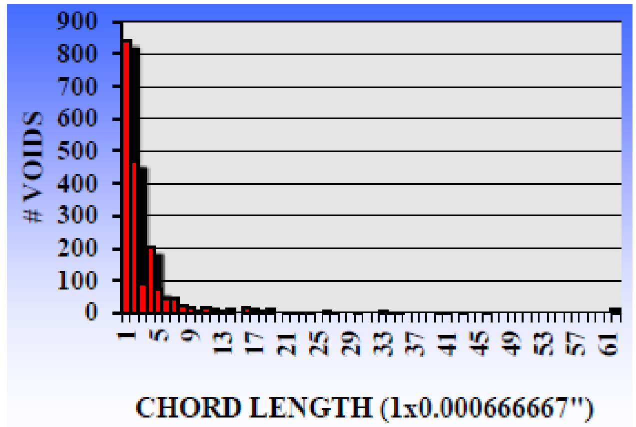
II. &Aggregate

1. &Coarse:19mm (¾") nominal sized superior lobe glacial gravel consisting predominately of rhyolite, granite, basalt, greywacke, chert and carbonates. The coarse aggregate appeared well graded and exhibited good overall
distribution.
2. &Fine: Natural quartz, feldspar, and lithic sand (granite, chert, carbonates, basalt, and rhyolite.) The grains were mostly sub-rounded with many smaller sub-angular particles. The fine aggregate appeared fairly well graded and exhibited good overall uniform distribution.

III. Cementitious Properties

1. &Air Content: 6.3% total
2. &Depth of carbonation:Ranged continuously from <1mm to 5mm depth from the top surface; but "spiking", intermittently up to 21mm depth along sub-vertical microcracking.
3. &Pozzolan presence:Fly ash was observed visually consistent with 5% replacement of portland cement.
4. &Paste/aggregate bond: Fair.
5. &Paste color:Pigmented with a color similar to Moderate Red (Munsell® 5R 4/6). Vitreous to sub-vitreous.
6. &Paste hardness: Relatively hard (Moh's 4).
7. &Microcracking: Several, sub-vertically oriented microcracks proceed up to 21mm depth from the top surface of the core. Several sub-vertical microcracks (incipient spalling) occur directly adjacent and sub- parallel to the corner spalled joint; proceeding through a generally sound coarse aggregate particle. ASR "reacted" coarse and fine particles exhibit internal cracking propagating into the paste as fine sub-horizontal swarms generally proceeding through the next adjacent reactive aggregate. The ASR induced microcracking is generally confined to between 10mm and 58mm depth in the core from the top surface. Several other fine microcracks were observed scattered in the paste at various depths and orientations in the concrete; in a shrinkage-type pattern.
8. &Secondary deposits: Secondary ettringite partially fills to fills numerous entrained sized voidspaces throughout the sample below approx. 5mm depth from the top surface; and lines most other voids. Clear to white ASR gel lines or fills voidspaces and microcracks adjacent to and proceeding through reacted 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 5% replacement of portland cement.
10. Cement hydration: Alites: Mostly fully. Belites: Well to fully.

Sample ID: LJ WB B (all voids)
Conformance: The concrete core sample originally contained an air void system which is consistent with current technology for freeze-thaw resistance.



Sample Data

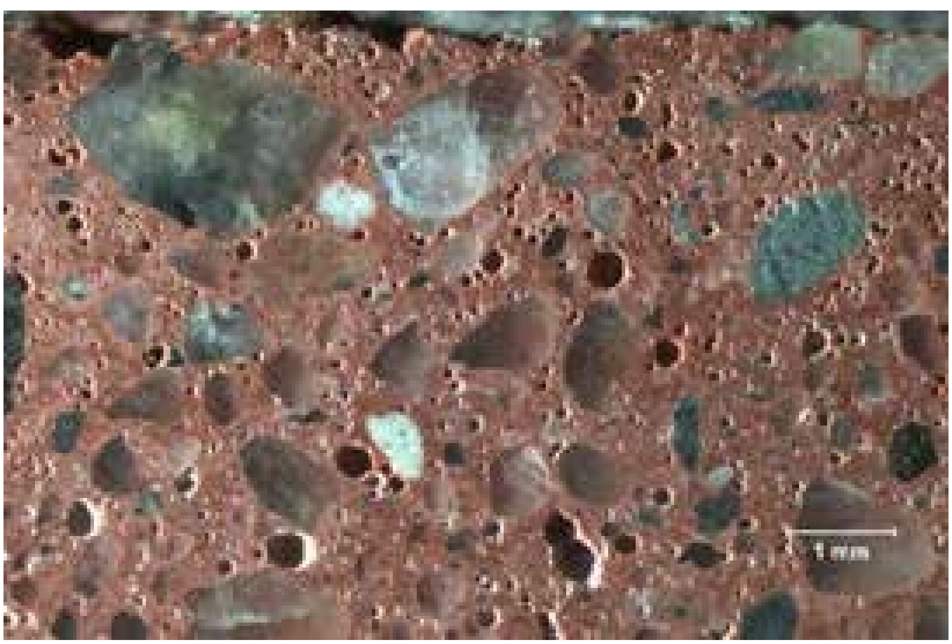
Description: Hardened Concrete Core
Dimensions: 151mm (6") diameter by 200mm (7 3/4") long

Test Data: By ASTM C:457

Air Void Content %	6.3
Entrained, % < 0.040"(1mm)	5.0
Entrapped, %> 0.040"(1mm)	1.3
Air Voids/inch	24.0
Specific Surface, in^2/in^3	1540
Spacing Factor, inches	0.003
Paste Content, % estimated	26
Magnification	75x
Traverse Length, inches	80
Test Date	10/15/2012

Report Prepared By:
Gerard Moulzolf, PG
Vice President/Principal Petrographer
MN License #30023

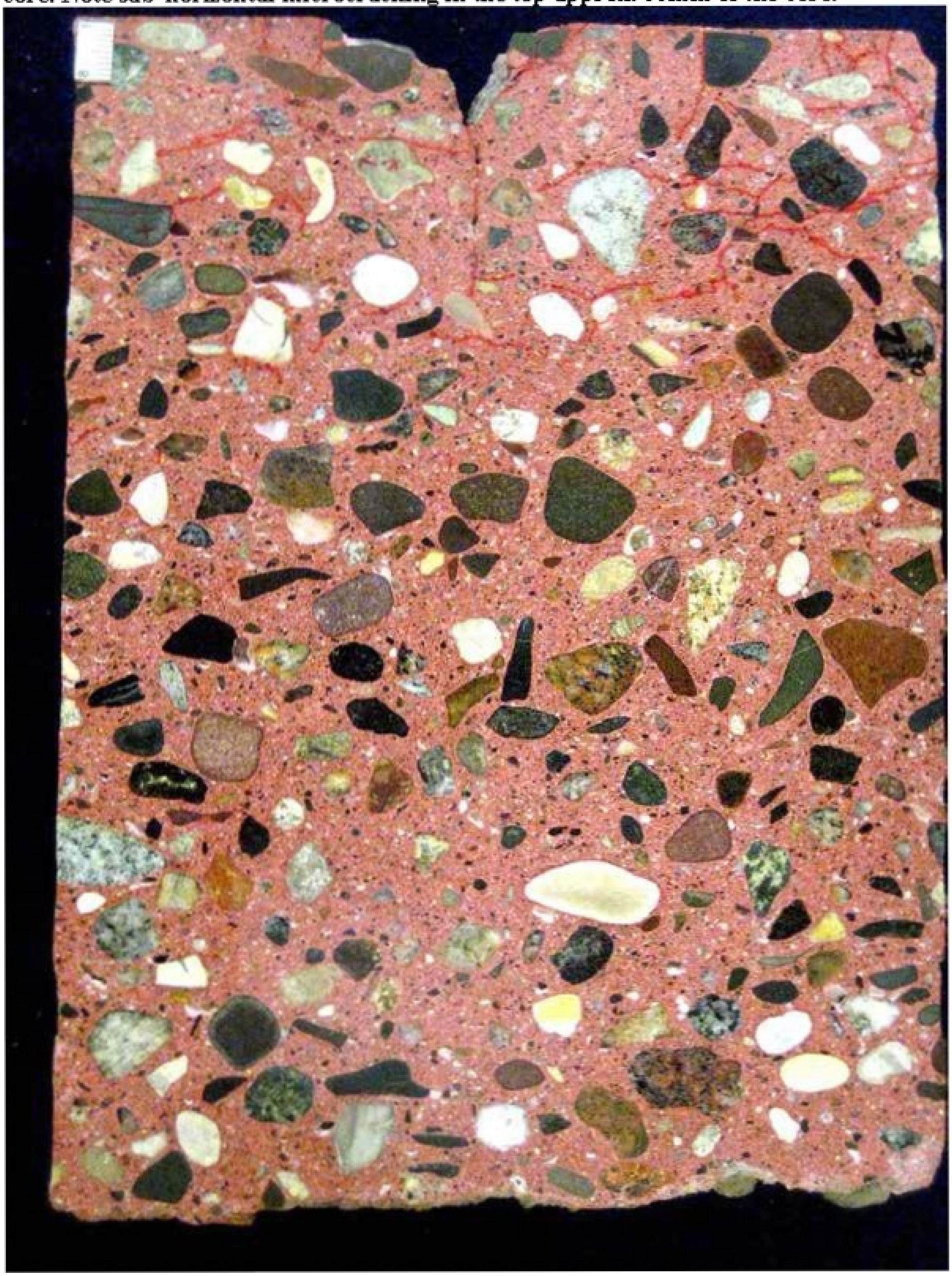
Magnification: 15x
Description: Unfilled hardened air-void system at the top surface.



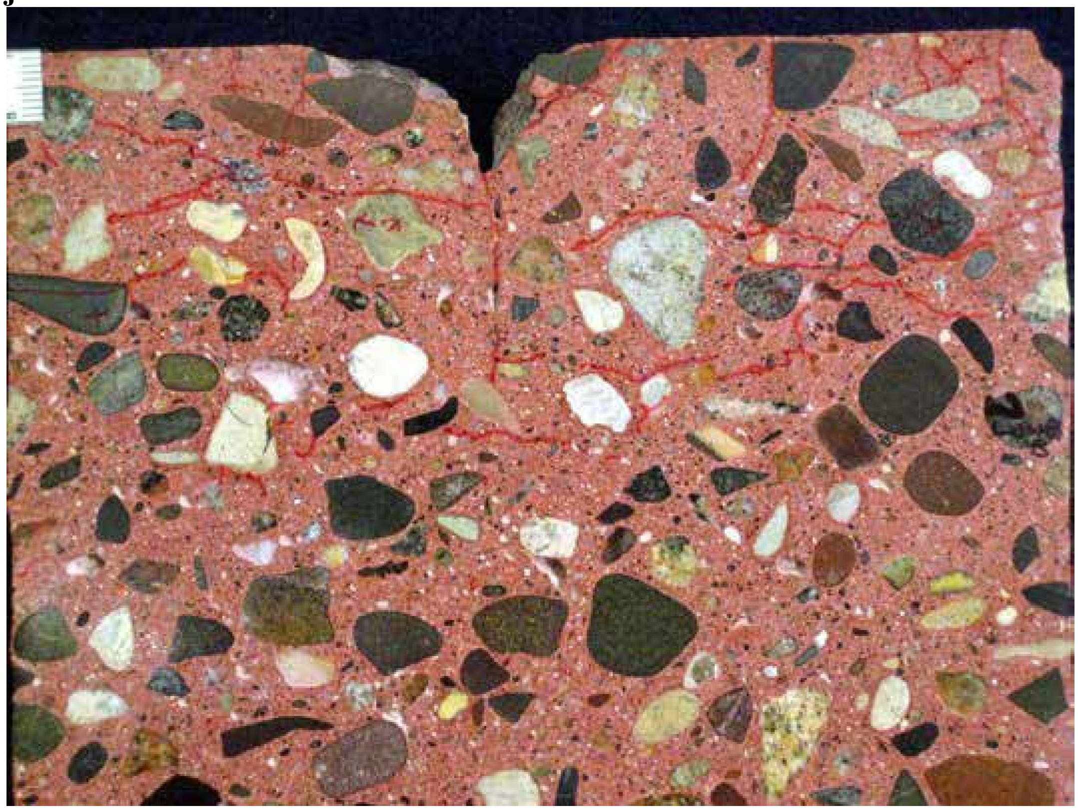
LJ WB B DESCRIPTION: Core sample as received. Top surface is left.

LJ WB B DESCRIPTION: Lightly textured and traffic-worn top surface of the core sample as received. Note spalling adjacent to un-activated joint.

LJ WB B DESCRIPTION: Sawcut and lapped cross section of 151mm diameter concrete core. Note sub-horizontal microcracking in the top approx. 60mm of the core.



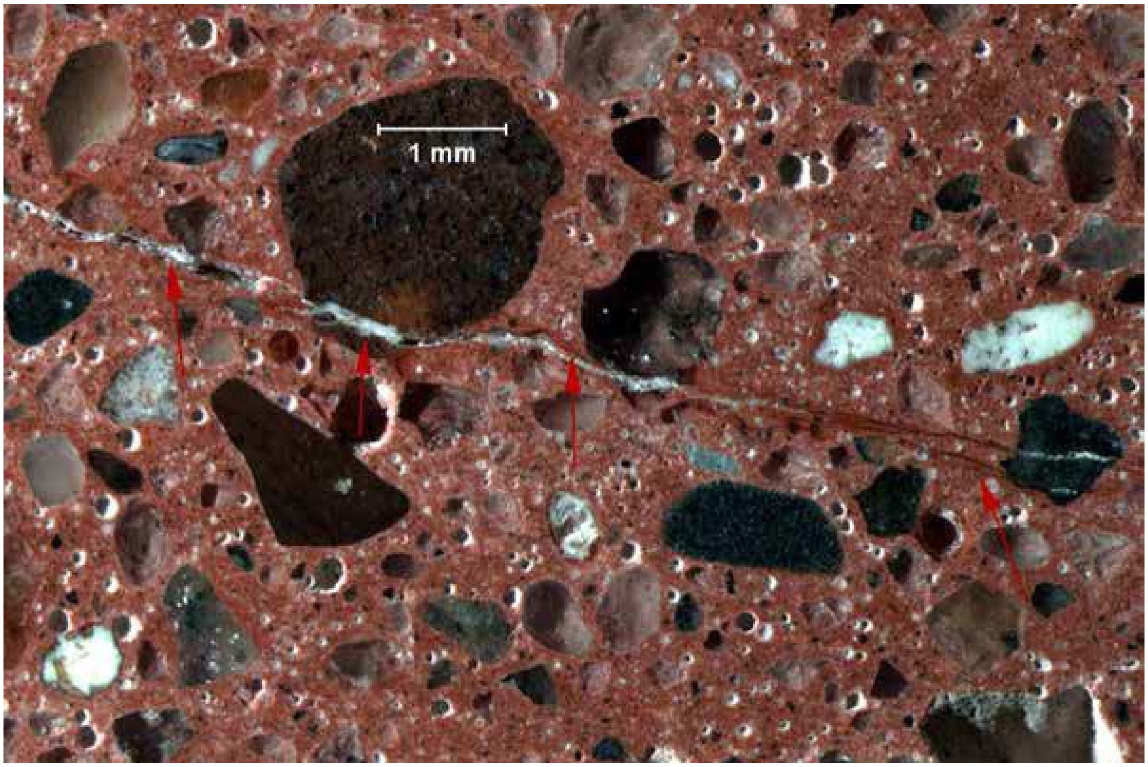
LJ WB B DESCRIPTION: ASR induced microcracking is mapped in red ink. The sub-horizontally oriented cracking is confined to the top 58mm and proceeds through several coarse and dozens of fine aggregates. Note un-activated, tooled, and spalled control joint.



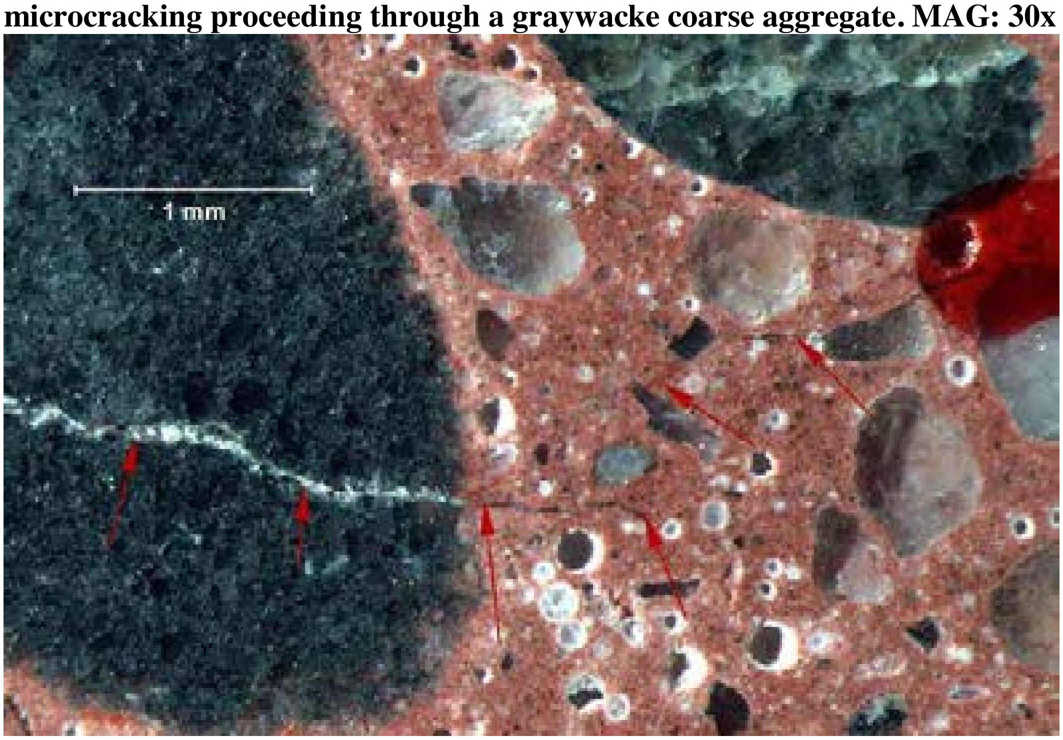
LJ WB B DESCRIPTION: Incipient spalling at the tooled joint occurs within a hard, sound and durable aggregate and is most likely a result of impacting. MAG: 5x

LJ WB B DESCRIPTION: White to clear ASR gel mostly fills sub-horizontally oriented

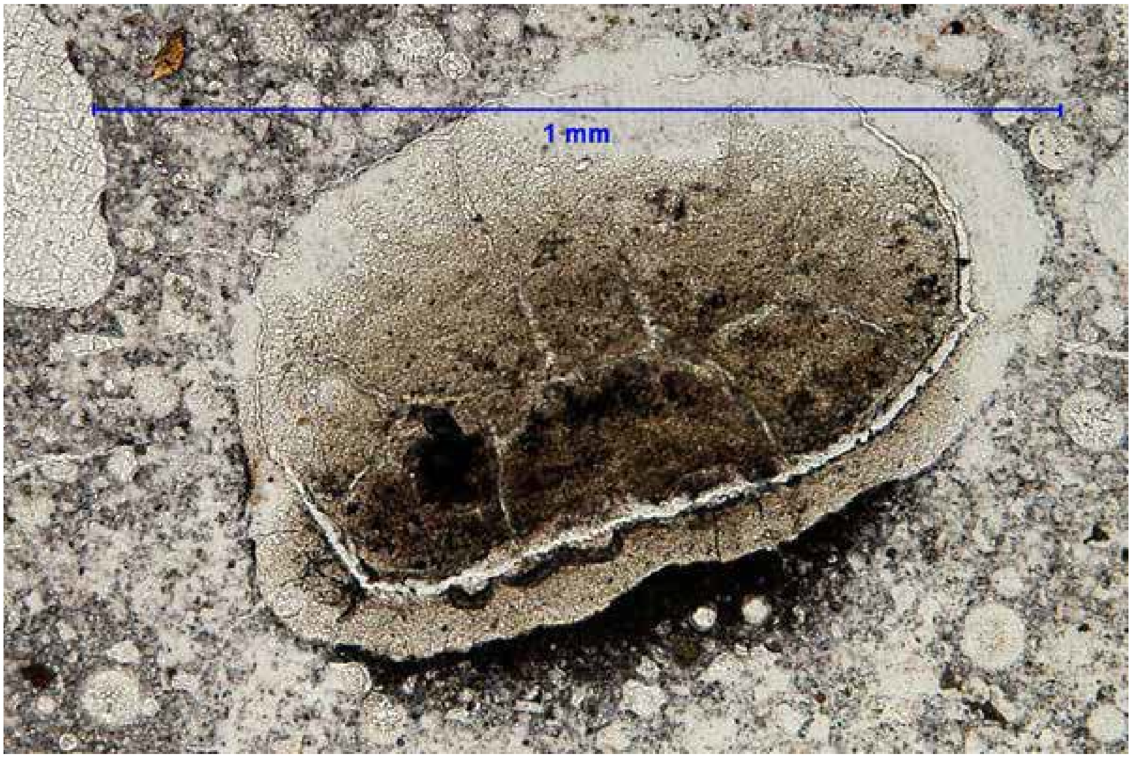
microcracking proceeding through three reactive fine aggregates. MAG: 15x



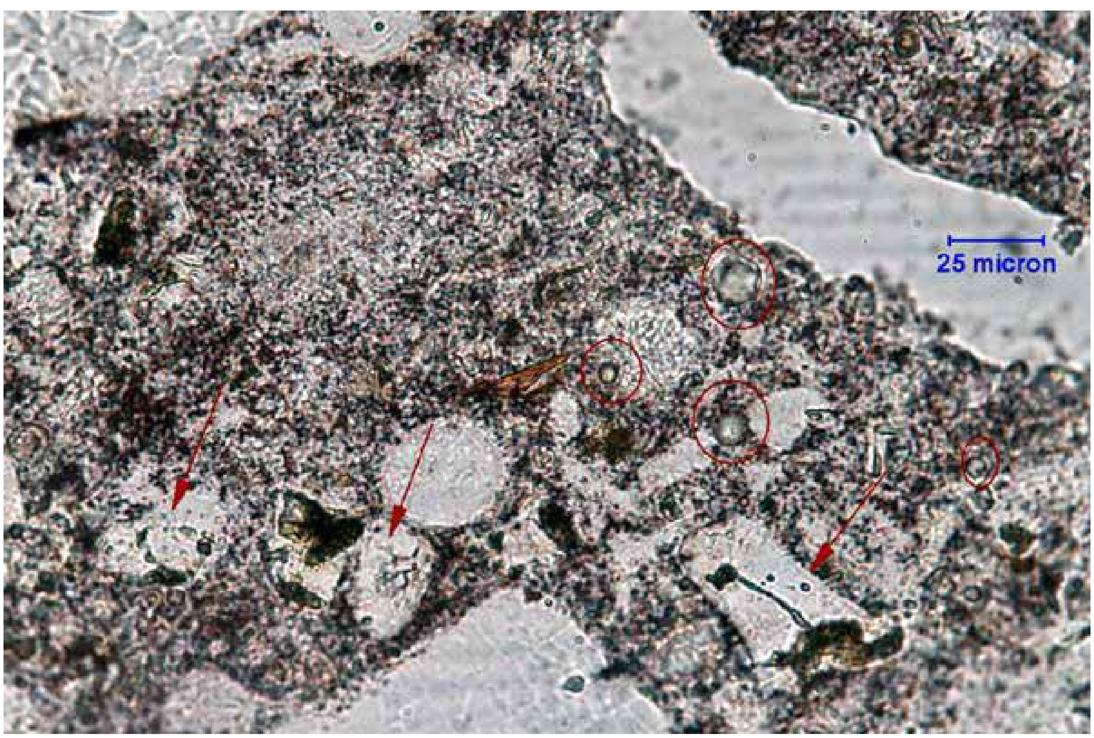
LJ WB B DESCRIPTION: White to clear ASR gel mostly fills sub-horizontally oriented microcracking proceeding through a graywacke coarse aggregate. MAG: 30x



LJ WB B DESCRIPTION: A reactive shale fine aggregate particle in thin section of concrete under plane polarized light. MAG: 100x



LJ WB B DESCRIPTION: Fully hydrated alite portland cement clinker particles (arrows) and a few flyash pozzolan particles (circled) in thin section of pigmented concrete paste under plane polarized light. MAG: 400x



APPENDIX B: SEM AND EDX ANALYSIS REPORT

Investigation and Assessment of Colored " Concrete Pavement "

LRRB Inv. 929 "

Amendment No. 1 to MnDOT Contract No. " 01219 "

Submitted by !

Lawrence Sutter, Ph.D. Michigan !
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MI 49931 !
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January 27, 2014 !

Background

Eleven (11) hardened concrete core samples were submitted for study to American Engineering Testing (AET) by representatives of the Minnesota Department of Transportation on June 13, 2012 (cores 14A, 14C, 14E, 96A, 9C, and 96D) and August 22, 2012 (cores Larpenteur Ave. & Fernwood St. A, Larpenteur Ave. & Fernwood St. B, Larpenteur Ave. & Fernwood St. C, Lake Johanna EB A, and Lake Johanna WB B). The purpose of study was to identify the causes of joint deterioration in the sampled pavements. The pavements in question varied in mixture design but all contained colored pigment.

The results of a preliminary petrographic examination are summarized in an October 26, 2012 AET report on project 24-00469.

The preliminary study reported the concrete examined had well-distributed, purposefully entrained, air-void systems with documented air-void system parameters considered freeze-thaw resistant under severe exposure conditions. Most of the examined concrete was generally placed at a "moderate" *w/cm*, estimated to be between 0.42 and 0.50. Cores from the Larpenteur & Fernwood project were placed at a moderately low *w/cm* estimated to be between 0.40 and 0.45. In some cores examined, there was strong evidence of chemical attack of the hardened cement paste, which could be contributed to the use of various deicer chemicals. In some cases, diagnostic features of alkali silica reaction (ASR) were noted where the aggregate used has a field performance history of not being ASR susceptible.

Based on the observations made as part of the preliminary petrographic examination, it was recommended that an additional study be performed to further examine i) the apparent chemical attack of the hardened cement paste, and ii) further investigate the reasons for ASR occurring with aggregates thought to be non-ASR susceptible.

Experimental Approach

Analysis Methods

To further understand the causes of the joint deterioration observed in these pavements, samples from selected cores from the referenced projects were analyzed using scanning electron microscopy (SEM) and energy dispersive x-ray spectrometry (EDX).

Samples taken from four (4) of the submitted cores were examined looking for evidence of chemical attack and also information to help understand the anomalous ASR that occurred. Samples were examined from 96A, 96D, Larpenteur Ave. & Fernwood St. A, and Larpenteur Ave. & Fernwood St. C. This report presents results from 96A and Larpenteur Ave. & Fernwood St. C.

All samples were analyzed using a Philips XL-40 Environmental Scanning Electron Microscope (SEM) equipped with an EDAX Phoenix Energy Dispersive X-ray spectrometer (EDS). In the SEM, information is obtained by scanning an electron beam over a selected area of the sample, releasing electrons and x-rays from the specimen area. Alternatively, the electron beam can be placed static on the specimen and electrons and x-rays are emitted from one specific point.

Gathering electrons scattered from the specimen, the SEM has the ability to produce backscattered electron images that show areas of different composition. Contiguous areas of a specific composition are referred to as phases and often the contrast seen in a backscattered electron image is referred to as phase contrast. In a given image, areas that have an average higher atomic number will appear brighter than areas that have a composition with an average lower atomic number. All SEM images shown in this report are backscattered electron images.

The EDS system is used to process the x-rays emitted from the specimen. The x-rays emitted are characteristic of the elements in a phase. Each element releases a unique x-ray spectrum and by identifying the energy of an x-ray, it can be associated with a specific element. By measuring the rate or intensity of the x-ray emission (e.g., number of x-rays per second), a quantitative phase analysis can be performed where elemental concentration can be determined for a volume of the sample on the order of a cubic micron (1 μm^3

Often when an EDS analysis is performed, the approach is to use what is referred to as a "standardless" analysis. As the name implies, no reference standards are analyzed to calibrate the analysis. Drawbacks of this method include an inherent inaccuracy when not using a reference standard. Another significant problem is the need to normalize the analysis to 100% total. By normalizing, the ability to identify undetected elements is lost and identified elements may be overestimated. For example, hydrated phases may contain a significant water content in the crystal structure. Hydrogen is undetectable by EDS; any element with an atomic number less than carbon is undetectable. Elements such as carbon and oxygen are difficult to analyze directly. To accurately identify mineral phases, it is often necessary to analyze just the cations (e.g., calcium, silicon) and determine the anions (e.g., carbon, oxygen) by calculation or by difference. Therefore to obtain accurate cation analyses, it is essential to not normalize the result, which means reference standards must be used to get confident results. Also, un-normalized results may not total to 100%, as not all the elements present may be analyzed. All phase analyses performed for this study were completed using reference standards.

The other use of the EDS system is to produce an x-ray map that shows elemental distribution. As the electron beam scans over the selected area of the specimen, the x-ray intensity of specific elements is monitored and an image is formed where high intensities (i.e., high concentrations) are shown as brighter areas of the element map. x-ray mapping is a convenient way to illustrate elemental associations or areas where elements either exist or are absent.

Sample Preparation

The cores selected for further analysis are shown below in Figure 1. Specimens were saw-cut from the cores and lapped using 60, 280 and 600 grit diamond lapping discs. The areas selected for SEM specimens are shown in Figure 2. Areas selected to prepare specimens for analysis in the SEM. (a) 96A, (b) Larpenteur & Fernwood A, (c) 96D, and (d) Larpenteur & Fernwood C. The specimens were epoxy impregnated to stabilize the samples and lapped again using 600 grit diamond discs. The lapped samples were mounted to glass slides using UV curing adhesive. After curing the adhesive, the excess concrete was cut from the section using a Buehler Petro-Thin sectioning machine and ground to an appropriate thickness using the Petro-Thin grinding wheel. Then using the 280 and 600 grit diamond lapping discs, a final lapping was applied to the exposed surface. The specimens selected for analysis are shown in Figure 3.

Results & Discussion

Site 96A

The deterioration observed in this concrete falls into two categories: chemical attack of the cement paste and chemical attack of the aggregate. Both mechanisms will be discussed as the results from the various analyses are presented.

The specimen studied includes the joint surface and the material adjacent to the joint. The specimen includes highly damaged concrete but the sample extends into the specimen far enough to include unaffected concrete. The outermost area of the joint is typified by the micrograph shown in Figure 4. This area is cement paste fragments and aggregate liberated from the concrete due to chemical attack from deicers or other weathering forces (e.g., freeze-thaw cycling). The x-ray intensity maps of this same area are shown in Figure 5 and are further described in Figure 6 through Figure 10. In Figure 4, smooth continuous grains are seen that are quartz sand or other homogenous, silica-rich fine aggregate. The majority of the non-quartz particles in the image are highly altered cement paste or aggregate, with small inclusions of ettringite, magnesium oxides (likely dehydrated magnesium hydroxide), and other phases. In Figure 6, a calcium-rich phase (blue colored) is seen surrounding most grains. Similarly the same phase is seen in Figure 7 as a carbon rich phase (also blue colored). Therefore, this phase is calcium carbonate, or calcite. Calcite is a common end product of hardened cement chemical weathering where calcium hydroxide is leached from the cement paste, re-precipitates in the concrete matrix, cracks, and voids, and then carbonates to calcite with exposure to atmosphere. The grain marked with A in Figure 6 is shown in greater detail in Figure 11 and the associated x-ray maps in Figure 12 though Figure 16. This appears to be an aluminum/silicon rich aggregate fragment that shows various other phases included. Figure 8 highlights the sand grains (red) and also shows a broad, low concentration distribution of magnesium likely associated with magnesium chloride deicing chemicals. Figure 9 includes sulfur in the x-ray map and when combined with calcium shows ettringite as a cyan color. Figure 10 indicates that grain A has a higher level of potassium than surrounding grains. Combined with the aluminum, silicon and calcium, this would indicate that grain A is a felsic rock fragment.

Figure 11 shows grain A from Figure 4, and Figure 12 shows the x-ray intensity maps associated with this same area. Figure 13 shows ettringite phases as purple regions and the calcite rim on the particle is clearly seen (blue rim). Figure 14 shows a number of orange phases that are combinations of magnesium and oxygen, more rich in magnesium. These are magnesium oxide phases but likely were originally magnesium hydroxide (brucite). In Figure 15 ettringite phases stand out clearly as cyan inclusions. Figure 16 shows the distribution of potassium, magnesium and iron in the aggregate fraction. The distribution is not uniform and in the case of magnesium does not seem to be associated with specific sub-particle phases, indicating the magnesium is likely from external sources and is migrating into the particle. As will be discussed, there is a particular felsic fine aggregate that appears to be susceptible to chemical attack in the concrete studied.

Figure 17 shows a region of the specimen adjacent to the joint (i.e., the joint is seen in the upper left-hand corner of the micrograph) but primarily includes concrete adjacent to the joint. Figure 18 presents the x-ray intensity maps gathered from this area while Figure 19 through Figure 23 show combinations of these maps in greater detail.

Figure 19 shows the combined aluminum, silicon, and calcium x-ray intensity maps. Prominent is the calcium rich matrix (blue color), which again represents the calcite matrix replacing cement. In Figure 17 the texture of the calcite can be seen and it clearly shows different regions of texture indicating successive layers of deposit. In the center of the micrograph is a feature (resembling a "squid" in appearance) that is also seen in the x-ray intensity maps that is aluminum and silicon bearing (Figure 19), and magnesium and iron bearing (Figure 20). The iron and magnesium are noted as it appears these elements may have been trapped as part of the deposition. The source of the magnesium is likely the deicers while the source of the iron appears to be the coloring added to the concrete. The iron coloring appears to be mobile as it is seen lining the interfaces around the aggregates in Figure 20 (i.e., thin green layer seen around aggregates) after the paste has undergone dissolution and re-precipitation as calcite. Also, as will be discussed further, there seems to be a coincidental occurrence of magnesium and iron in a number of locations observed.

Figure 21 shows the combined phosphorous, calcium, and magnesium x-ray intensity maps. Of particular interest in this x-ray map is the coincidental occurrence of phosphorous with calcium, and separately with magnesium. Figure 22 shows the distribution of magnesium and iron. A cyan color indicates the coincidence of magnesium and iron, which is common. Figure 23 is included primarily to show the carbon x-ray intensity map to confirm the matrix is carbonate.

Referring to the aggregate labeled as A in Figure 17, note in the lower right corner of the particle is a large yellow phase and 3-4 smaller yellow phases distributed throughout the grain. These yellow phases are apatite ($Ca_5(PO_4)_3F$). Example analyses are presented below in Table 1.

Table 1. Example analyses of apatite phases. !

Oxide	Point 1	Point 2	Nominal
F	NA	1.65	2.2
Na_2O	0.63	0.55	
MgO	0.61	0.84	
Al_2O_3	0.88	0.60	
SiO_2	1.62	1.45	
P_2O_5	39.0	41.13	42.2
SO_3	0.14	0.14	
Cl_2O	2.7	0.49	
K_2O	0.13	0.16	
CaO	51.6	51.8	55.6
Fe_2O_3	0.20	0.0	
TOTAL	97.5	98.82	

NA = not analyzed

Also seen in aggregate A is a magenta rim surrounding the apatite grain where magenta indicates the coincidental occurrence of phosphorus and magnesium. Magenta phases appear throughout aggregate A and dark purple phases occur throughout aggregate A and to a much lesser extent aggregate B. Figure 24 shows a backscattered image of aggregate A and three locations are shown where quantitative analyses were performed. The results are shown in Table 2.

Table 2. Analyses from grain A in Figure 24.

Oxide	Area A	Area B	Area C
Na_2O	0.41	9.80	0.52
MgO	0.47	0.34	9.48
Al_2O_3	1.08	19.5	18.4
SiO_2	98.2	68.3	38.9
P_2O_5	0.09	0.00	1.50
SO_3	0.00	0.00	0.00
Cl_2O	0.05	0.00	0.05
K_2O	0.12	0.13	1.67
CaO	0.19	0.83	7.08
Fe_2O_3	0.00	0.00	5.87
TOTAL	100.6	99.0	83.4

Area A and Area B represent quartz and albite phases, respectively, both common in feldspar rocks. Area C is a highly altered material. This judgment is based upon its composition, which does not resemble any common mineral, and its morphology as seen in Figure 25. The morphology is very bladed, uncommon in such rocks. Also, looking at the analysis total for Area C in Table 2, it can be seen the total is significantly less than 100% indicating the material is porous. Also note the presence of phosphorus in area C, confirming what is seen in the x-ray intensity map. The phosphorus likely results from the dissolution of apatite within the aggregate.

The aggregate shown as grain A in Figure 24 is one of a number of felsic rock types present in the concrete. More common are minerals such as grain C in Figure 17. Aggregates composed of common feldspar minerals were prevalent but those with apatite inclusions seem to be minerals that are reacting. Moving away from the joint to unaffected concrete, the latter type of aggregate is more easily seen. An example is shown in Figure 26 and the corresponding analyses are shown in Table 3. The results presented in Table 4 are for phases typical of the much more common type of felsic grains present in the fine aggregate. These analyses are typical of grains such as shown in Figure 27, and also grain C in Figure 17. These grains do not appear to be reactive in the deicer environment. In Table 4, Area A is a typical anorthite phase while Area B is a typical albite phase.

Table 3. Analyses from grain shown in Figure 26.

Oxide	Area A	Area B	Area C	Area D	Area E
Na_2O	1.10	9.64	0.70	0.63	0.34
MgO	9.63	0.35	12.2	0.61	0.60
Al_2O_3	6.25	19.56	16.3	0.88	1.05
SiO_2	46.8	67.6	32.4	1.62	3.70
P_2O_5	0.06	0.00	0.15	39.0	0.64
SO_3	0.00	0.00	0.14	0.14	0.30
Cl_2O	0.92	0.00	0.12	2.70	0.07
K_2O	0.90	0.21	1.92	0.13	0.11
CaO	11.6	0.57	0.36	51.6	0.79
Fe_2O_3	19.7	1.03	25.7	0.20	94.7
TOTAL	96.9	98.9	90.1	97.5	102.3

Table 4. Analyses from common felsic grains in the fine aggregate, as shown in Figure 27.

Oxide	Area A	Area B
Na_2O	1.00	9.80
MgO	0.46	0.34
Al_2O_3	18.0	19.5
SiO_2	63.6	68.3
P_2O_5	0.07	0.00
SO_3	0.02	0.00
Cl_2O	0.04	0.00
K_2O	16.5	0.13
CaO	0.86	0.83
Fe_2O_3	0.00	0.00
TOTAL	100.6	98.8

The area shown in Figure 28 and the associated x-ray intensity maps in Figure 29 through Figure 33 show an area on the concrete away from the affected area (i.e., away from the joint). Figure 30 shows cement paste that is calcium silicate, denoted by shades of blue and cyan indicating a mixture of calcium and silicon. Also seen are the felsic aggregates common in the fine aggregate fraction and ettringite infilling (mixture of calcium and aluminum).

Figure 31 shows the matrix is oxide, not carbonate. Also seen in Figure 31 are orange inclusions that are mixtures of magnesium and oxygen (i.e., magnesium oxide). Magnesium oxide inclusions are common throughout the concrete, from the joint inward. This would indicate that magnesium-bearing solutions are moving through the concrete and magnesium is depositing in voids as either an oxide or hydroxide. Evidence of both were found with magnesium oxide being much more common. Presumably hydroxide phases would oxidize or dehydrate over time, or carbonate. All three forms of magnesium are seen in the voids of the specimen. Figure 32 shows the relationship between aluminum, sulfur, and calcium. Primarily ettringite phases are highlighted (green or cyan). Figure 33 illustrates a common observation of iron and magnesium in coincidence (represented by a cyan or blue-green color).

The area shown in Figure 34 is included to further illustrate observations on the paste composition away from the joint. In the center of this area is an aggregate fragment and the remainder of the image is cement paste. Figure 35 shows the summary of x-ray intensity maps. Figure 36 shows a calcium silicate paste (cyan color) and ettringite infilling voids. As can be seen, the voids are almost all filled. Figure 37 shows the magnesium oxide infilling of voids not filled by ettringite. The light blue color is indicating magnesium rich infilling that may be carbonated while the yellow is magnesium oxide. Figure 38 further delineates the ettringite (cyan). Figure 39 shows the coincidence of magnesium and iron. It is presumed the iron coalesced on the aggregates as part of mixing, or it migrated there as pore water moved through the concrete. The magnesium is presumed to be from deicers and it seems to be preferentially attracted to those areas with concentrated iron. Last, Figure 40 shows distribution of phosphorus, in some cases reporting with calcium and may be apatite fragments (upper left corner), but it is also seen surrounding the aggregate fragment (light purple) and is therefore assumed to also be part of the pore water movement, with the source of the phosphorous being the dissolved apatite.

Regarding the aggregate dissolution, refer to Figure 41and Figure 42. The former shows example areas from adjacent and near the joint while the latter shows areas away from the joint or any visible distress. Note the porous aggregate seen in Figure 41while the aggregate in Figure 42 shows no sign of dissolution. The evidence would suggest the aggregates near the joint are undergoing reaction and dissolution. Being alkali-rich felsic rocks, this dissolution will likely also release alkali ions that could impact the total alkali of the system and potentially affect ASR susceptible aggregates.

The exact mechanism of attack is unclear. Given the lack of apatite phases in the aggregate near the joint, as compared to aggregates at depth away from the joint, these phases seem to be involved with the dissolution process. However, there also appears to be a relationship between magnesium and iron from the coloring that may also be involved.

Figure 43 shows an aggregate that appears to have partially reacted. The central core is still dense and without porosity while perimeter has become more porous. Figure 44 through Figure 48 present x-ray intensity maps from the region of this aggregate presented in Figure 43(b). Figure 45 shows the aluminum, silicon, and calcium map of this region and it can be seen where the dense core (yellow) occurs. The outer region indicates only silicon. Examining Figure 43(b) it can be seen that regions on the edge rich in silicon also are porous, indicating a material has leached from these phases. As can be seen in Figure 46, the silica phases on the outer edge do occur with sodium (cyan), but do not occur with potassium (yellow). Silicon does occur with potassium on the interior. This would suggest potassium is being leached from the aggregate. Figure 47 shows the occurrence of the magnesium phases in this aggregate, and the coincidence of iron. This will be discussed further in reference to Figure 49. Likewise, Figure 48 shows the distribution of phosphorus and the coincidence with calcium indicating small apatite grains in the matrix of the aggregate.

Figure 49 is a closer examination of this same aggregate. Note the bright iron phases forming box like perimeters around the magnesium phases. Figure 51 shows the distribution of major elements and again shows the silica rich phases. Figure 52 shows the relationship between the silica phase, sodium, and alkali. At the higher magnification some potassium bearing phases are seen but clearly, there are phases where the potassium has been depleted. Figure 53 shows the magnesium rich phases and the coincidence of oxygen (i.e., magnesium oxide). Figure 54 shows clearly the iron rimming the magnesium phase. It is not clear if the occurrence of potassium in the region of magnesium and iron is a transient of the dissolution process. In other words, if the interaction of magnesium and iron is leading to the dissolution of potassium bearing phases, perhaps this is a remnant of a partially completed dissolution. Finally, Figure 55 shows the occurrence of phosphorus, the apatite phase, and its proximity to the magnesium rich phase. One hypothesis is the apatite is going into solution and the magnesium/iron combination is re-precipitating in the void space created in that dissolution.

Site Larpenteur Ave. & Fernwood St. C

The concrete from this site appeared to be less affected, though it was distressed. As seen in Figure 56, the paste is more intact as compared to site 96A. Figure 57 through Figure 62 present the x-ray intensity maps associated with the area shown in Figure 56. Figure 58 indicates there is a layer of calcite at the joint, as see in 96A, but the paste is not converted to calcite. Aggregates do not show signs of dissolution. Figure 59 indicates the paste is not significantly carbonated and magnesium oxide inclusions are noted. Figure 60 shows some ettringite but much of the infilling seen in this concrete was Friedel's Salt rather than ettringite. The areas in this x-ray map that are cyan or blue-green are ettringite. The blue-only inclusions are Friedel's Salt. Figure 61 indicates no appreciable level of phosphorus, in contrast to site 96A. Figure 62 shows the coincidence of magnesium and iron and as seen in the 96A concrete, there is a noticeable coincidence between these two elements. However, this trend is not as strong in this concrete as was seen in the 96A concrete. Another area near the surface was examined and the micrograph of that area is shown in Figure 63. The x-ray intensity maps for the area shown in Figure 63 are presented in Figure 64 through Figure 69. Overall, the areas presented are similar and no obvious deterioration mechanism is apparent other than the paste dissolution indicated by the calcite layer at the joint.

The fine aggregate used in the L&F site appears similar to that used in 96A. The most striking difference between the two sites, other than the degree of damage, is the L&F site appears to have a much higher amount of larger entrained air voids. This can be seen in Figure 70 and the other micrographs in Figure 70 through Figure 75.

One observation was the cement paste in the L&F specimen appeared altered in regions. Figure 71 through Figure 73 show this observation. The alteration appears as a decrease in paste density, a more grainy appearance, as compared to the more dense paste, as seen away from the joint and shown in Figure 75. The areas of alteration seem to correspond with clusters of air voids, although this trend is not universal.

To determine if there was a significant chemical difference between the different paste regions, quantitative analyses were performed on areas of the paste. These results are presented in Tables 5-7. It is difficult to analyze cement paste particularly when air contents are high. The analysis is of a volume of material below the specimen surface and can be affected by the presence of porosity of any kind. There appears to be a general trend of lower calcium contents in the altered paste. This would be consistent with calcium hydroxide being leached from the paste, which occurs in the presence of deicers.

Also of note, air voids at or near the affected zone were found to be filled with a calcium rich gel material (e.g., CaO ~35%, SiO_2~ 10%, MgO 1%, Al_2O_3~2%). The presence of this material was wide spread. It was co-mingled with ettringite or Freidel's Salt in many cases. This was a further indication of chemical dissolution of the cement paste.

Table 5. Analyses from paste areas near the joint that appeared to be altered. Labeled areas are shown in Figure 73.

Oxide	Area A	Area B	Area C
Al_2O_3	2.97	4.31	3.14
SiO_2	28.7	20.4	23.0
CaO	38.7	37.9	42.4
CaO/SiO_2	1.35	1.86	1.85

Average CaO/SiO_2 = 1.68

Table 6. Analyses from paste areas near the joint that do not appeared to be altered. Labeled areas are shown in Figure 73.

Oxide	Area D	Area E	Area F
Al_2O_3	3.29	4.09	5.35
SiO_2	31.1	30.3	35.3
CaO	44.8	45.9	45.3
CaO/SiO_2	1.44	1.51	1.28

Average CaO/SiO_2 =1.41

Table 7. Analyses from paste areas well away from the joint that do not appear to be altered. Labeled areas are shown in Figure 75.

Oxide	Area A	Area B	Area C
Al_2O_3	5.47	4.35	3.00
SiO_2	28.7	44.9	29.8
CaO	68.0	63.8	49.1
CaO/SiO_2	2.37	1.42	1.65

Average CaO/SiO_2 =1.81

Conclusions

For the concrete materials analyzed, there appears to be strong evidence of paste dissolution. Magnesium rich inclusions throughout indicate magnesium chloride solutions are permeating the concrete, likely as a result of deicer exposure. There appears to be an affinity for iron by magnesium ions. There was not a clear indication this affinity resulted in paste damage, per se. If there is a chemical attraction between these ions, that would increase the driving force for the solutions to penetrate the concrete (i.e., concentration-driven diffusion). However, there was not evidence to support or deny this hypothesis. The most striking observations were in the 96A concrete where there appears to be good evidence the fine aggregate is reacting in the presence of the magnesium and undergoing partial dissolution. These fine aggregates are potassium and sodium feldspars and the leaching process could be resulting in an increased alkali loading of the concrete, and subsequent alkali-silica reaction (ASR). In the case of the L&F core sample, the only apparent mechanism was paste dissolution. There was no sign of aggregate dissolution.

Recommendations

It is recommended that a more detailed analysis of the fine aggregate used in this concrete be conducted. Observations here should be confirmed by examining the natural aggregate. Laboratory leaching tests of the aggregate should be conducted to determine if leaching of alkalis and the general process of dissolution can be identified. Additionally, MnDOT may want to consider developing a “salt soundness” test for evaluating aggregates, particularly if the laboratory testing indicates aggregate dissolution in the presence of deicers (or water) is in fact occurring.

Figures &

(a) (b) (c) (d)

Figure 1. Cores previously analyzed by optical microscope. Re-sampled for analysis in the SEM. (a) 96A, (b) Larpenteur Fernwood A, (c) 96D, and (d) Larpenteur Fernwood C.

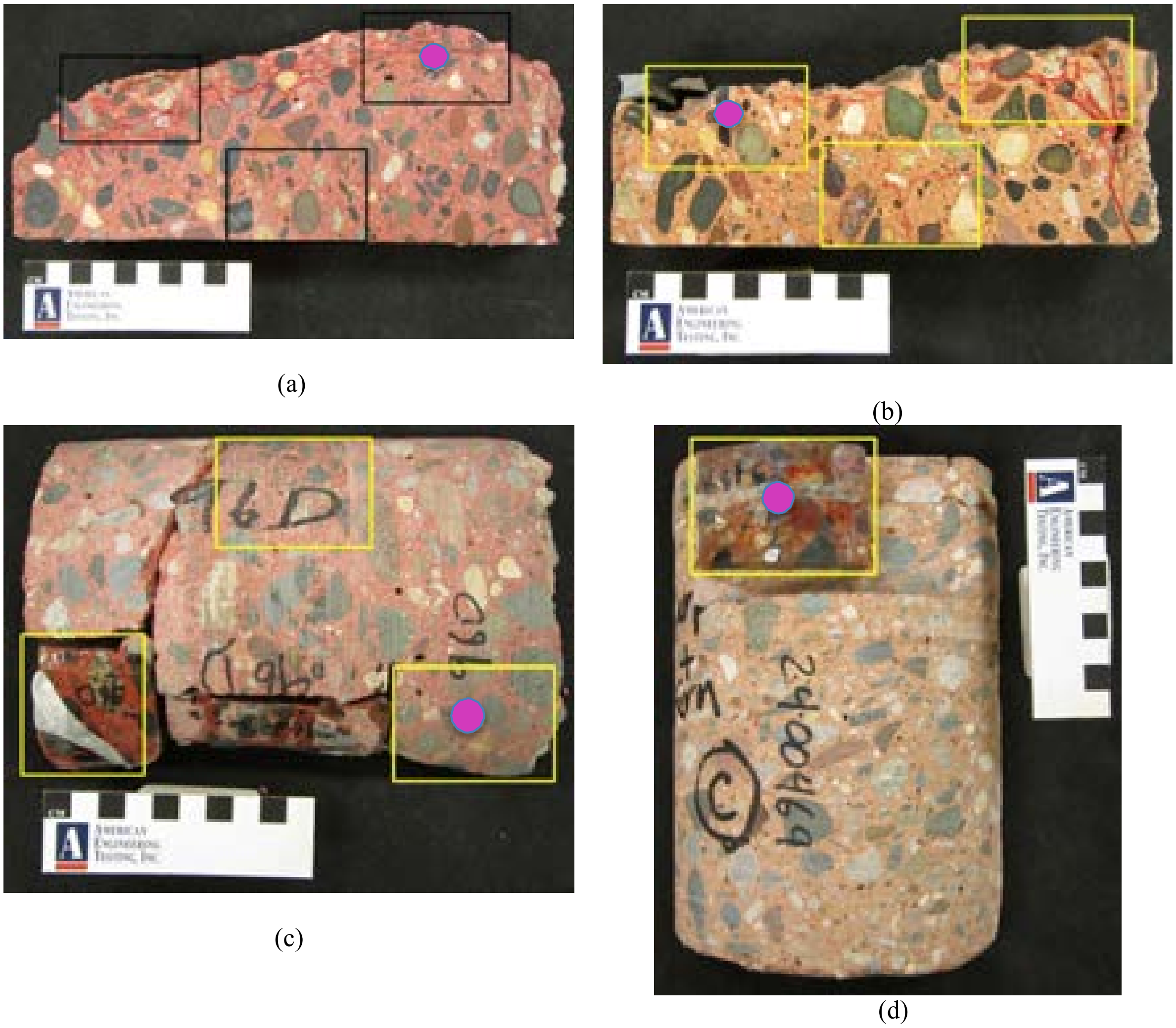
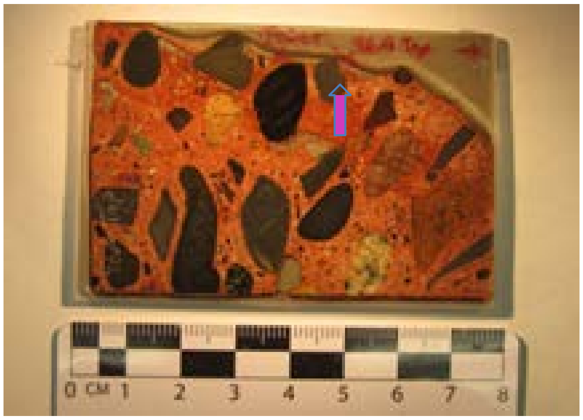
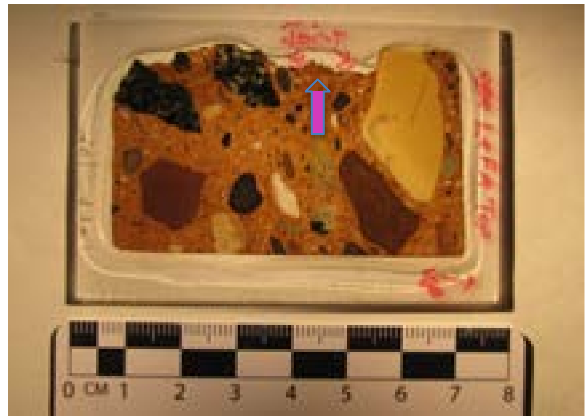


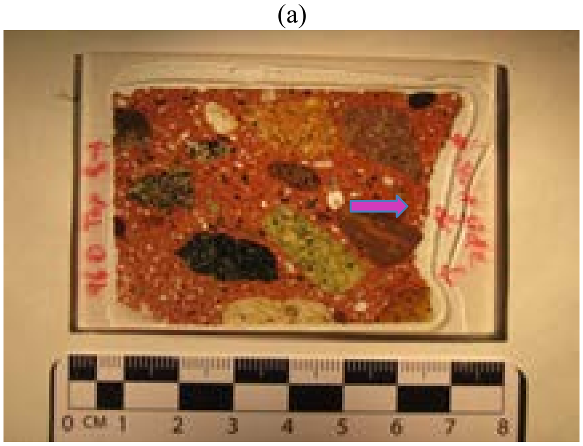
Figure 2. Areas selected to prepare specimens for analysis in the SEM. (a) 96A, (b) Larpenteur Fernwood A, (c) 96D, and (d) Larpenteur Fernwood C. The magenta dot indicates the specimens shown in Figure 3.



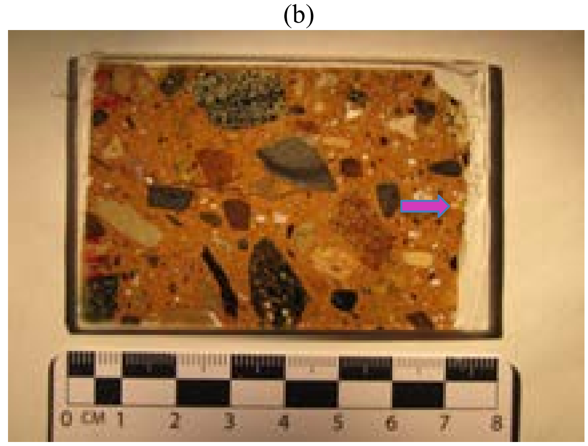
(a)



(b)



(c)



(d)

Figure 3. Specimens prepared for analysis in the SEM. (a) 96A, (b) Larpenteur & Fernwood A, (c) 96D, and (d) Larpenteur Fernwood C. Magenta arrow indicates location of the joint showing deterioration.

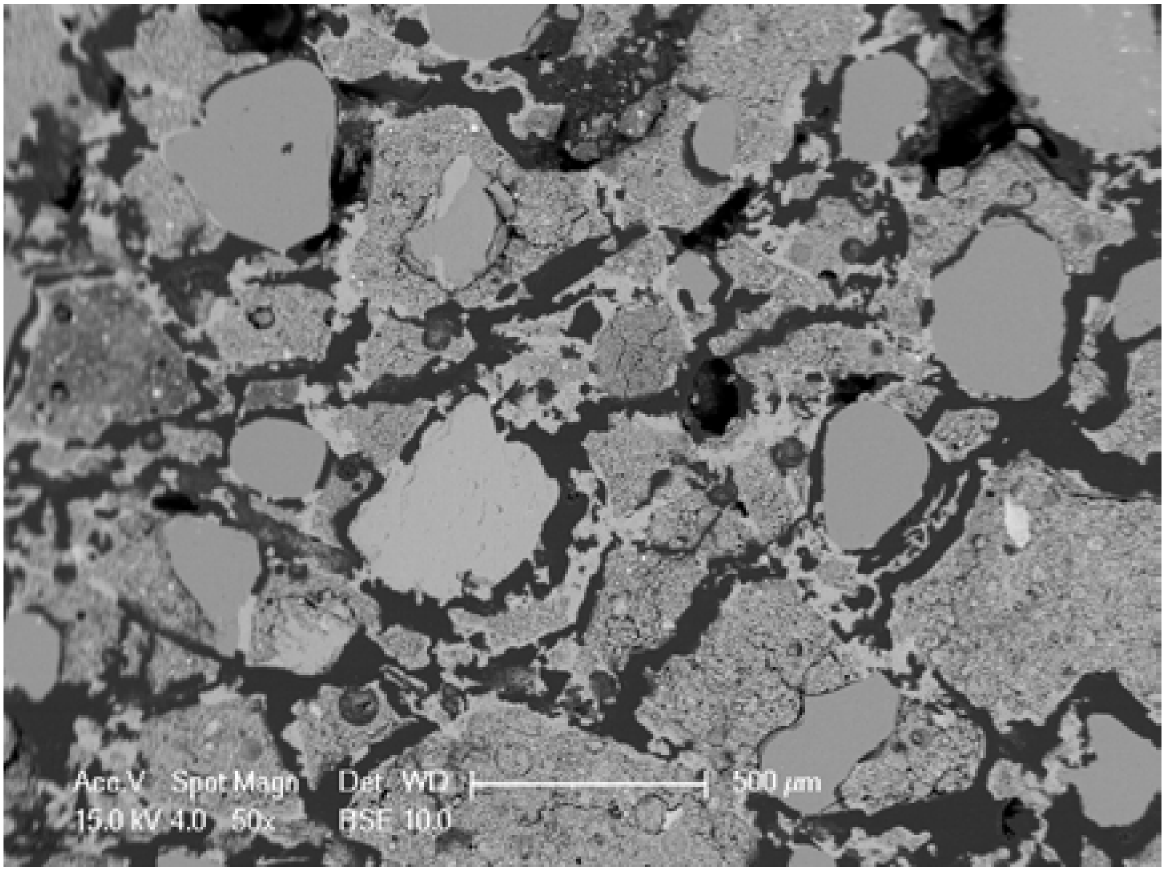


Figure 4. Backscattered electron image of badly cracked and weathered cement paste and aggregate at the joint. Specimen prepared from core sample 96A.

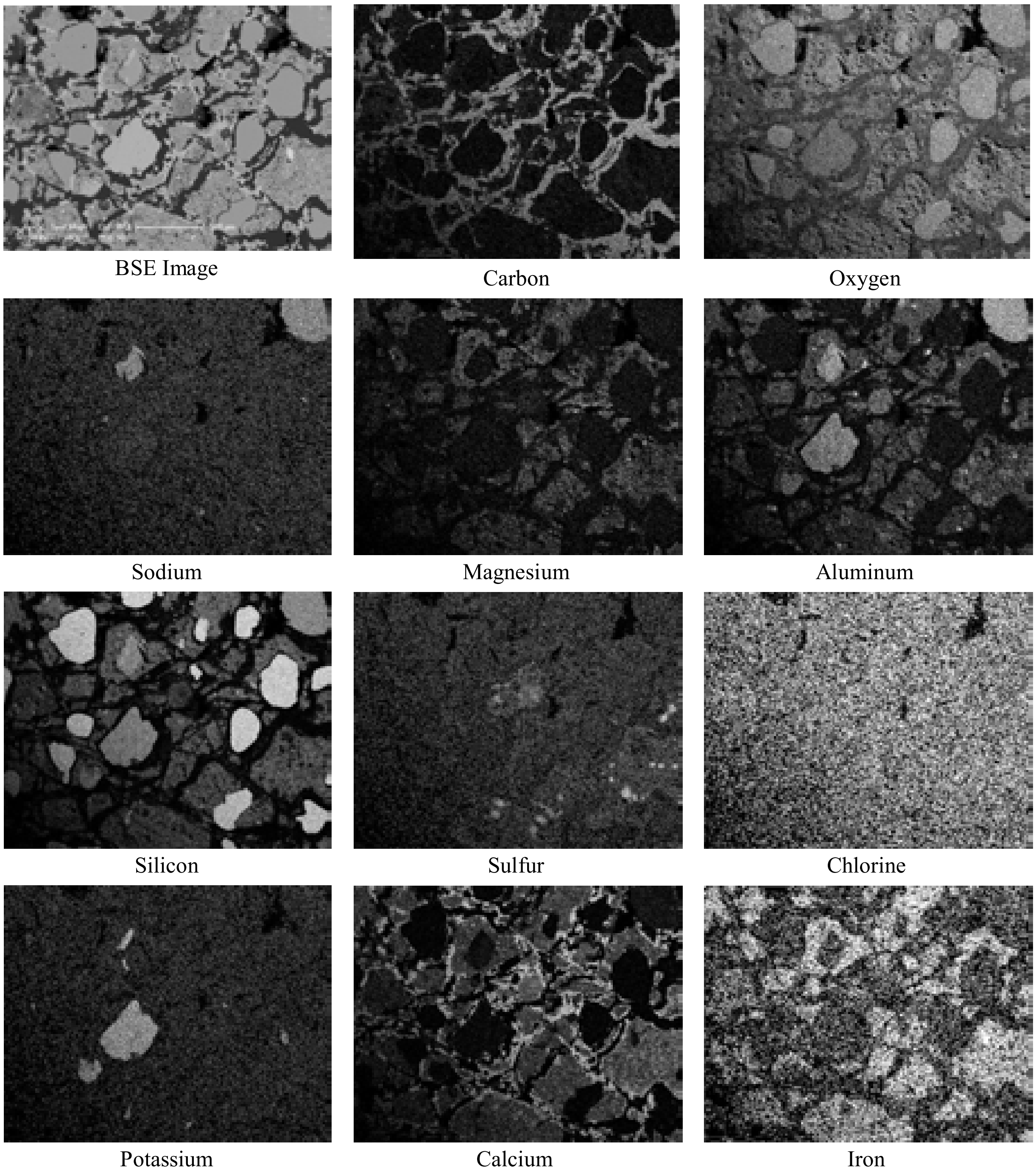


Figure 5. X-ray intensity maps of the same area shown in Figure 4.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

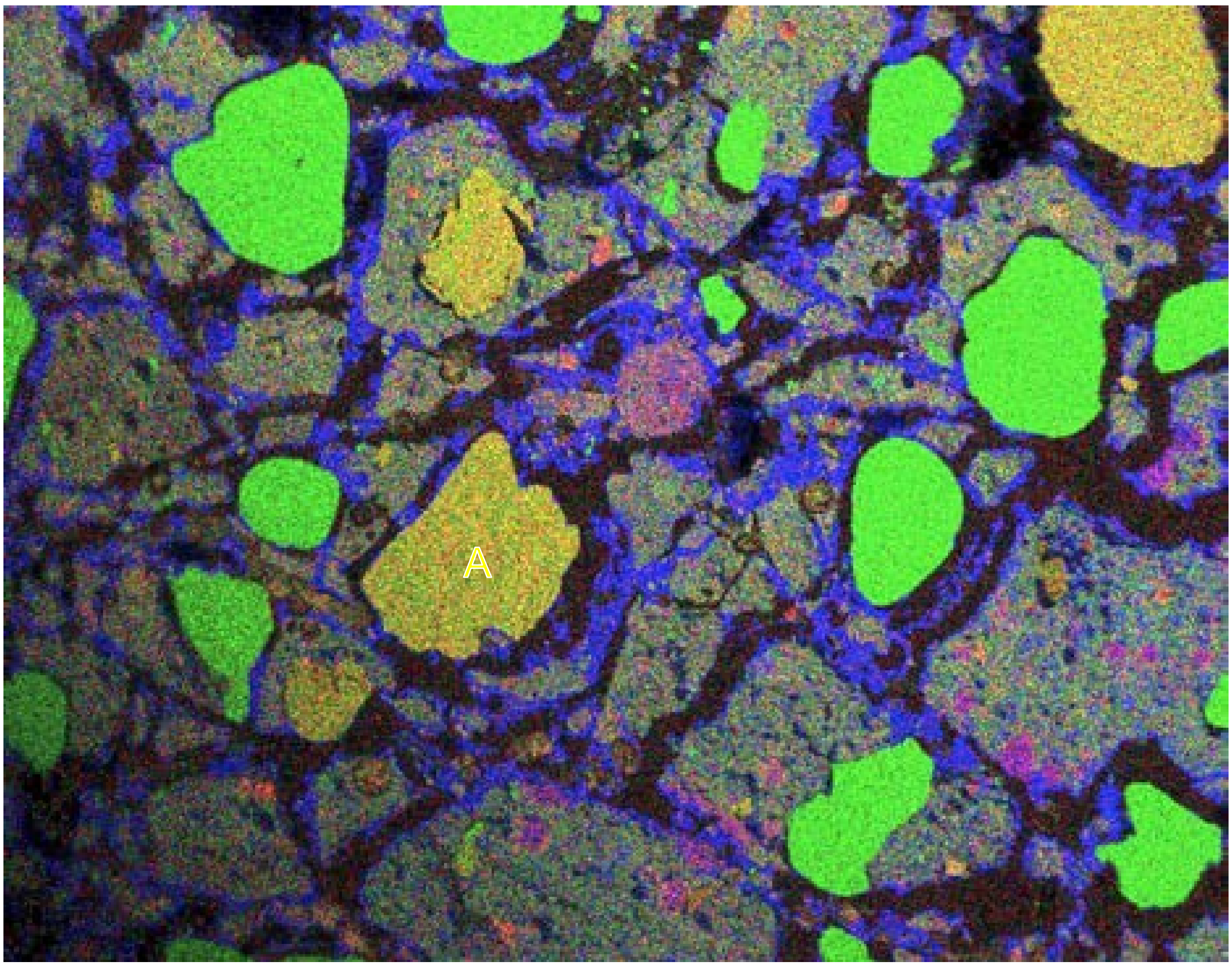


Figure 6. Combined x-ray intensity maps from the area shown in Figure 4 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color. The grain marked with A is shown in greater detail in Figure 11 and the associated x-ray maps in Figure 12 though Figure 16.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

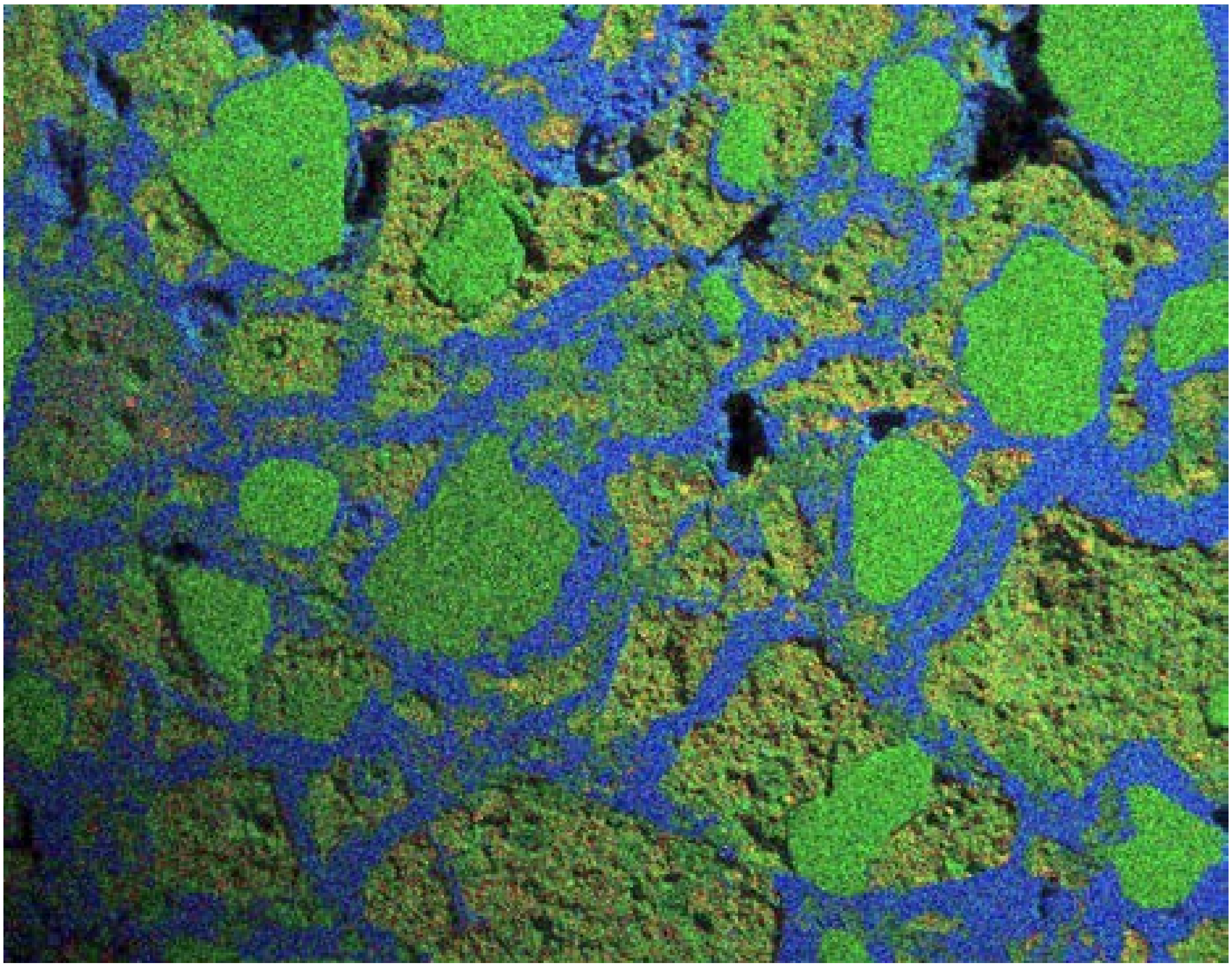


Figure 7. Combined x-ray intensity maps from the area shown in Figure 4 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	Si
G	Mg
Yellow	Si + Mg

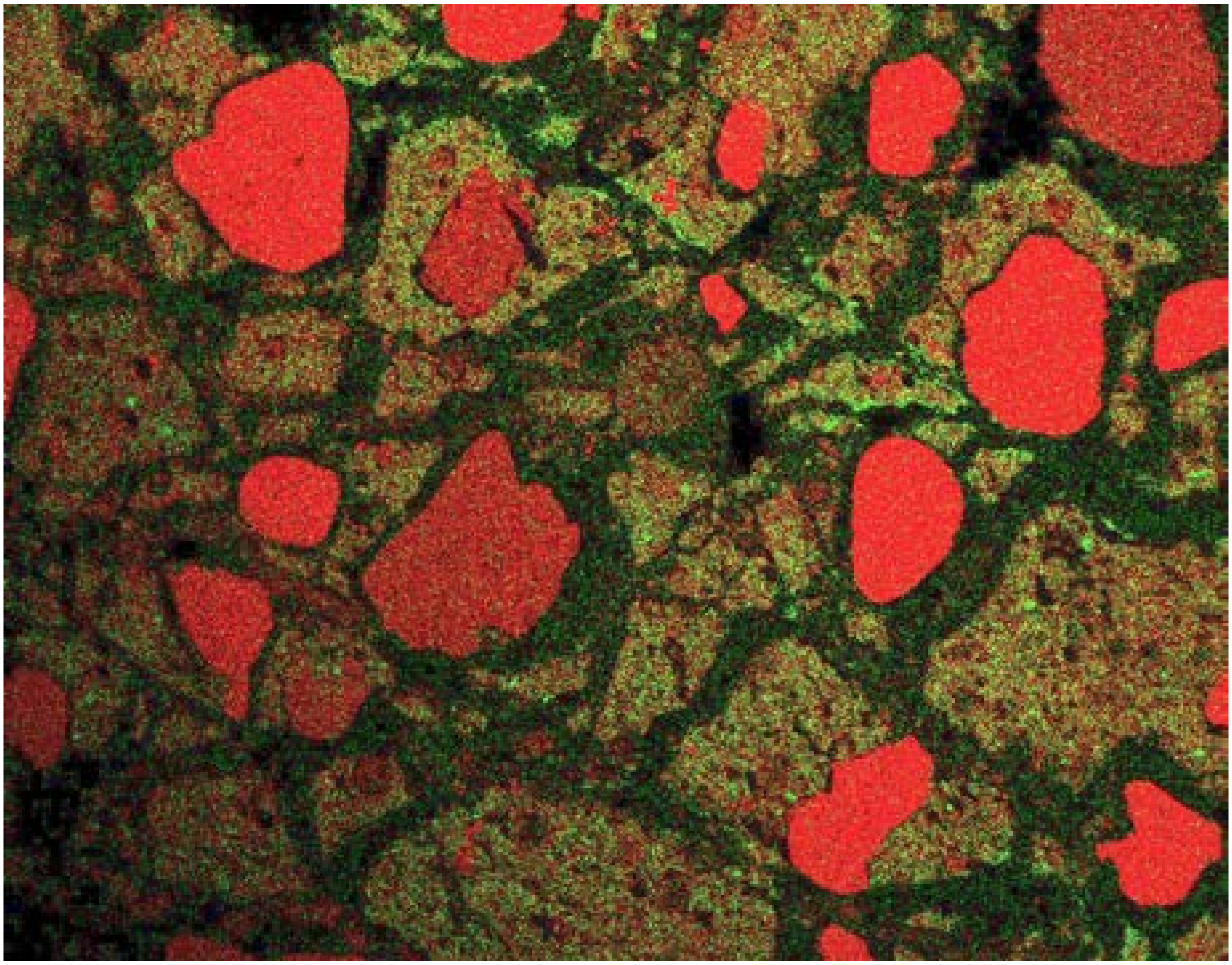


Figure 8. Combined x-ray intensity maps from the area shown in Figure 4 where maps for silicon (red color) and magnesium (green color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow) indicate varying rations of the elements combined to form that color.

R	Al
G	S
B	Ca
Yellow	Al + S
Purple	Al +Ca
Cyan	S + Ca

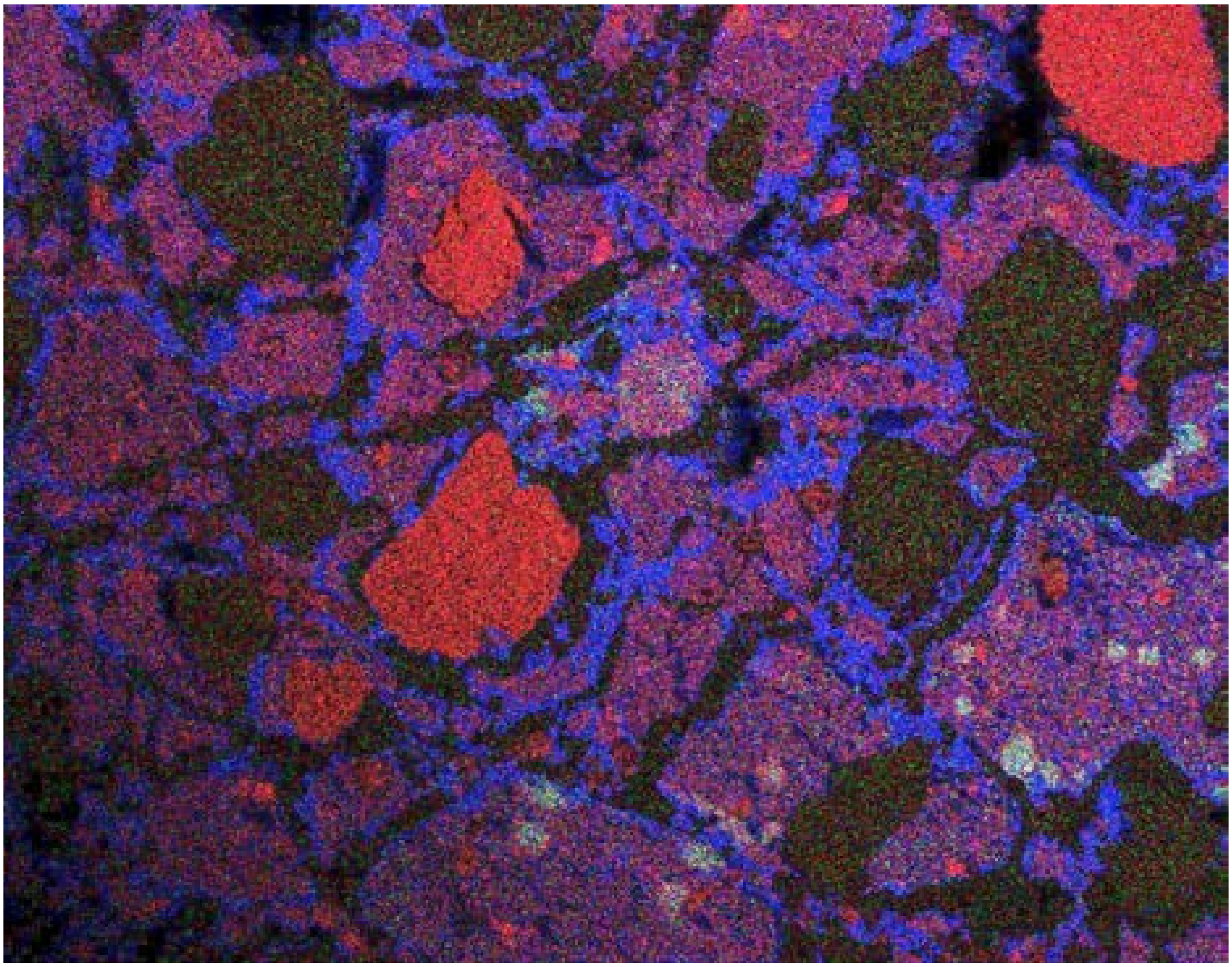


Figure 9. Combined x-ray intensity maps from the area shown in Figure 4 where maps for aluminum (red color), sulfur, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	K
G	Fe
B	Mg
Yellow	K + Fe
Purple	K + Mg
Cyan	Fe + Mg

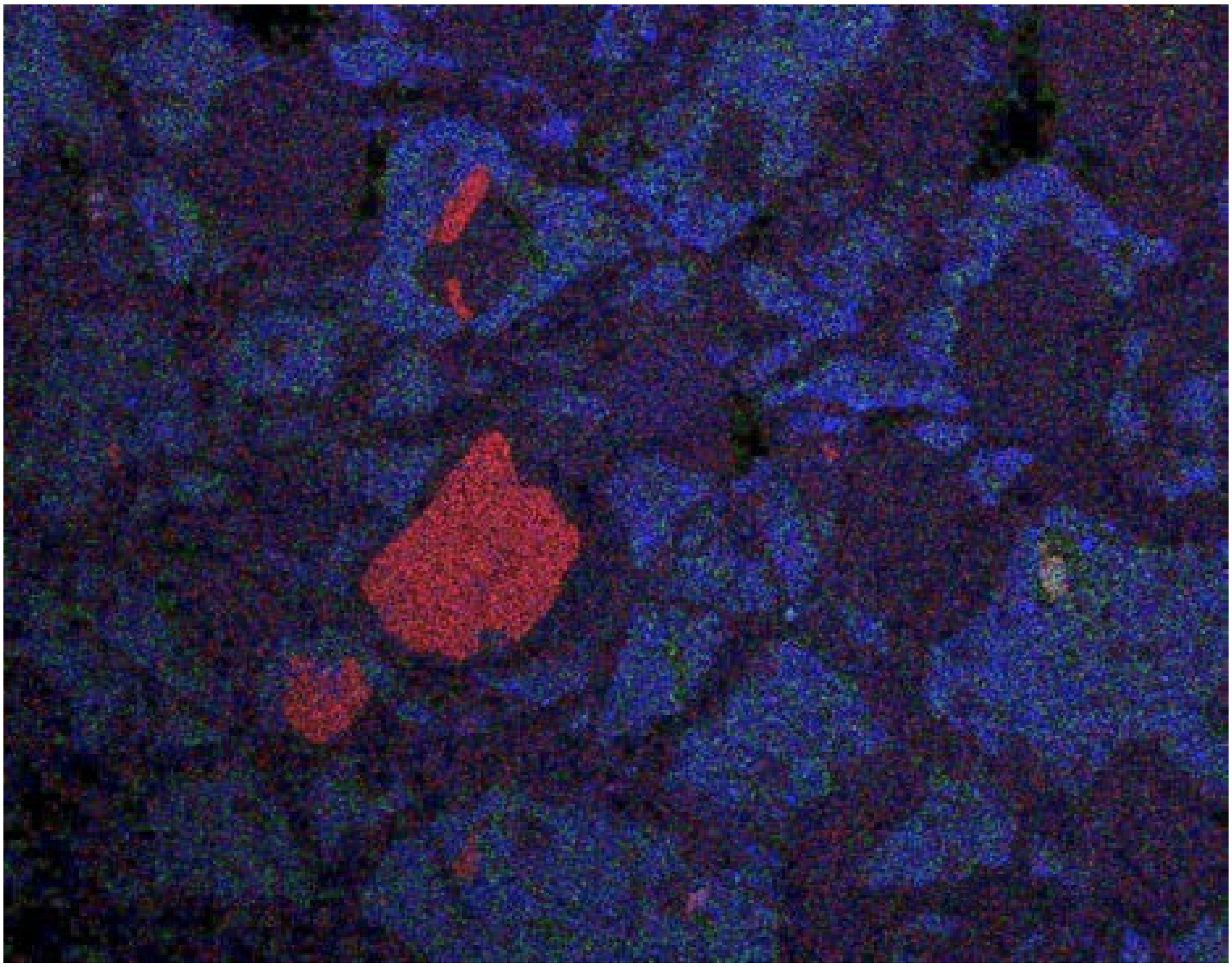


Figure 10. Combined x-ray intensity maps from the area shown in Figure 4 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

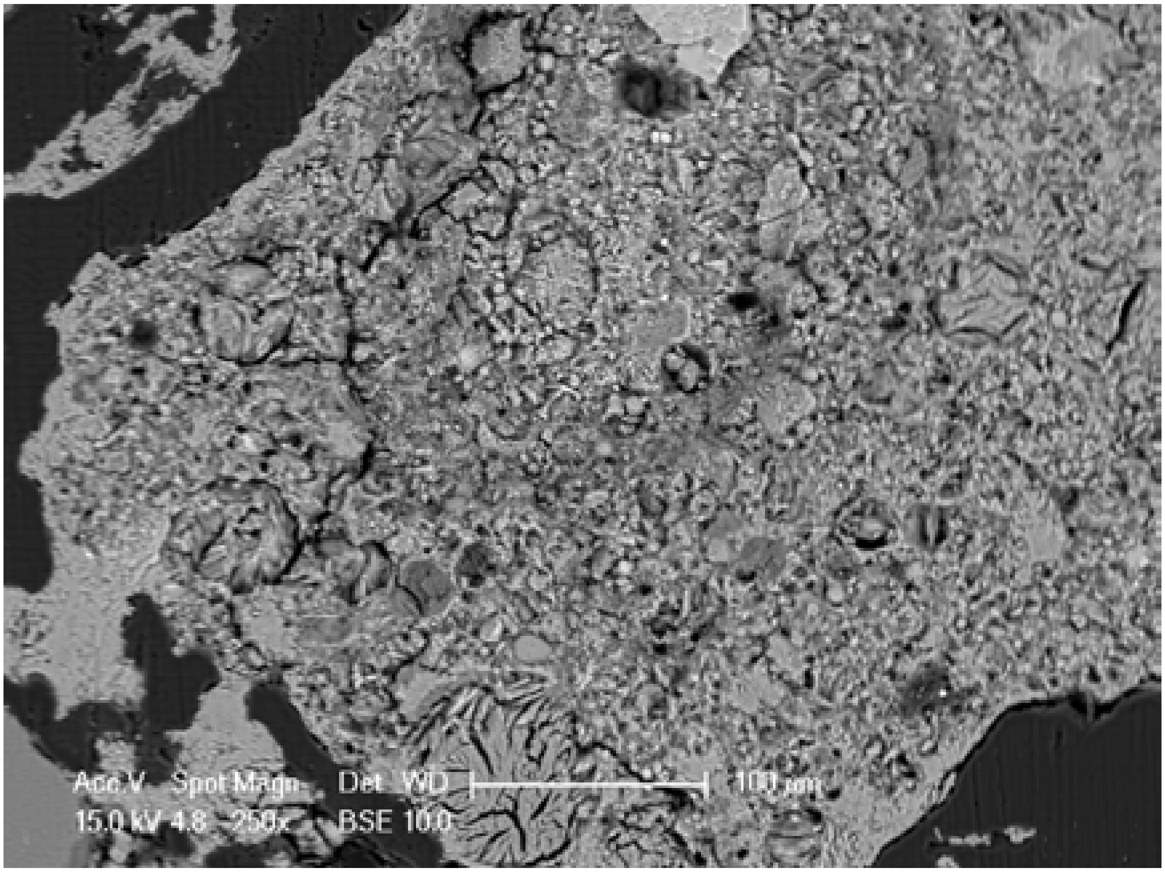


Figure 11. Backscattered electron image of grain A shown in Figure 6.

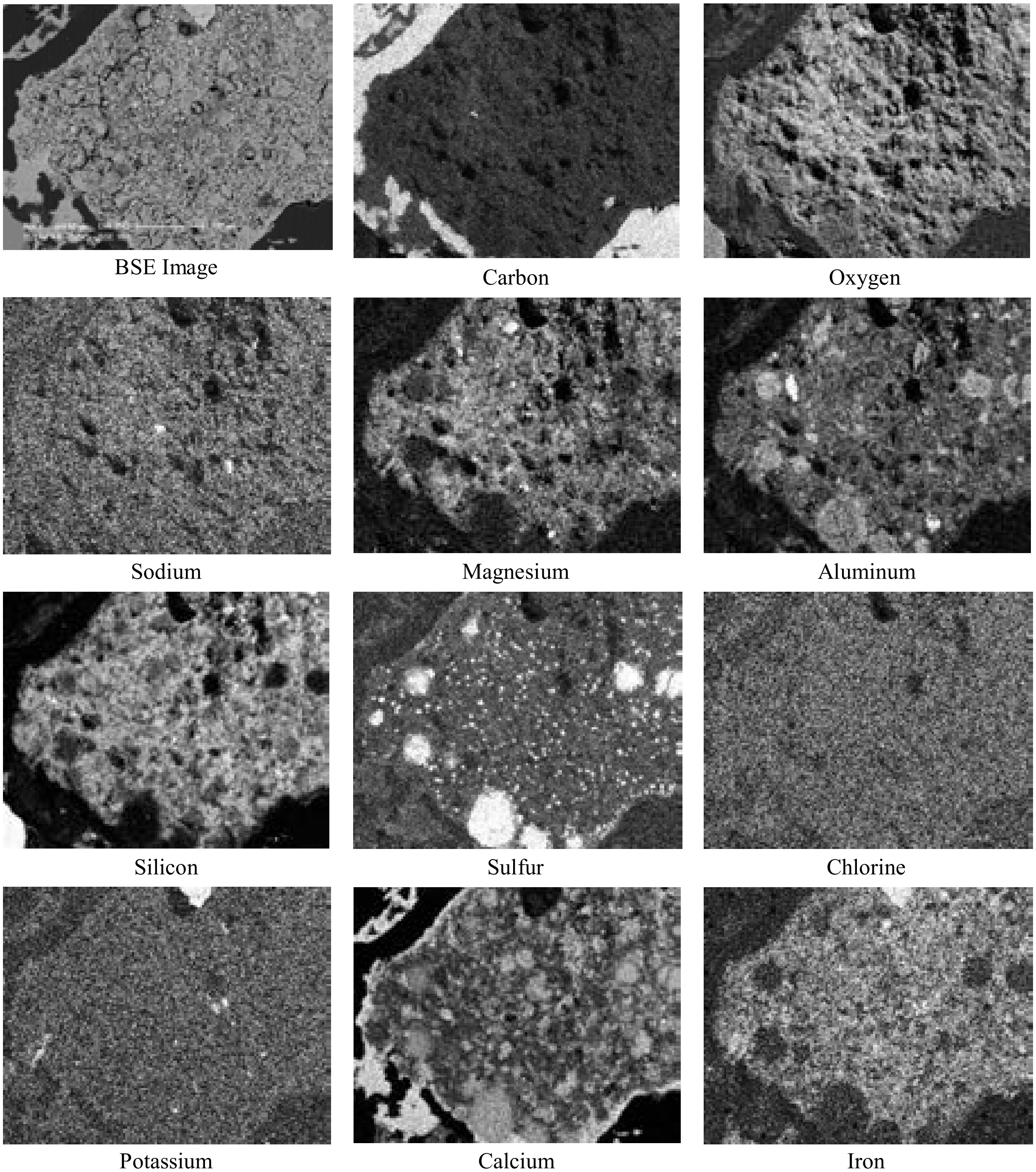


Figure 12. X-ray intensity maps of the same area shown in Figure 11.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

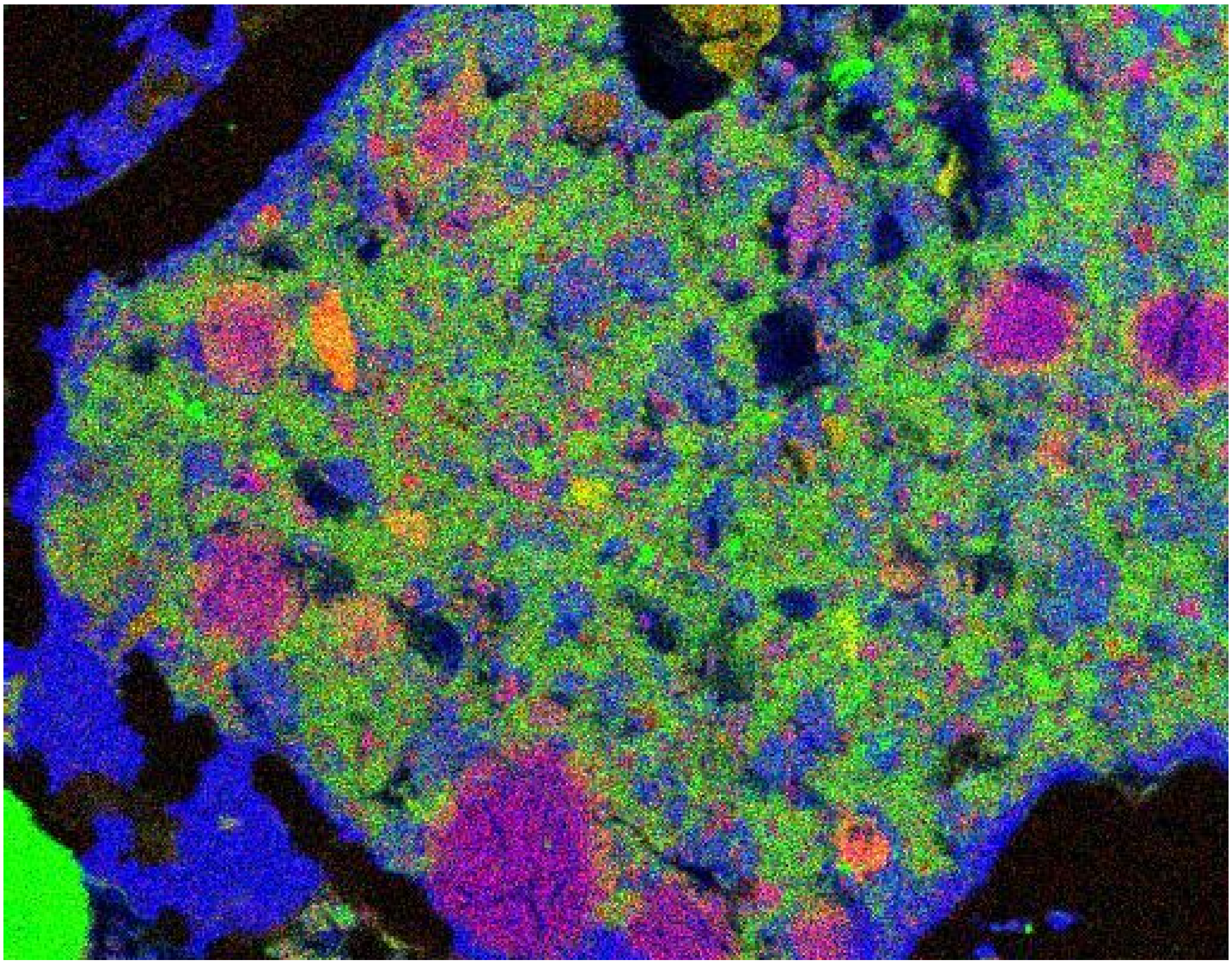


Figure 13. Combined x-ray intensity maps from the area shown in Figure 11 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C

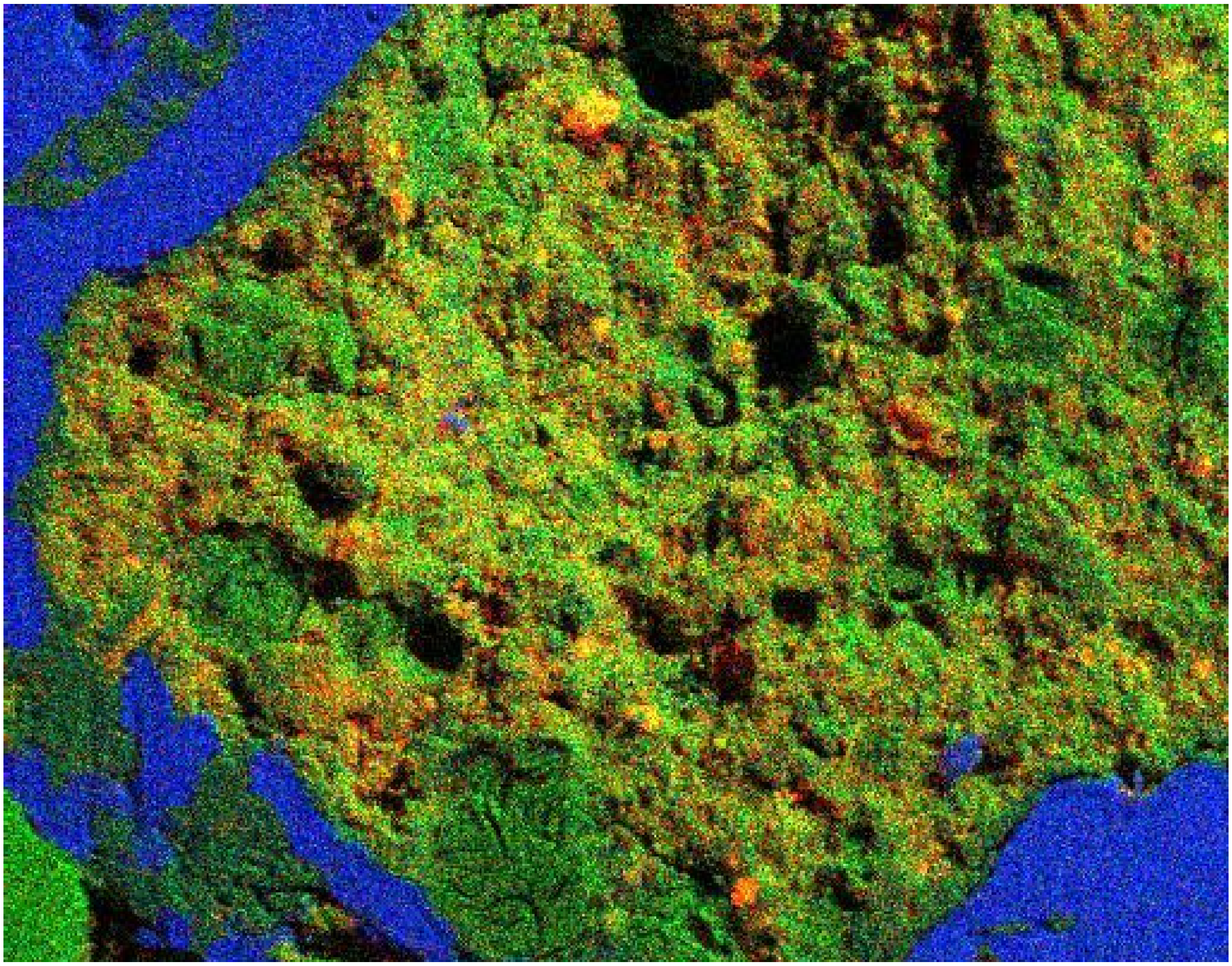


Figure 14. Combined x-ray intensity maps from the area shown in Figure 11 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow) indicate varying rations of the elements combined to form that color.

R	Al
G	S
B	Ca
Yellow	Al + S
Purple	Al +Ca
Cyan	S + Ca

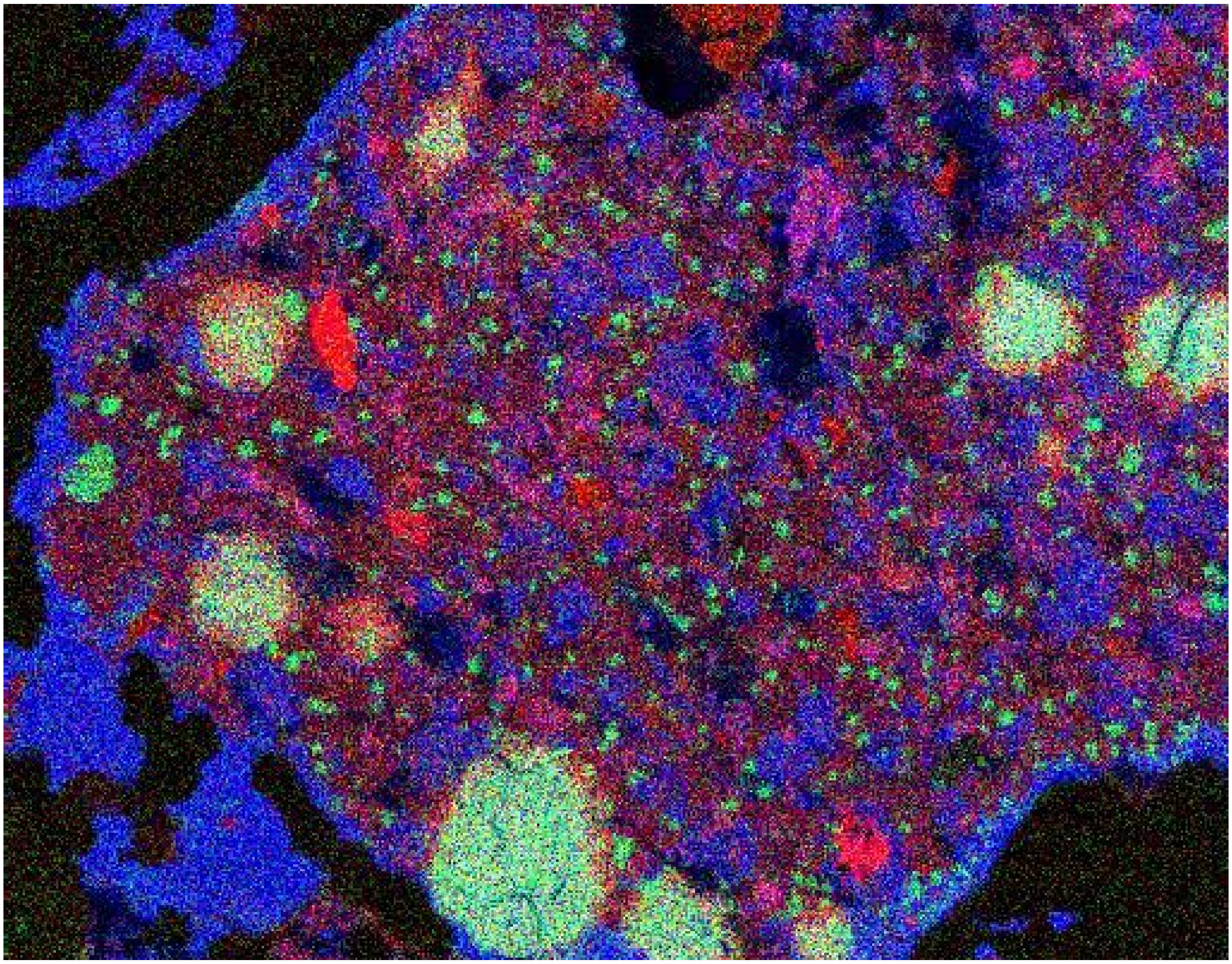


Figure 15. Combined x-ray intensity maps from the area shown in Figure 11 where maps for aluminum (red color), sulfur, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	K
G	Fe
B	Mg
Yellow	K + Fe
Purple	K + Mg
Cyan	Fe + Mg

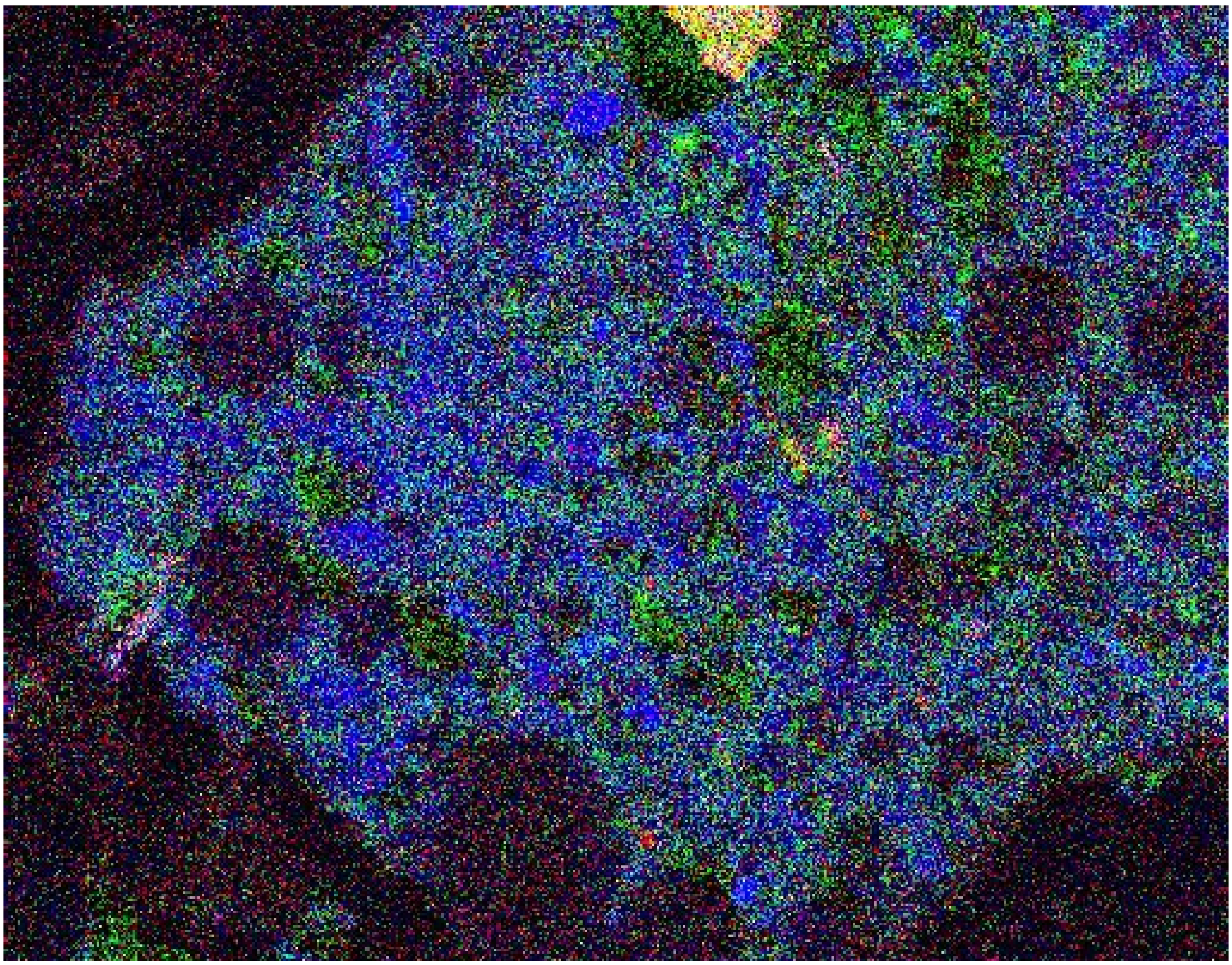


Figure 16. Combined x-ray intensity maps from the area shown in Figure 11 where maps for potassium (red color), iron, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

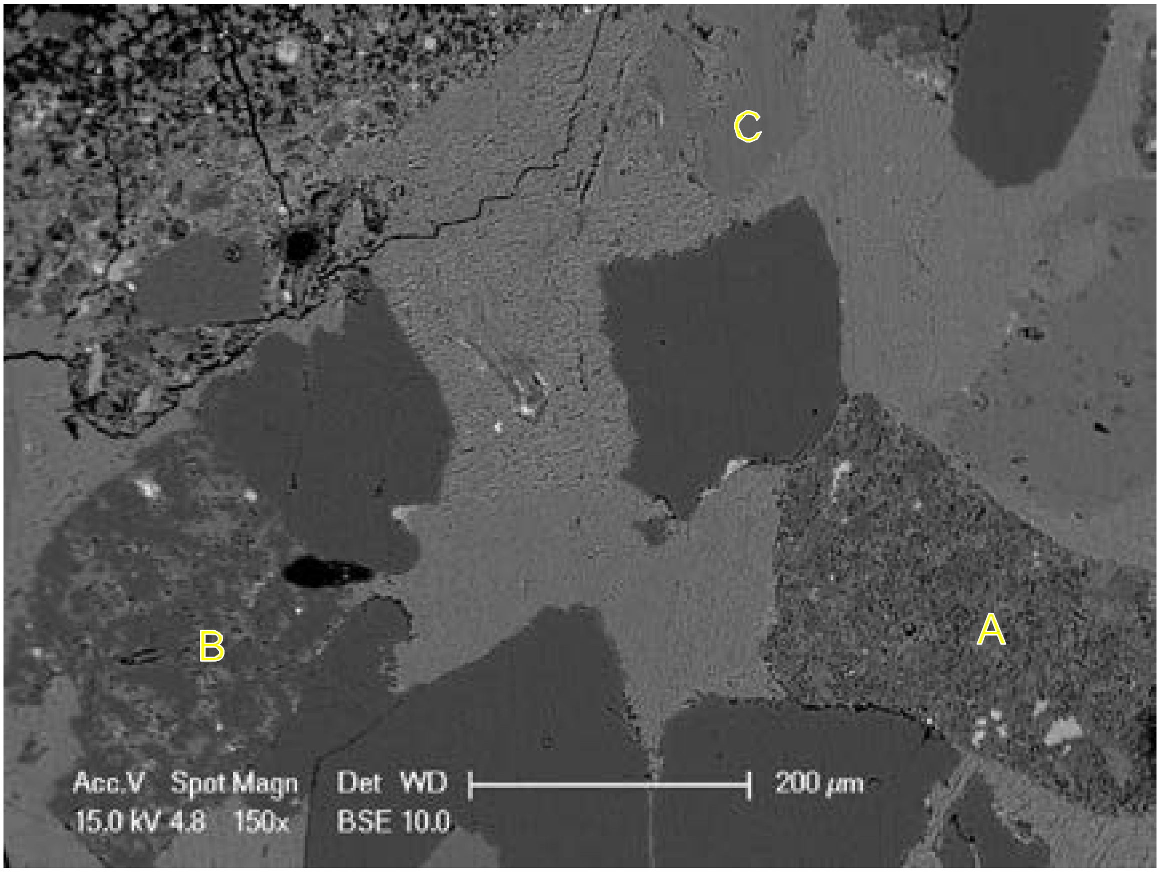


Figure 17. Backscattered electron image of chemically altered cement paste. Massive calcium carbonate forms the matrix around aggregates. Specimen prepared from core sample 96A.

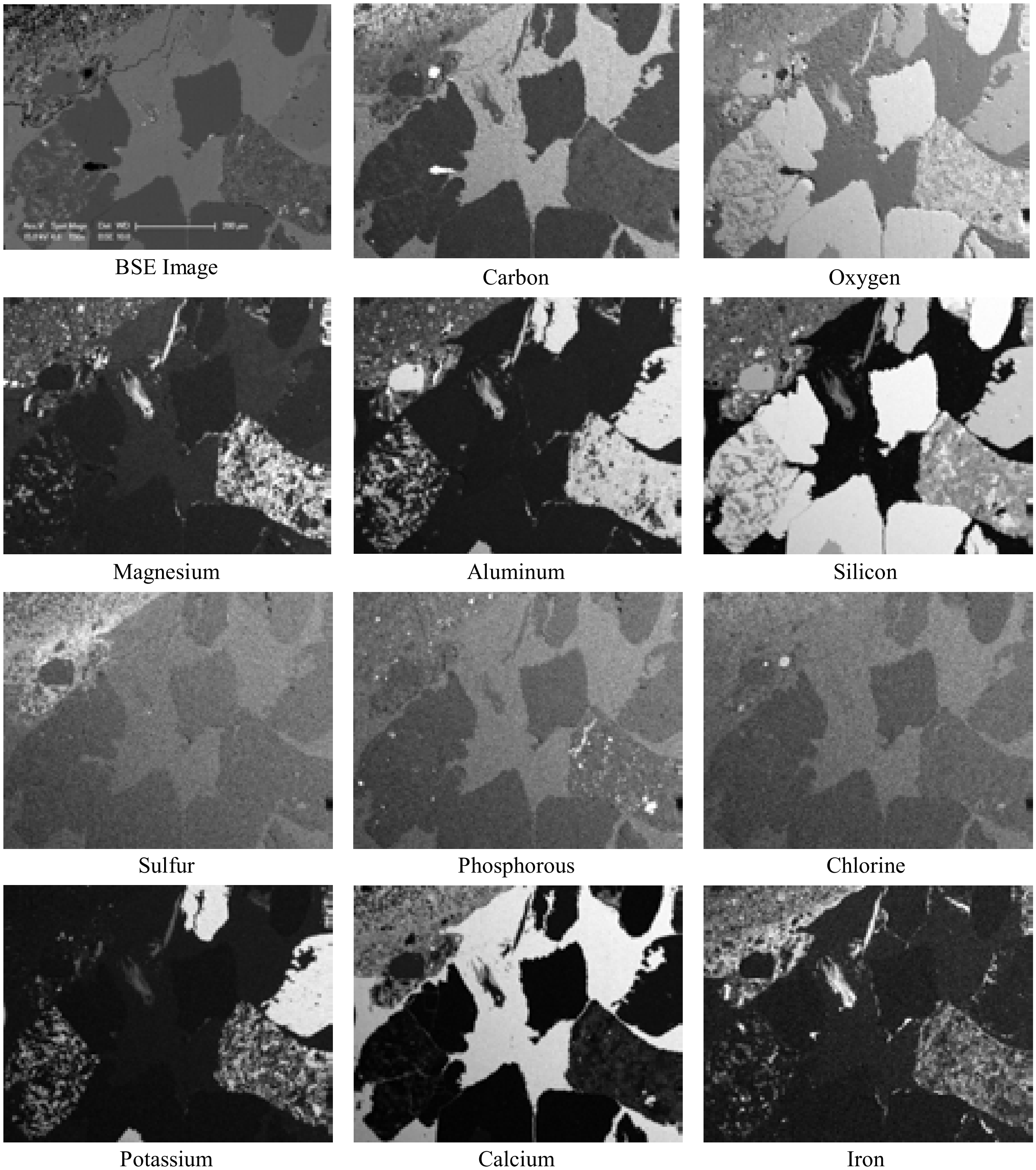


Figure 18. X-ray intensity maps of the same area shown in Figure 17.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

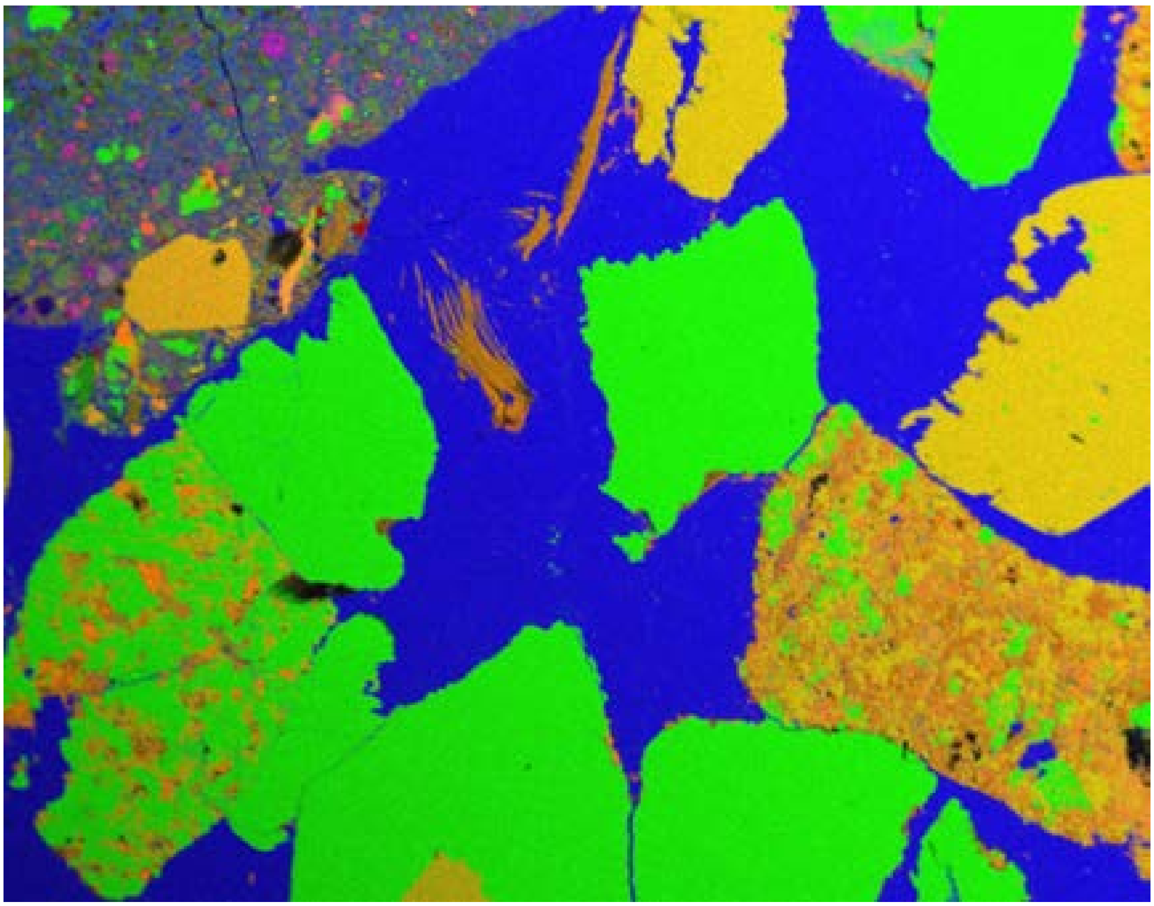


Figure 19. Combined x-ray intensity maps from the area shown in Figure 17 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	K
G	Fe
B	Mg
Yellow	K + Fe
Purple	K + Mg
Cyan	Fe + Mg

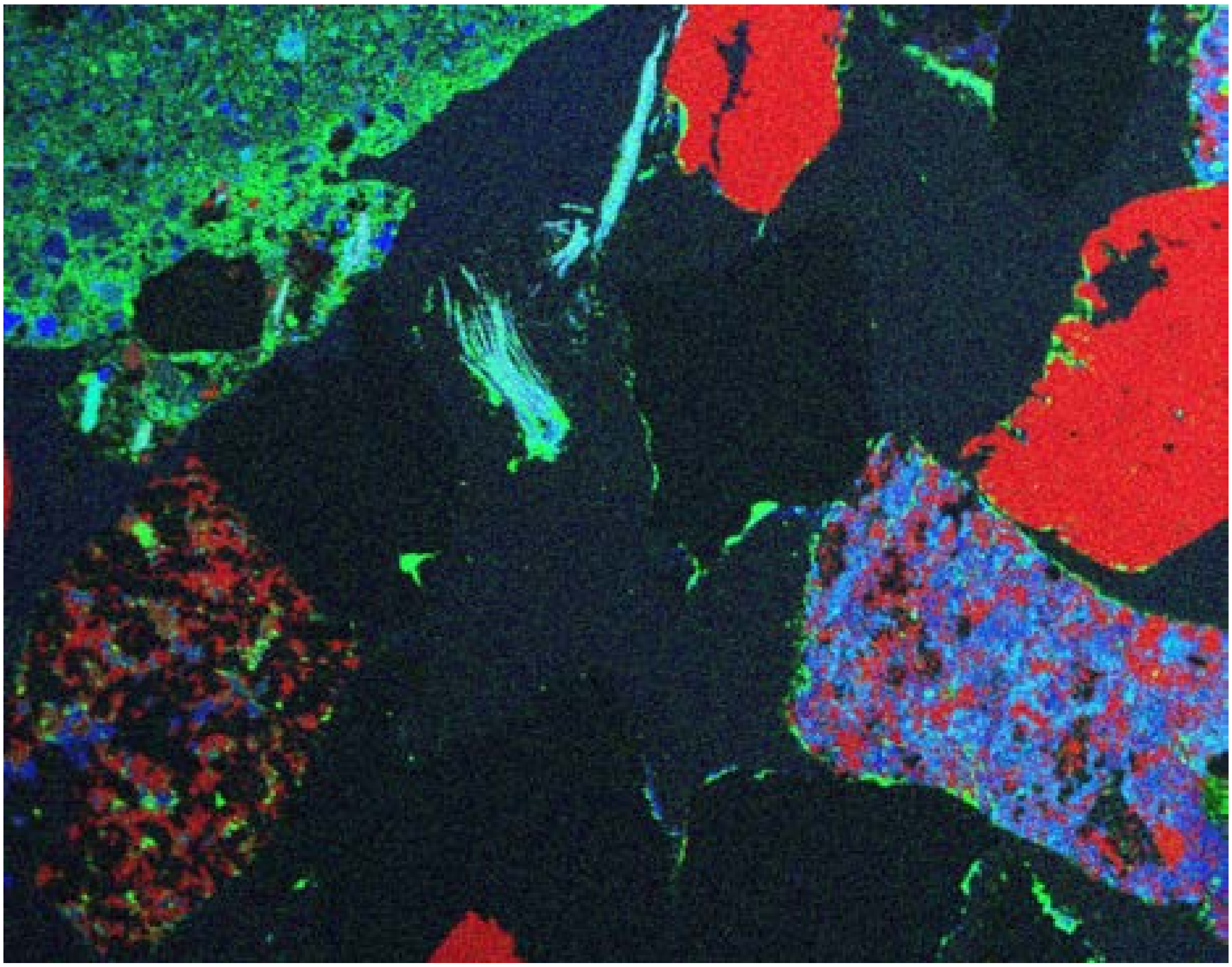


Figure 20. Combined x-ray intensity maps from the area shown in Figure 17 where maps for potassium (red color), iron, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	P
G	Ca
B	Mg
Yellow	P + Ca
Purple	P + Mg
Cyan	Ca + Mg

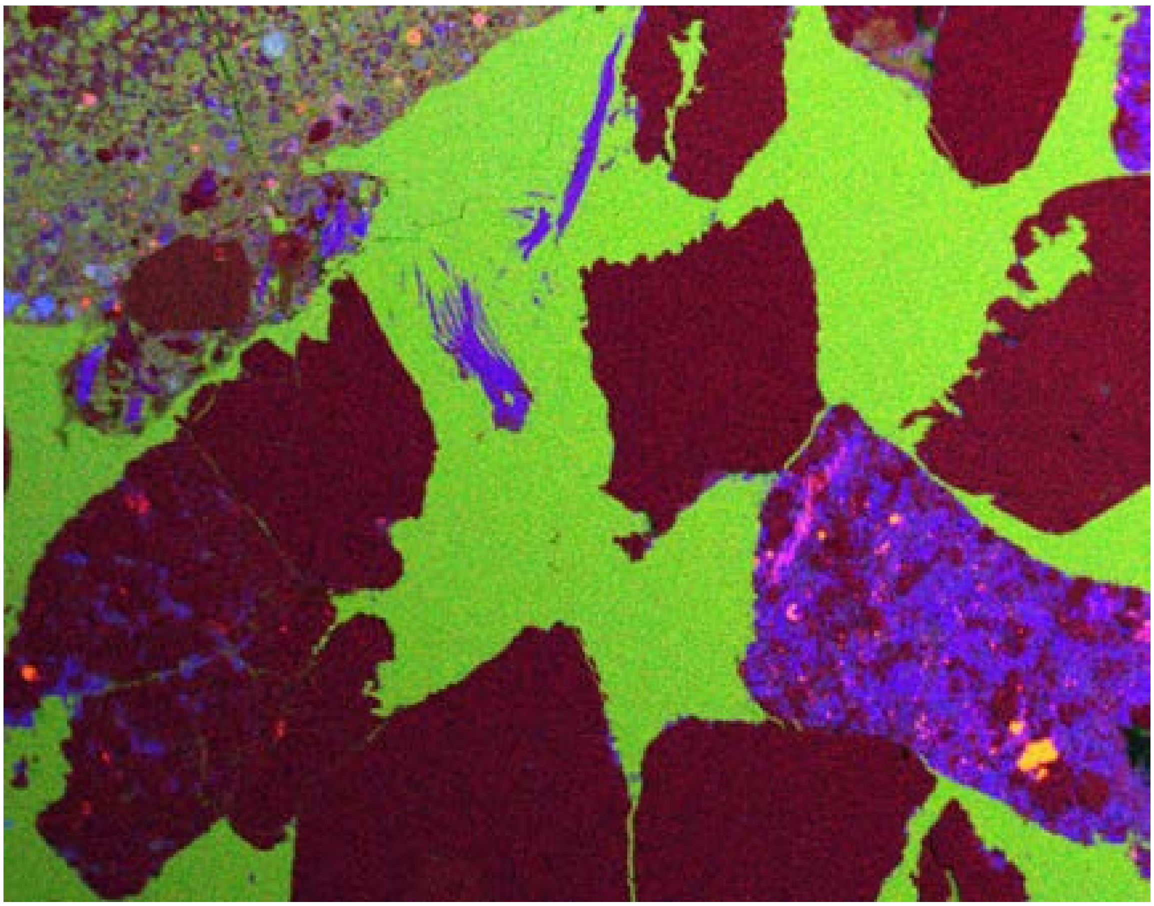


Figure 21. Combined x-ray intensity maps from the area shown in Figure 17 where maps for phosphorous (red color), calcium, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying rations of the elements combined to form that color.

R	
G	Fe
B	Mg
Cyan	Fe + Mg

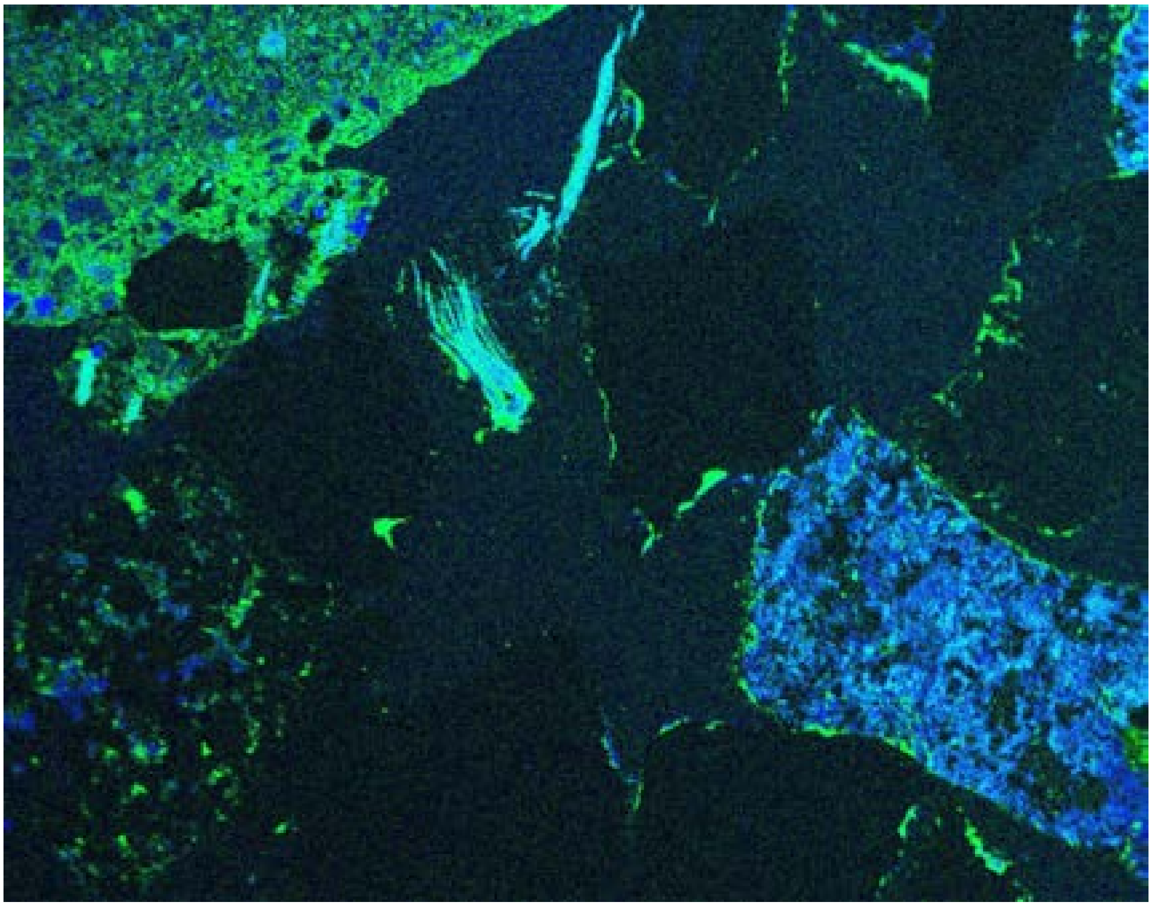


Figure 22. Combined x-ray intensity maps from the area shown in Figure 17 where maps for iron (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., cyan) indicate varying rations of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

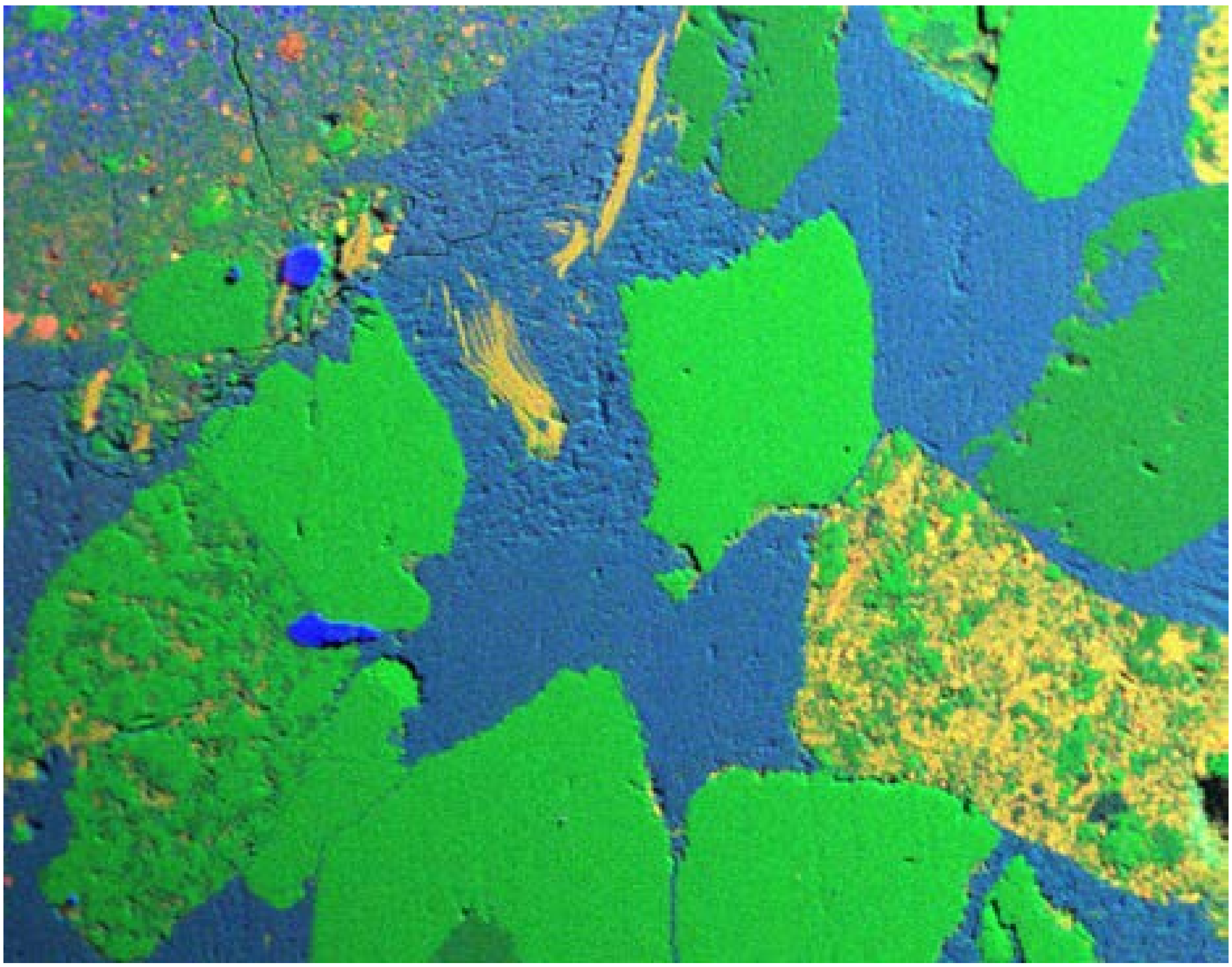


Figure 23. Combined x-ray intensity maps from the area shown in Figure 17 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange) indicate varying rations of the elements combined to form that color.

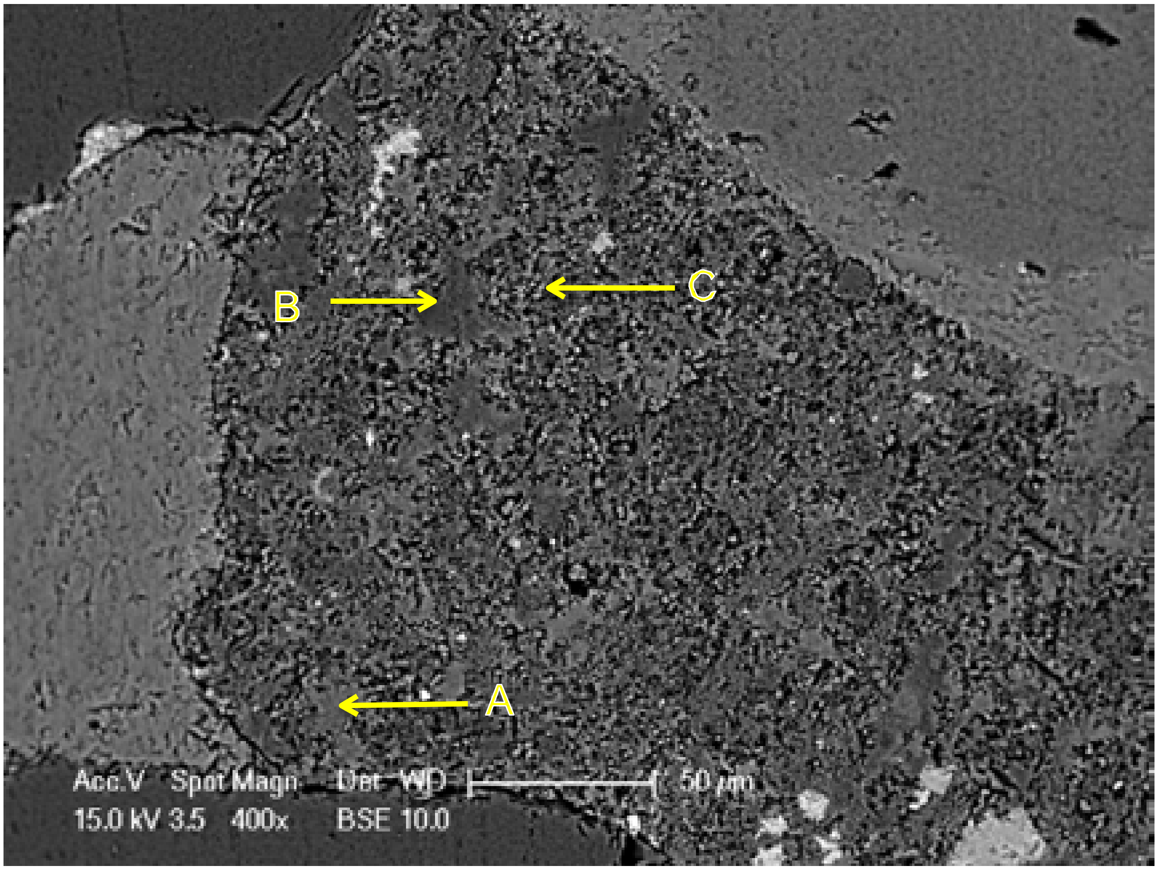


Figure 24. Backscattered electron image of grain A shown in Figure 17. Areas marked A, B, and C represent analyses shown in Table 2.

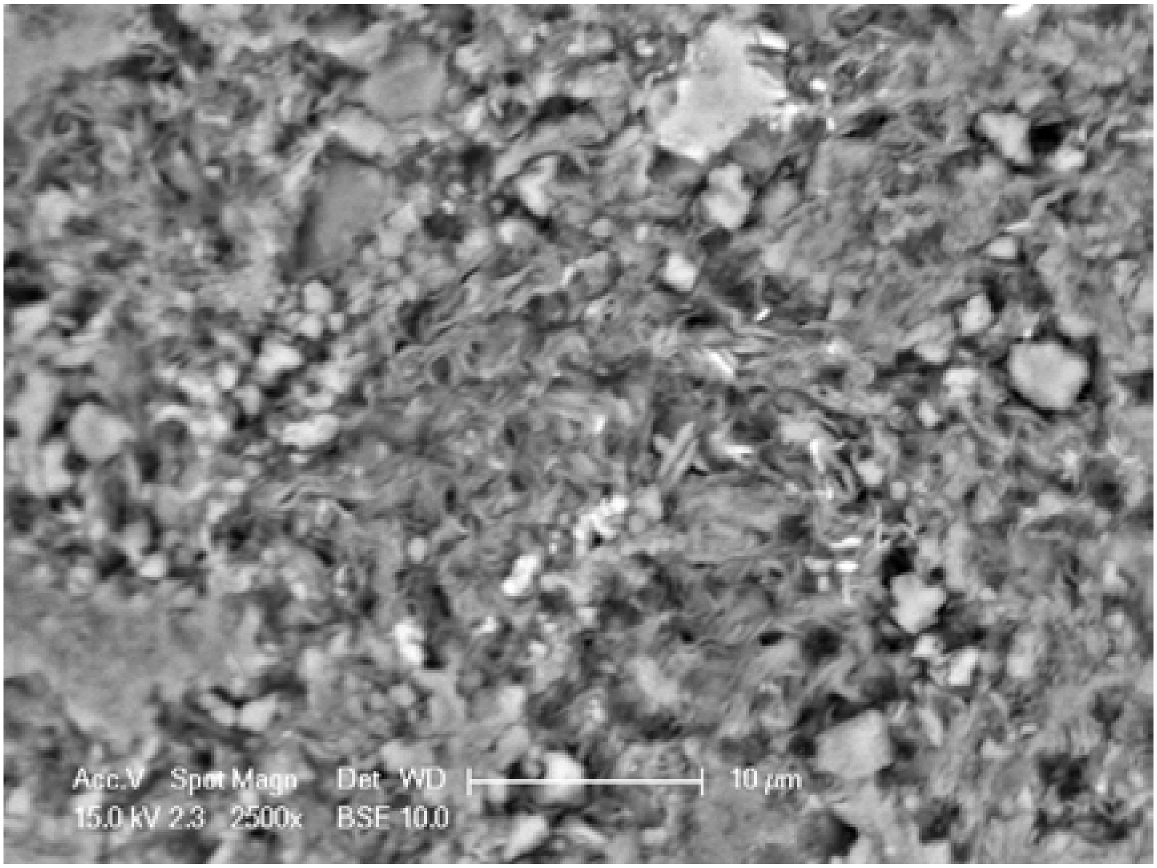
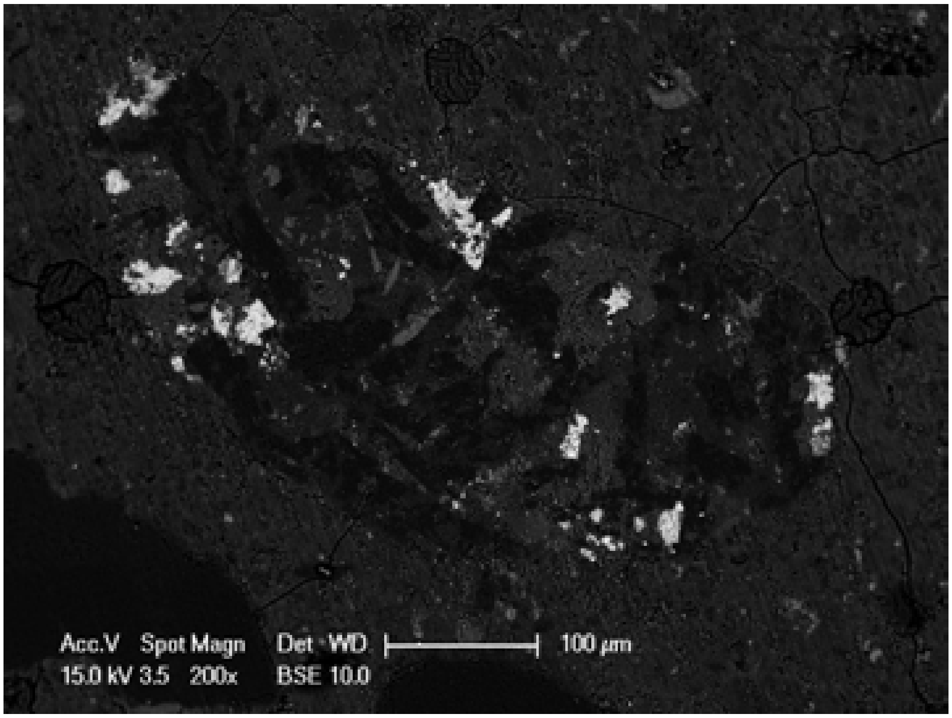
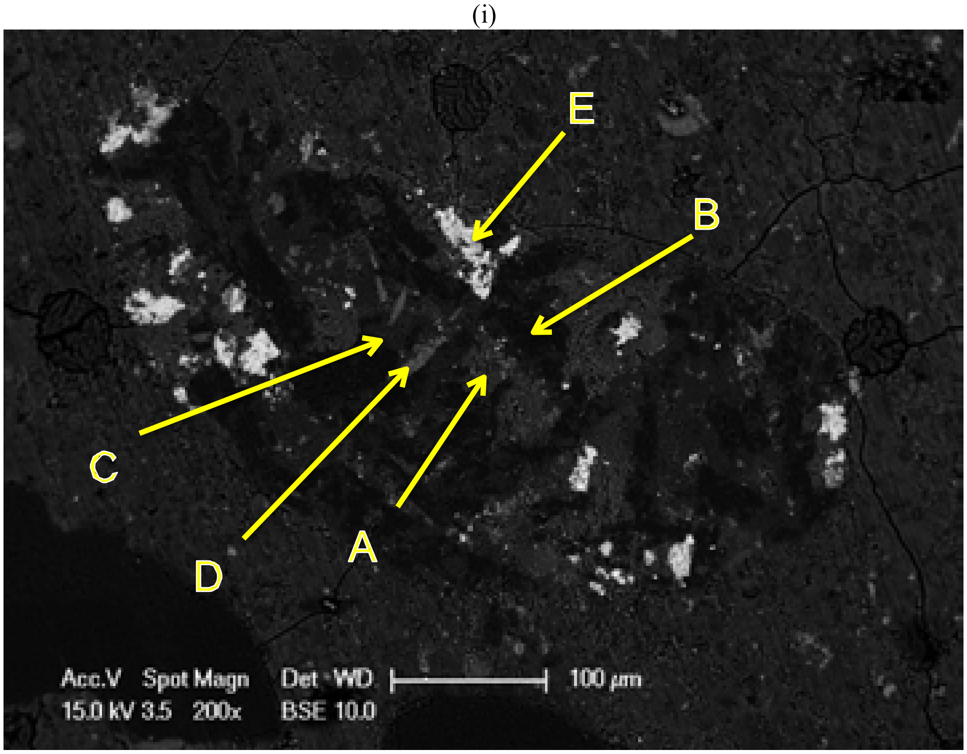


Figure 25. Backscattered electron image of area C shown in Figure 24.



(i)



(ii)

Figure 26. Backscattered electron image of unreacted apatite-bearing feldspar. Both images (i) and (ii) are the same. Micrograph (ii) is labeled to identify analysis areas for results shown in Table 3.

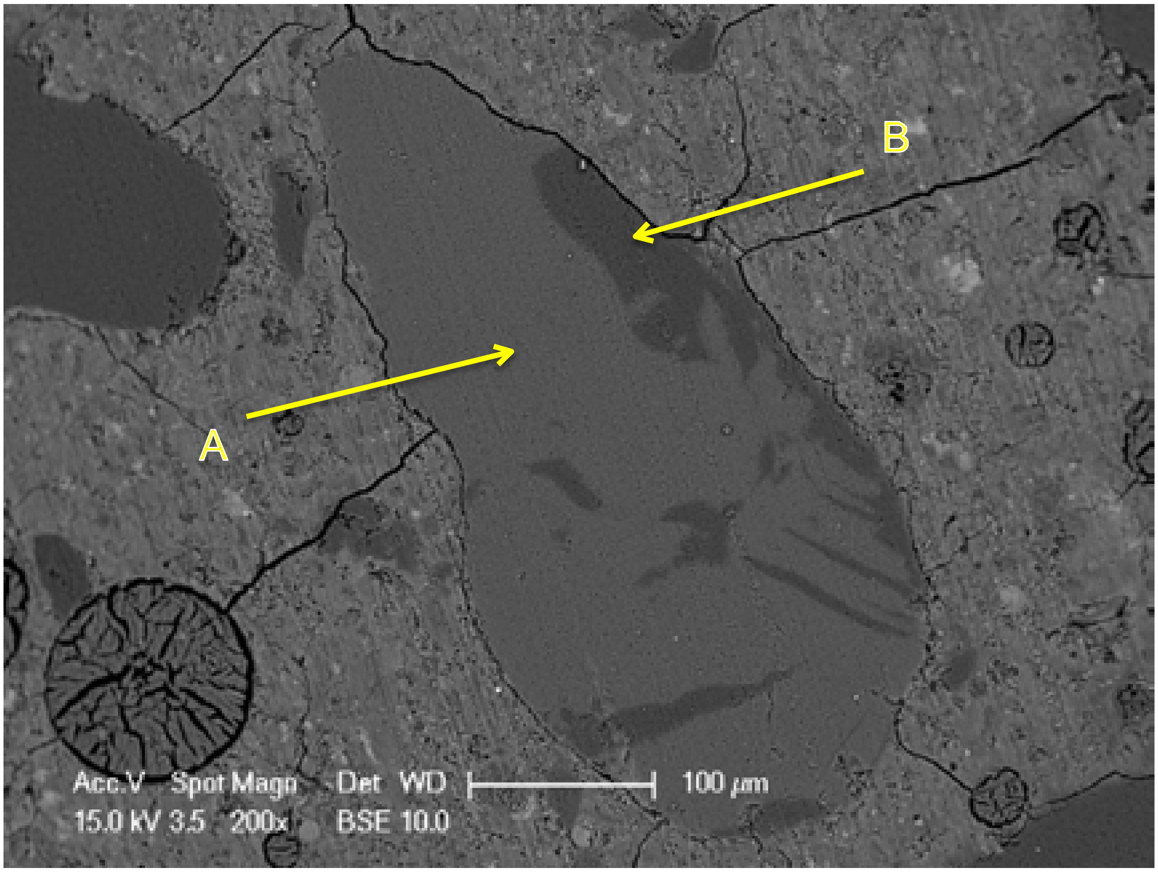


Figure 27. Example of other felsic aggregate type. Analysis areas A and B correspond to results presented in Table 4. Specimen prepared from core sample 96A.

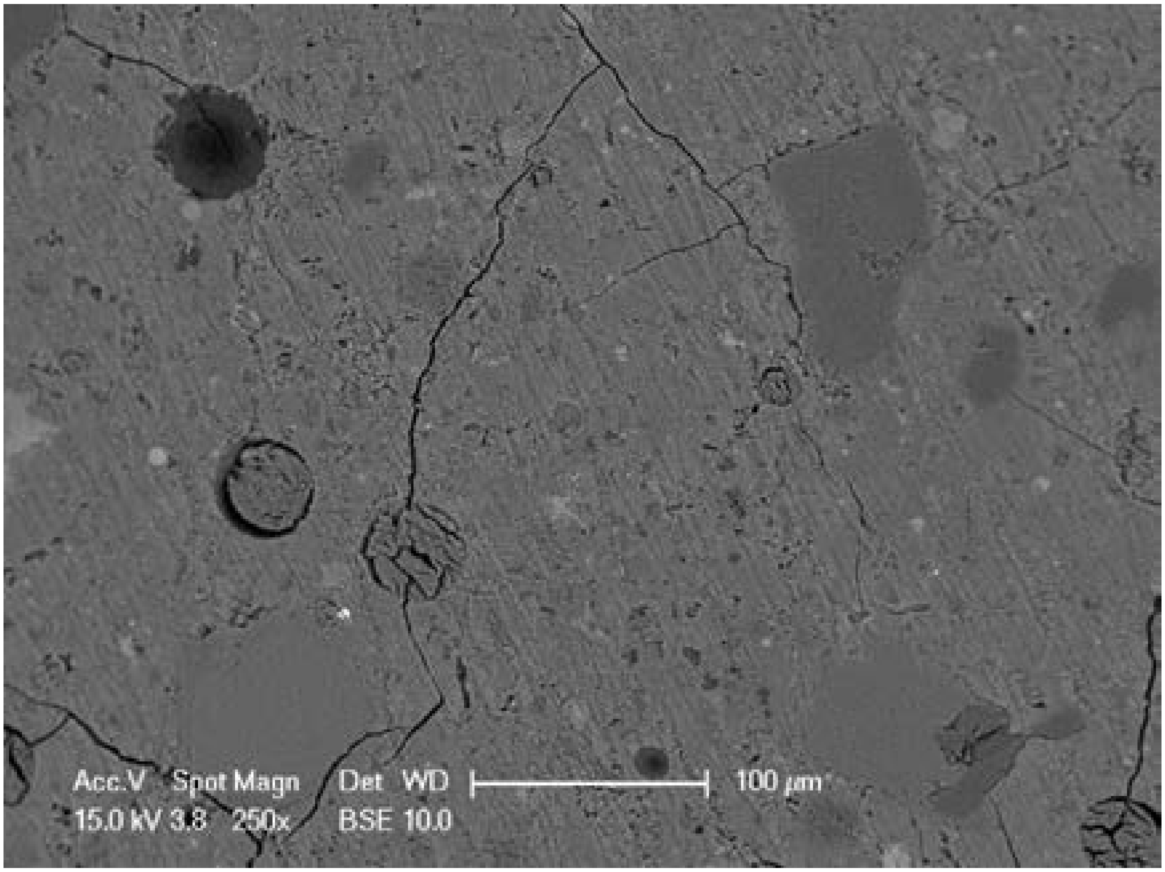


Figure 28. Backscattered electron image of cement paste away from the joint. Specimen prepared from core sample 96A.

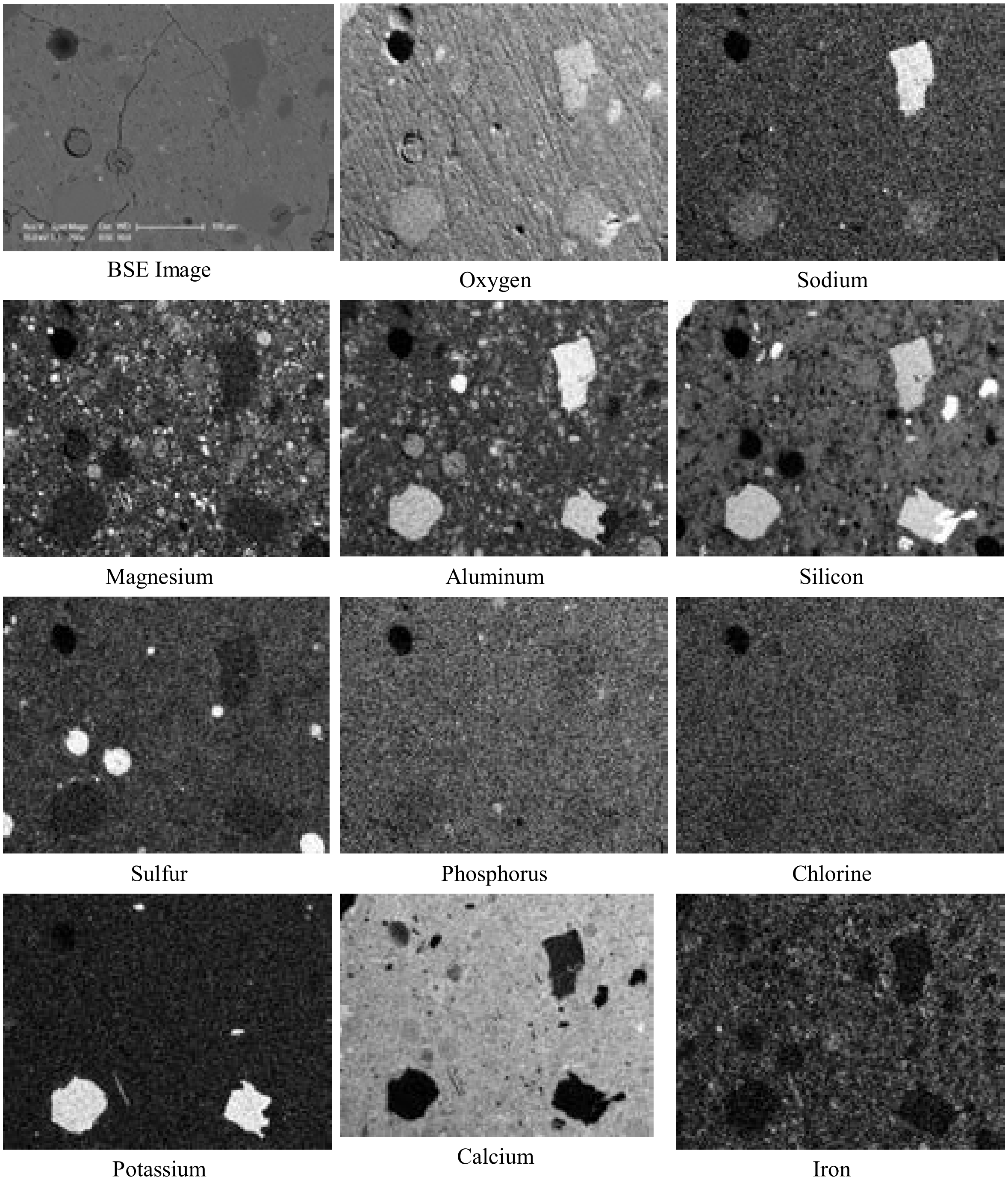


Figure 29. X-ray intensity maps of the same area shown in Figure 28.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

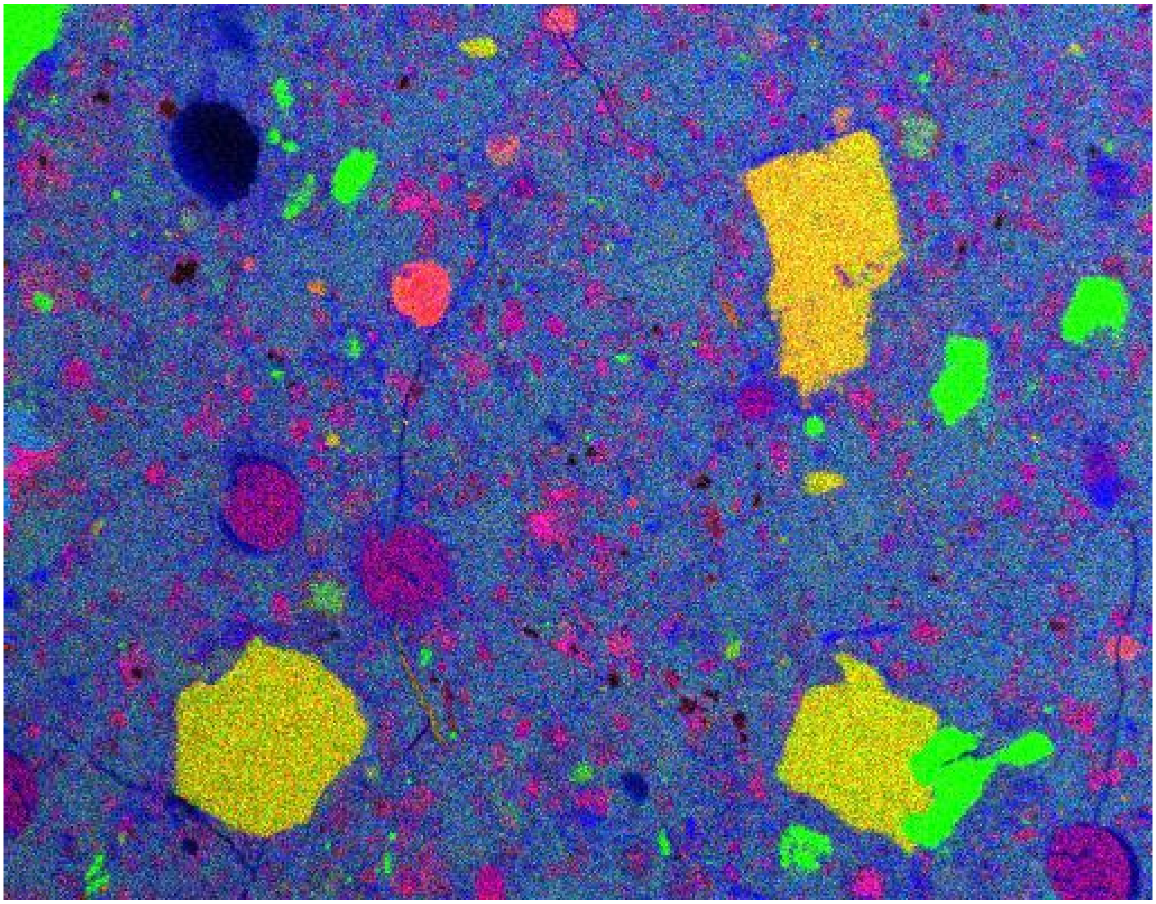


Figure 30. Combined x-ray intensity maps from the area shown in Figure 28 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

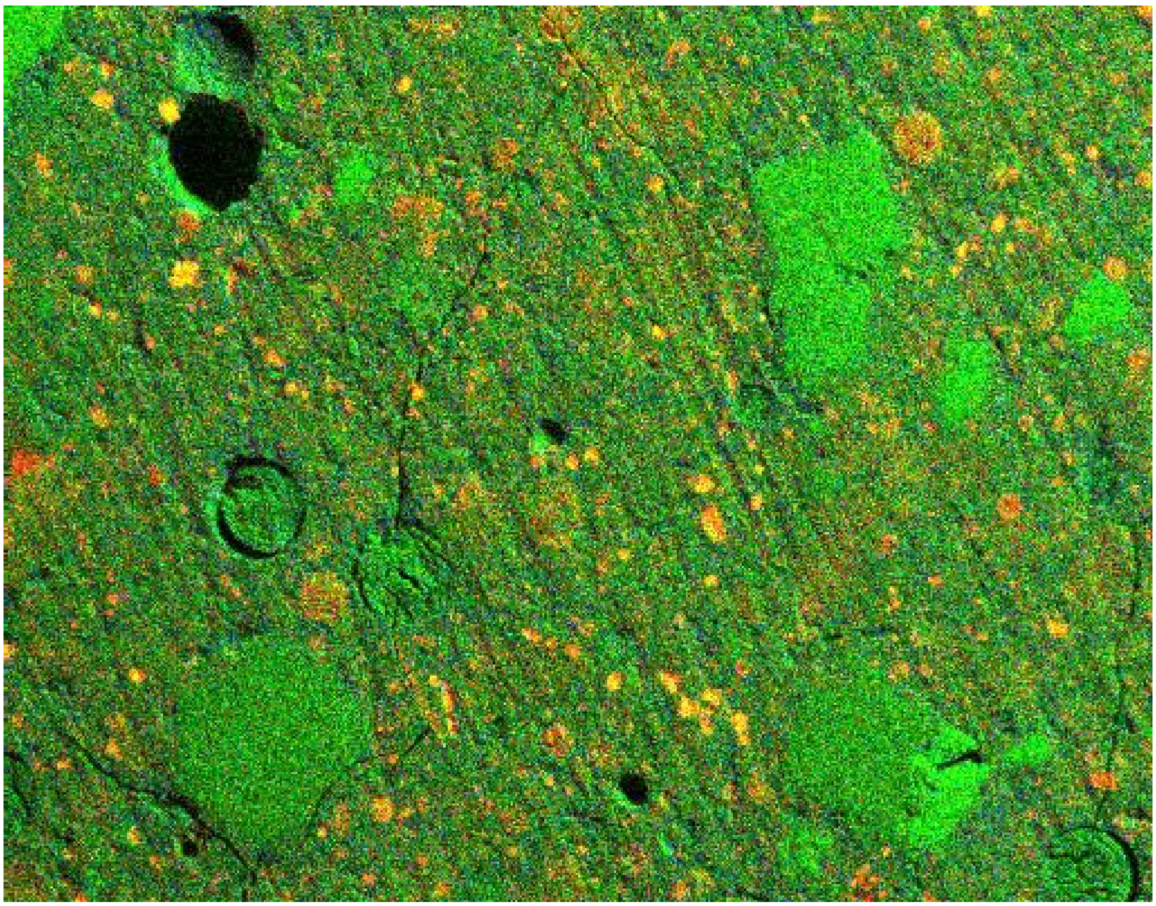


Figure 31. Combined x-ray intensity maps from the area shown in Figure 28 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange) indicate varying ratios of the elements combined to form that color.

R	Al
G	S
B	Ca
Yellow	Al + S
Purple	Al +Ca
Cyan	S + Ca

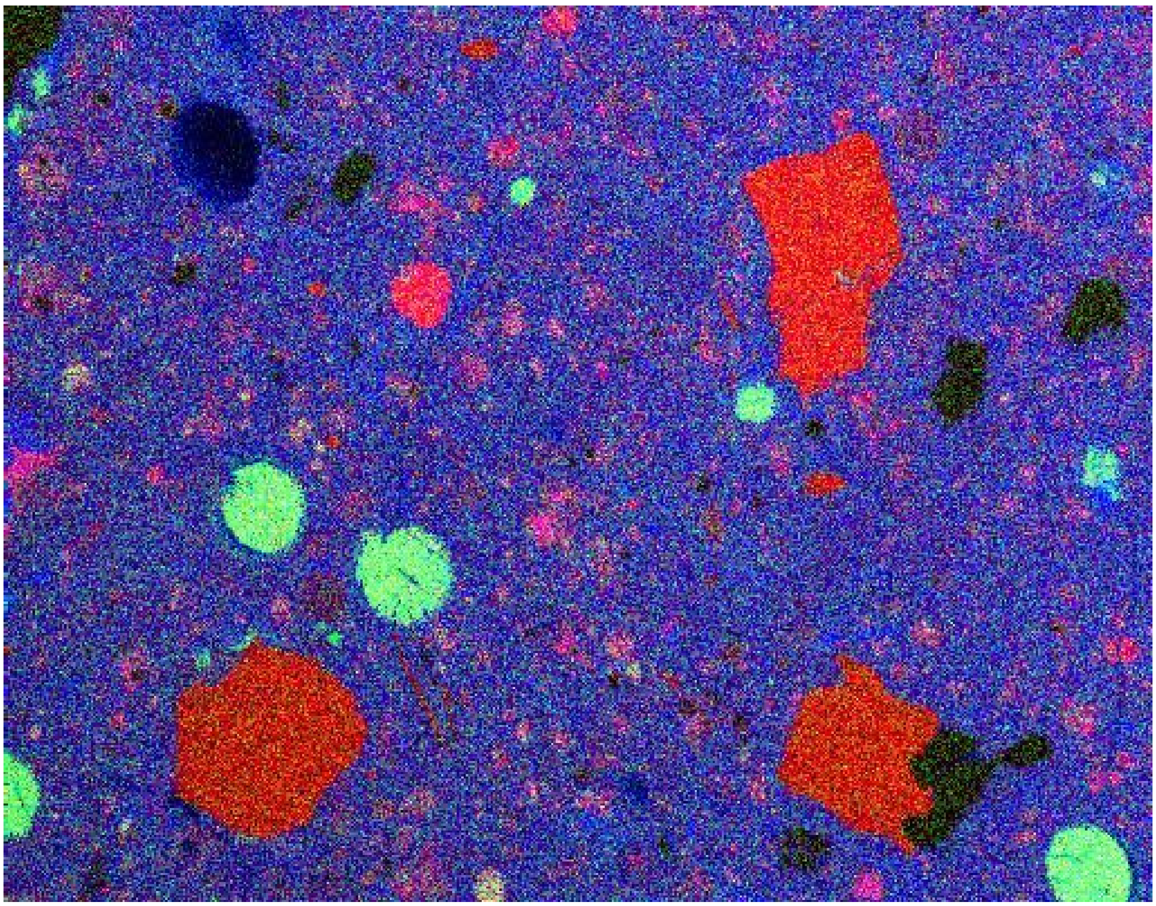


Figure 32. Combined x-ray intensity maps from the area shown in Figure 28 where maps for aluminum (red color), sulfur, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	
G	Fe
B	Mg
Cyan	Fe + Mg

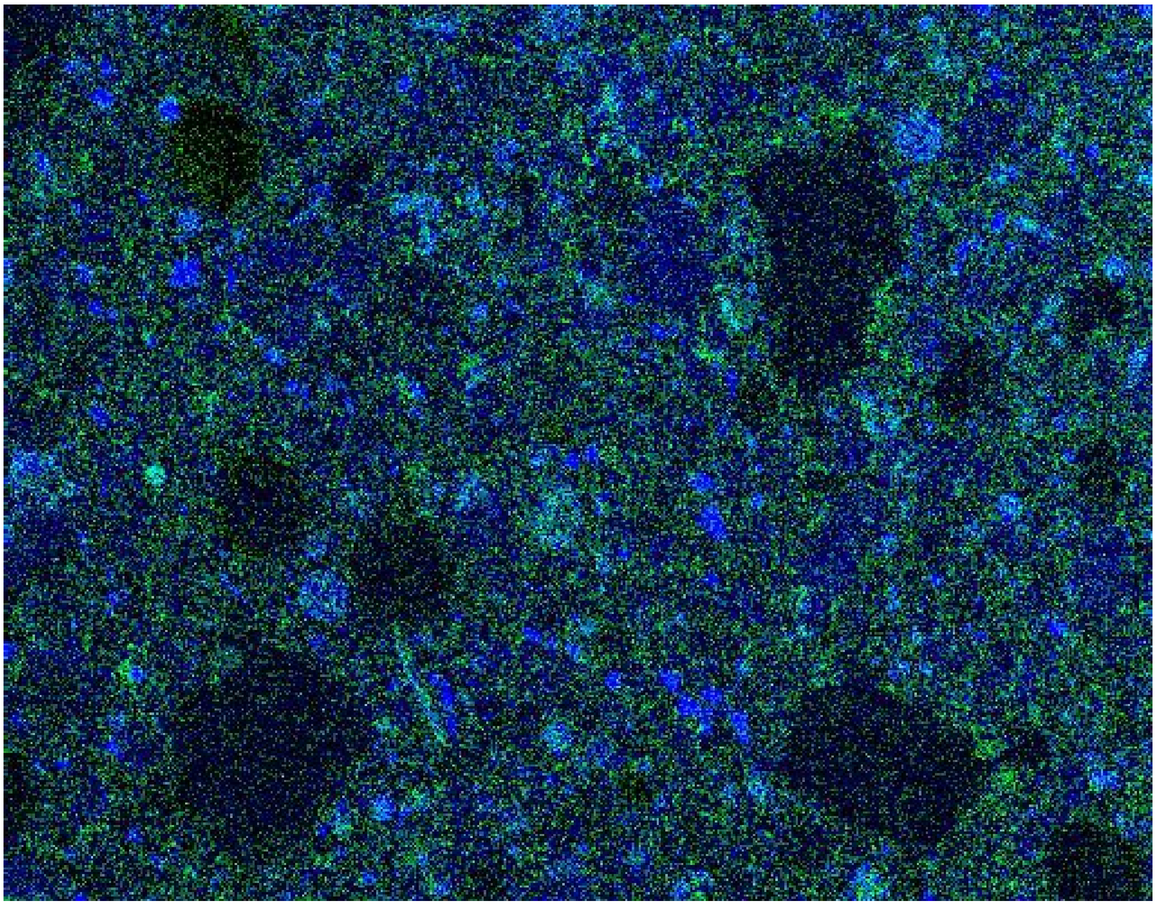


Figure 33. Combined x-ray intensity maps from the area shown in Figure 28 where maps for iron (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., cyan) indicate varying ratios of the elements combined to form that color.

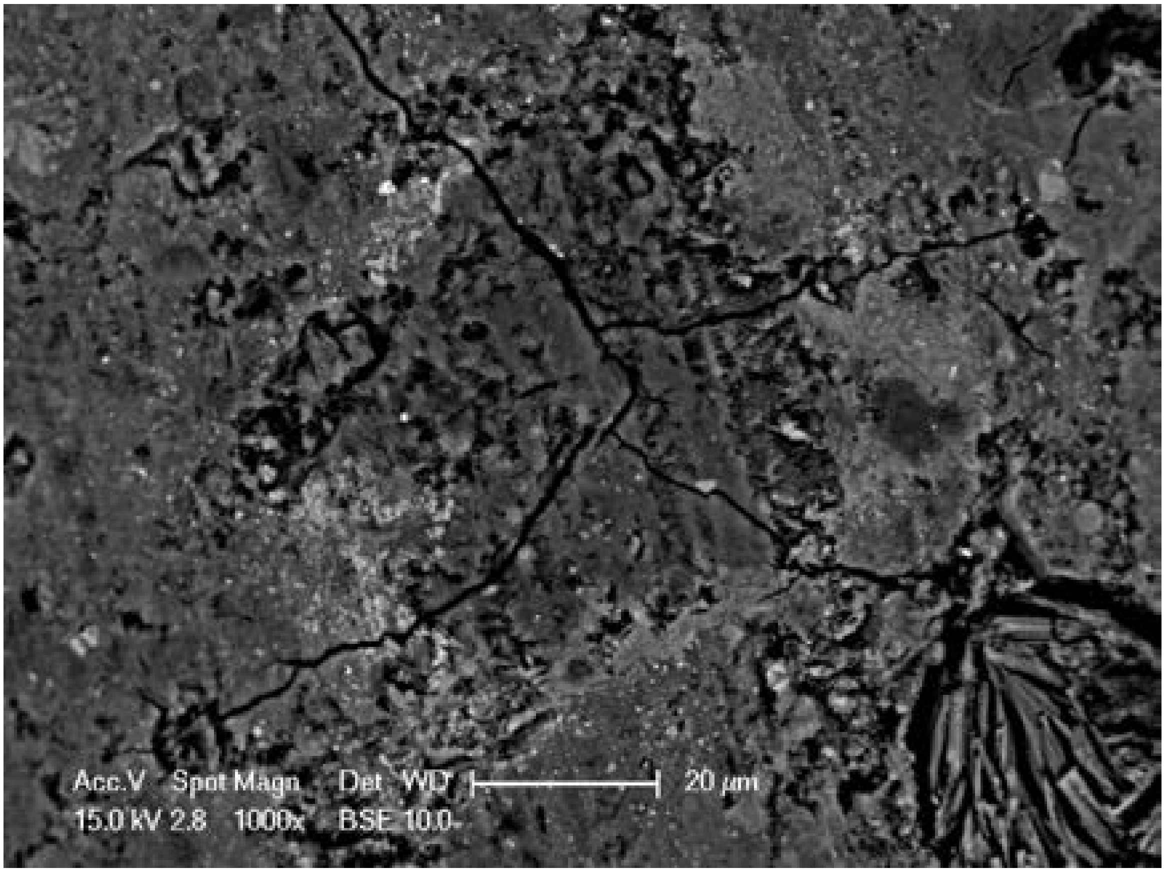


Figure 34. Backscattered electron image of small aggregate fragment away from joint. Specimen prepared from core sample 96A.

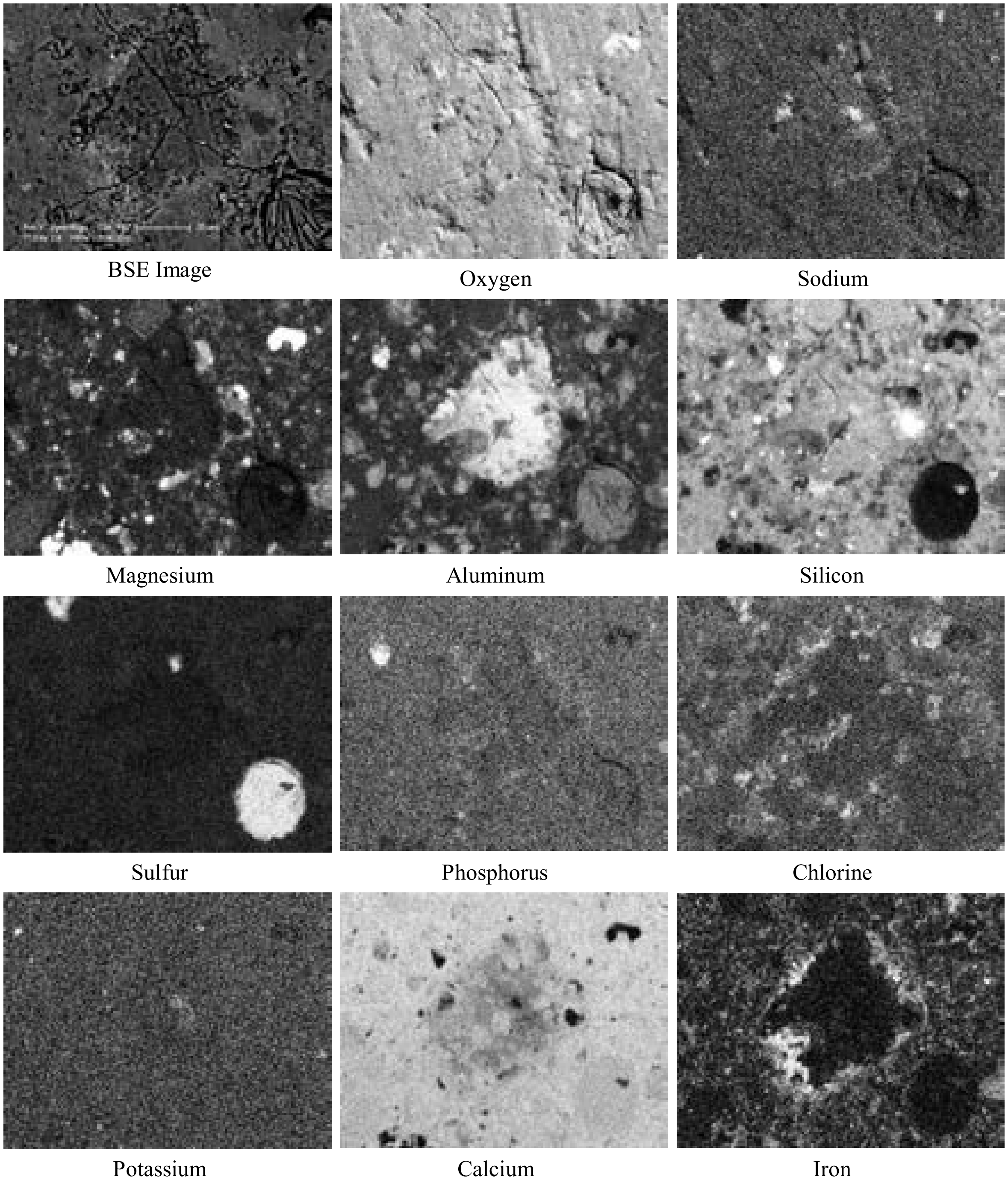


Figure 35. X-ray intensity maps of the same area shown in Figure 34.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

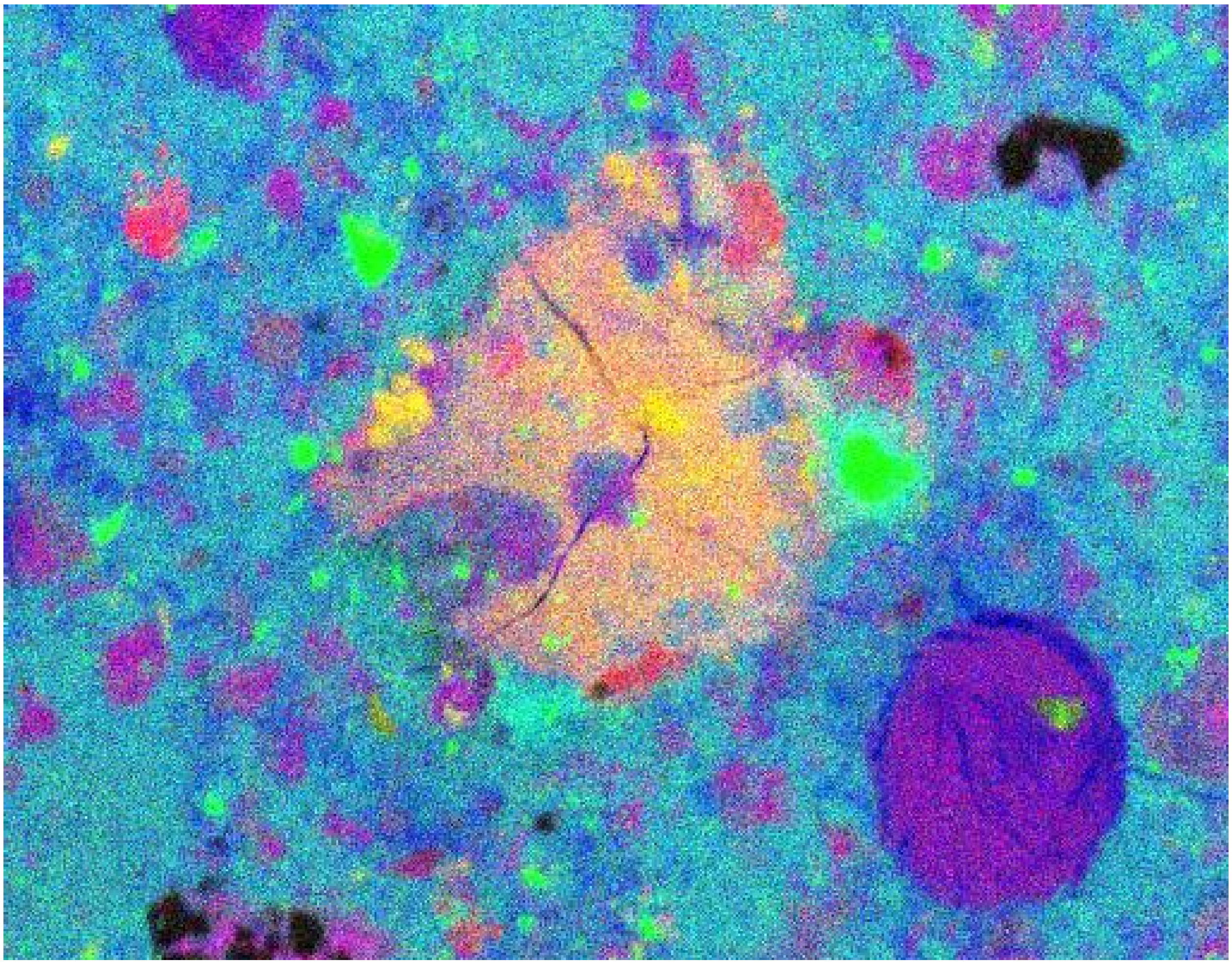


Figure 36. Combined x-ray intensity maps from the area shown in **FIGURE** where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

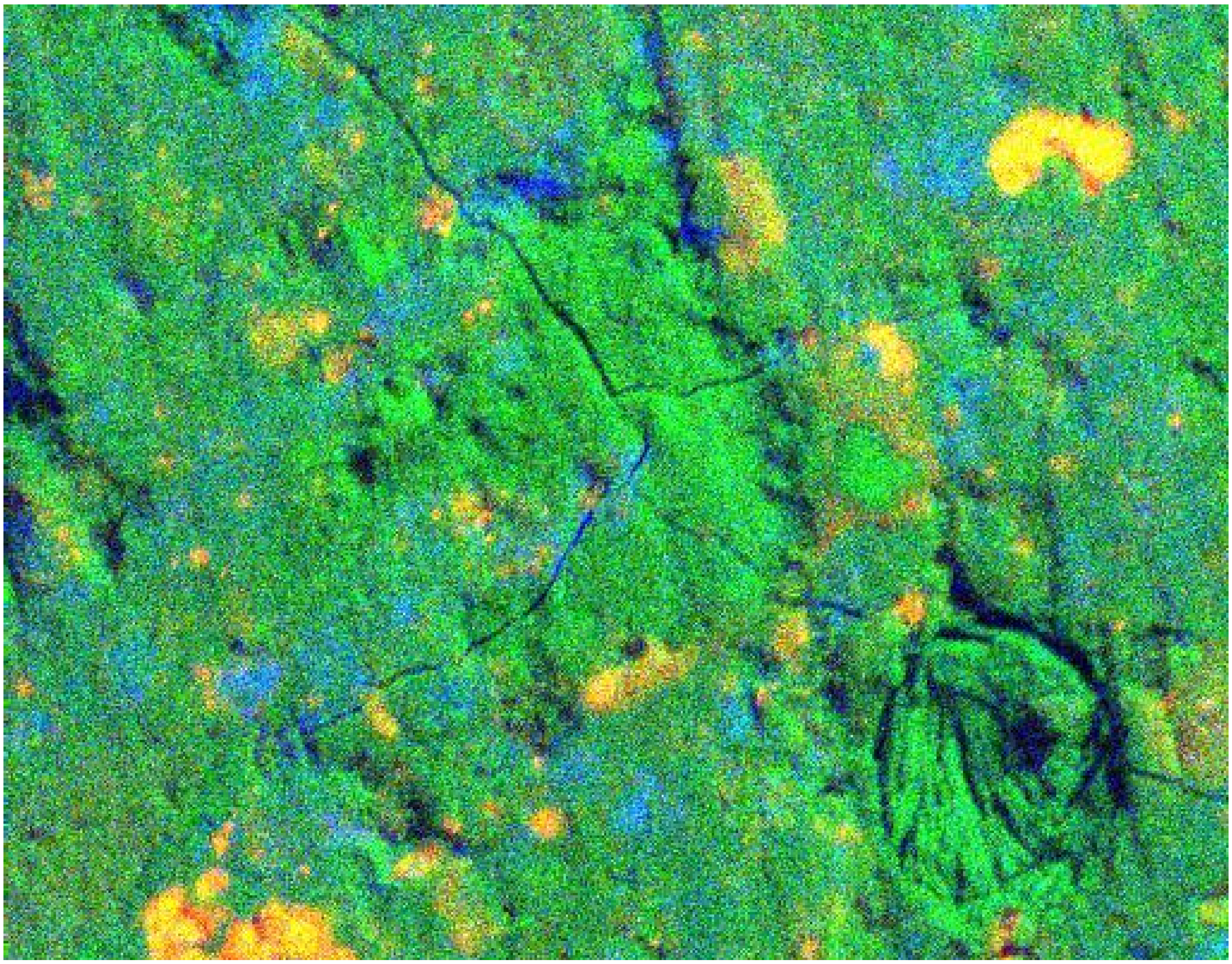


Figure 37. Combined x-ray intensity maps from the area shown in **FIGURE** where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange) indicate varying ratios of the elements combined to form that color.

R	Al
G	S
B	Ca
Yellow	Al + S
Purple	Al +Ca
Cyan	S + Ca

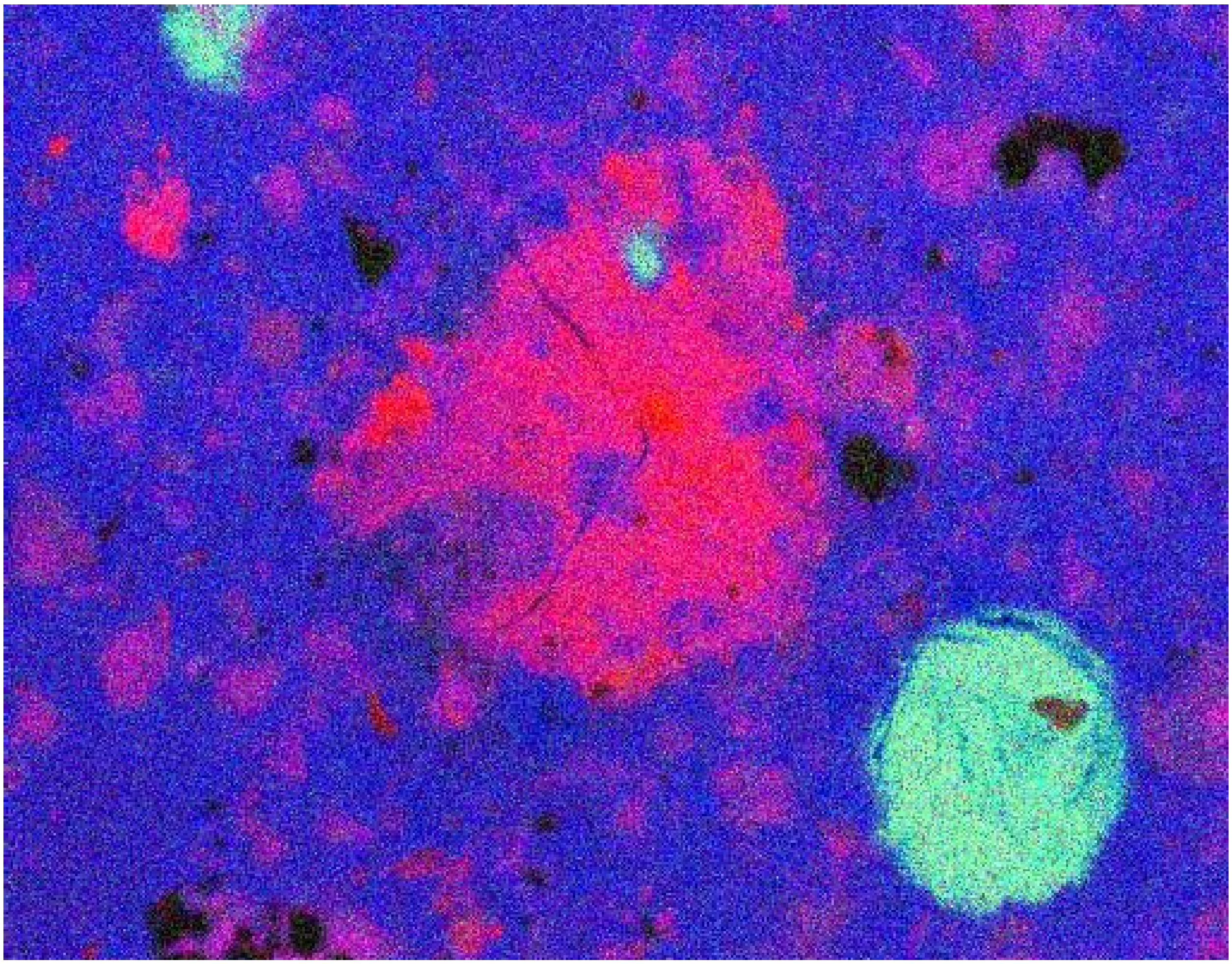


Figure 38. Combined x-ray intensity maps from the area shown in **FIGURE** where maps for aluminum (red color), sulfur, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	K
G	Fe
B	Mg
Yellow	K + Fe
Purple	K + Mg
Cyan	Fe + Mg

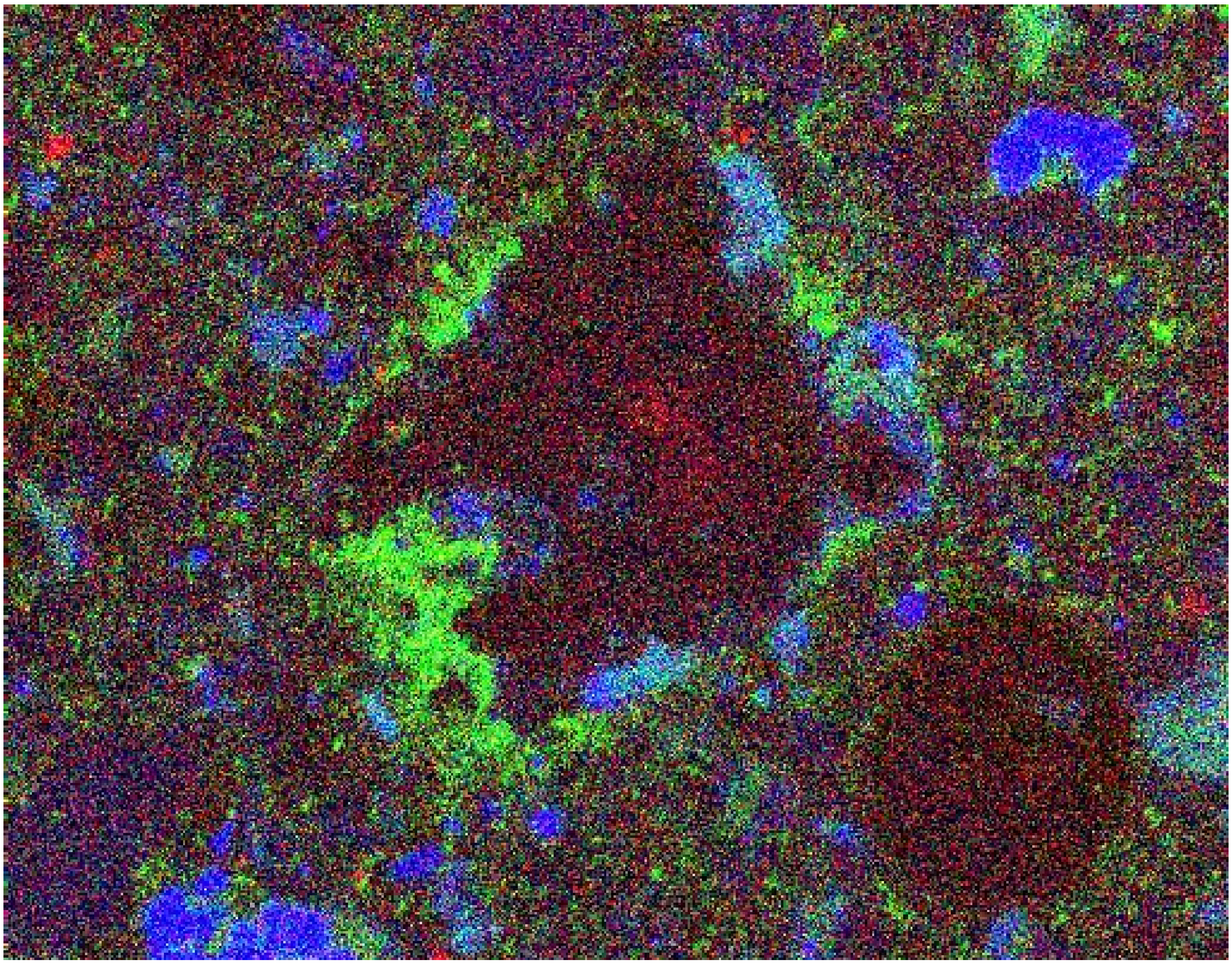


Figure 39. Combined x-ray intensity maps from the area shown in **FIGURE** where maps for potassium (red color), iron, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	P
G	Ca
B	Mg
Yellow	P + Ca
Purple	P + Mg
Cyan	Ca + Mg

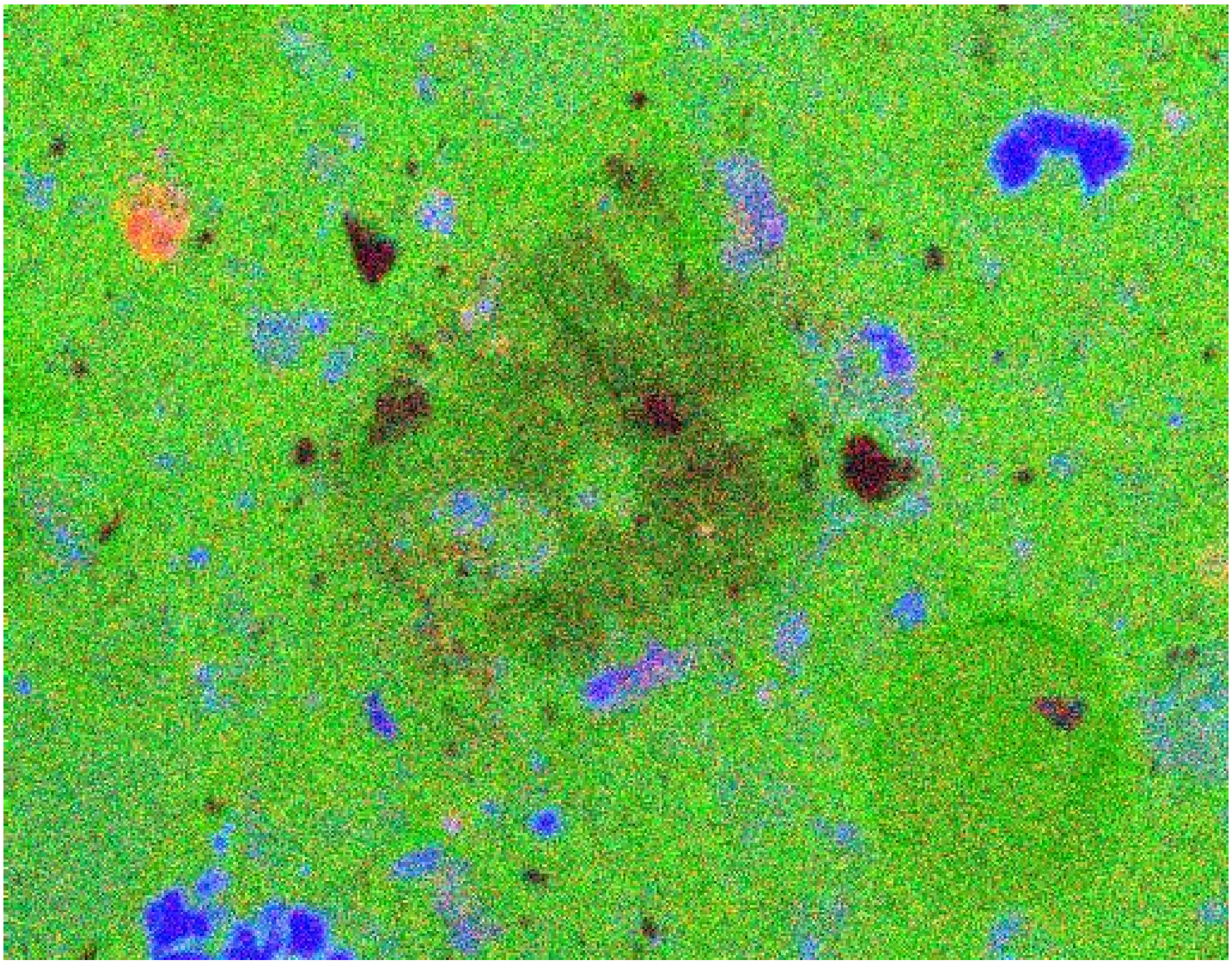
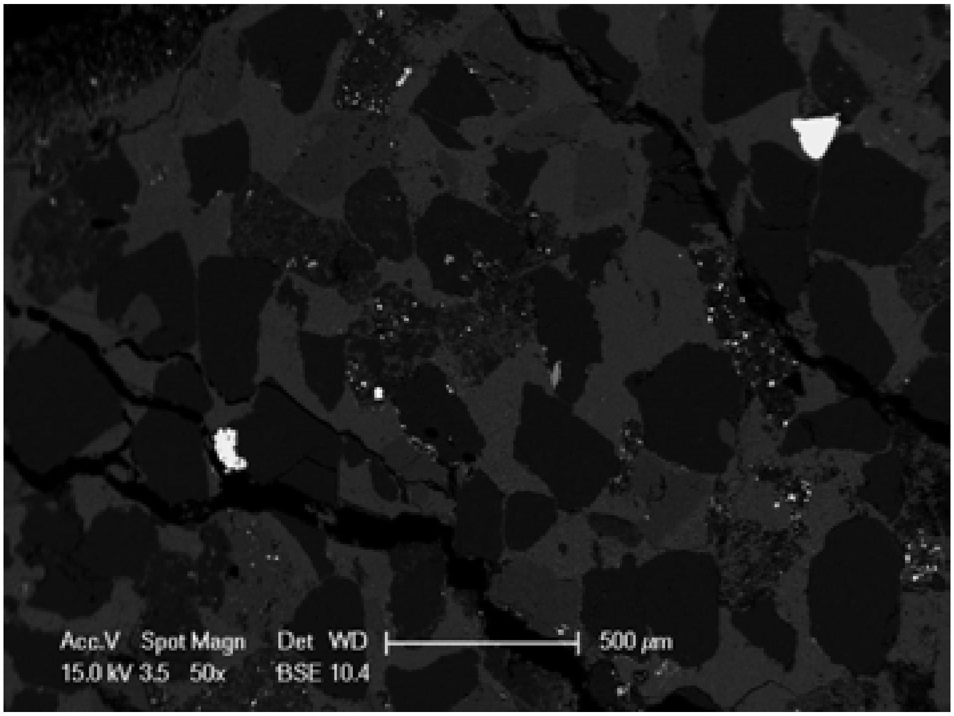
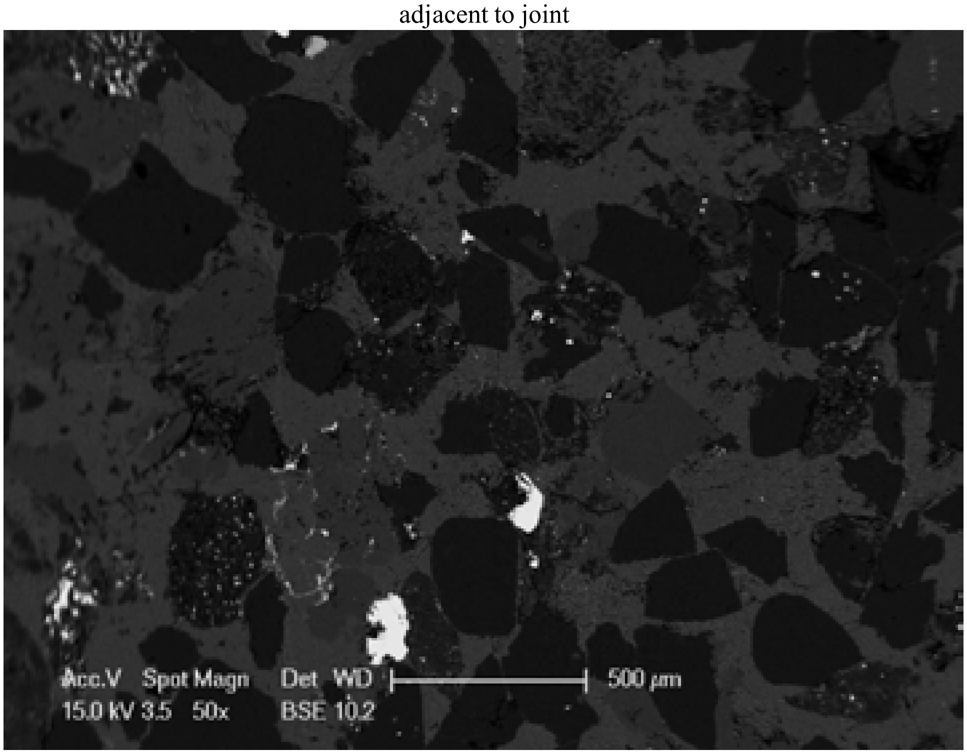


Figure 40. Combined x-ray intensity maps from the area shown in **FIGURE** where maps for phosphorous (red color), calcium, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

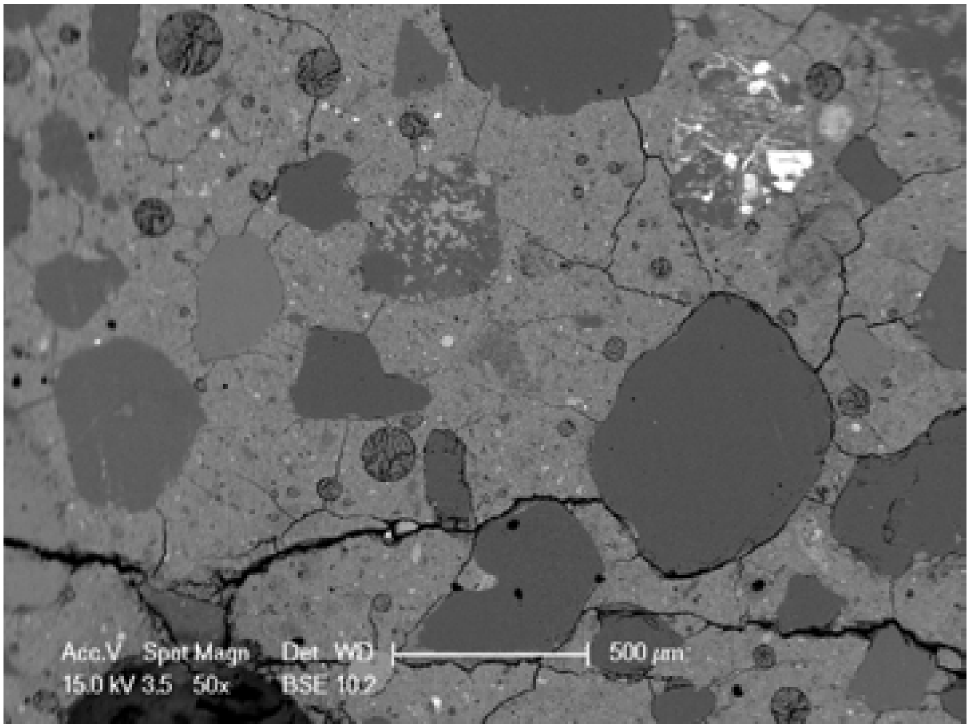


adjacent to joint

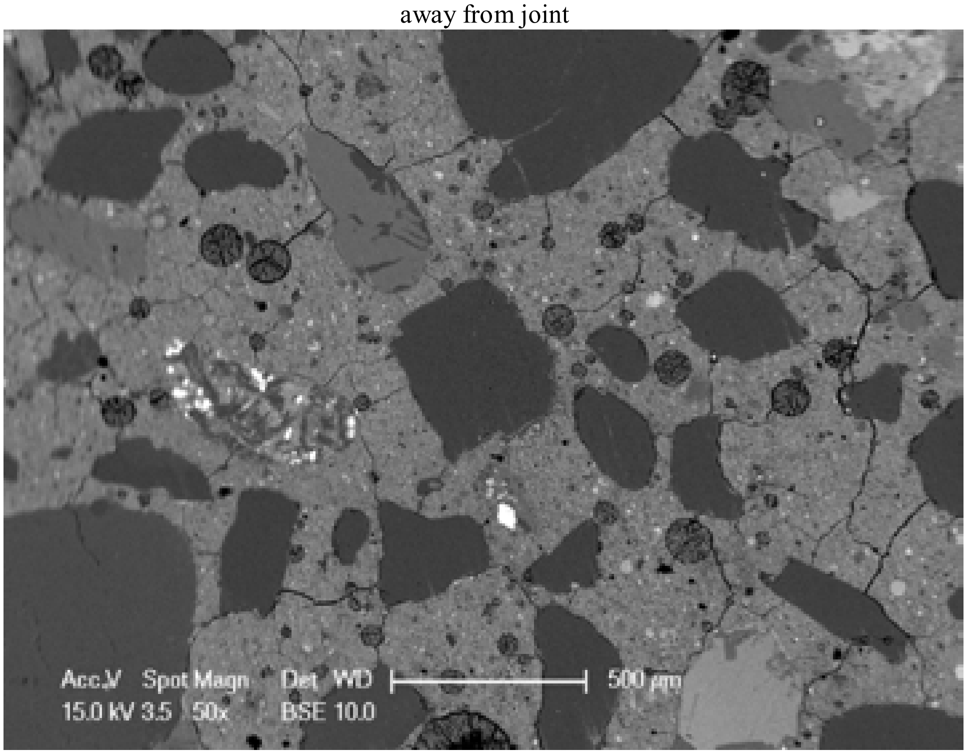


near joint

Figure 41. Backscattered electron images of cement paste showing porous aggregate. Specimen prepared from core sample 96A.

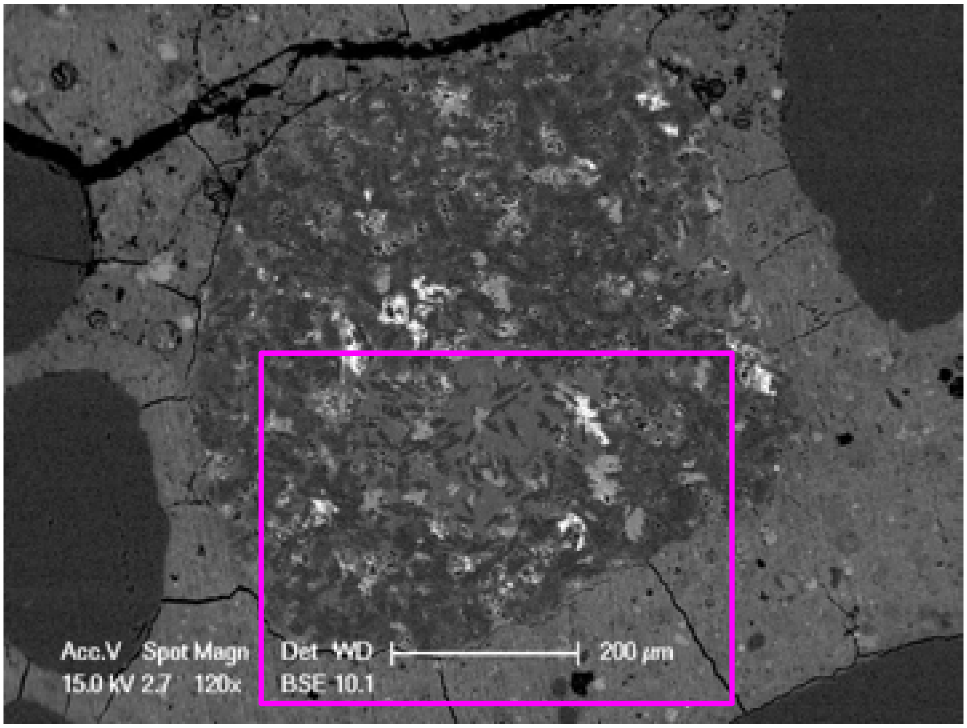


away from joint

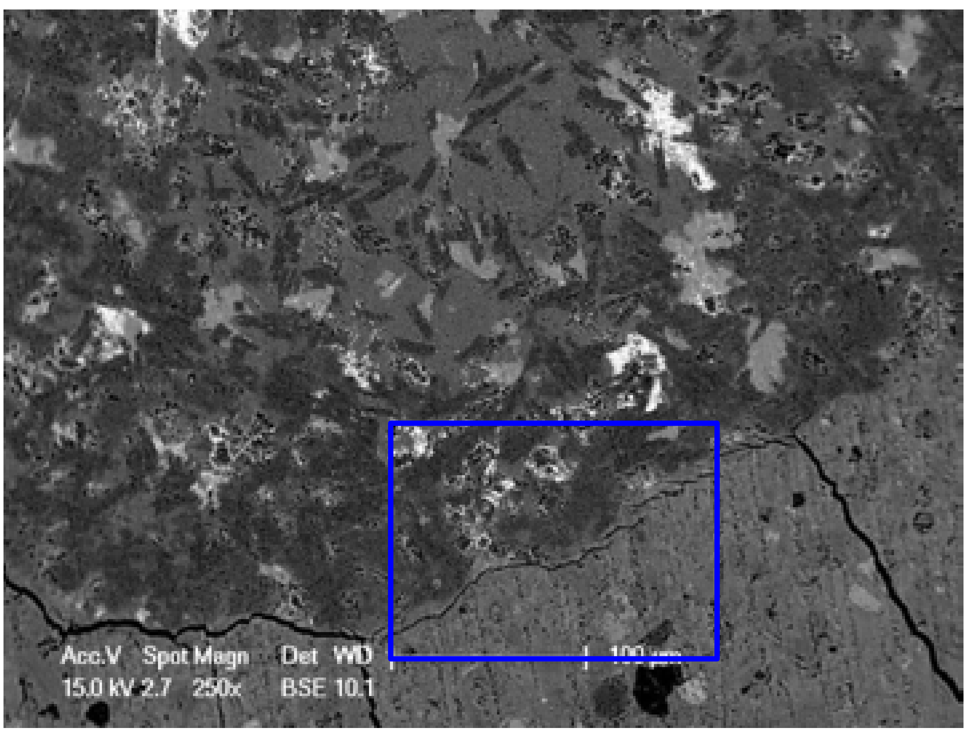


away from joint

Figure 42. Backscattered electron images of cement paste showing aggregate without porosity. Specimen prepared from core sample 96A.



(a)



(b)

Figure 43. Backscattered electron image of aggregate particle that has undergone partial dissolution. Micrograph (b) is the area outlined in magenta in micrograph (a). Figure 49 is the area outlined in blue in micrograph (b). Specimen prepared from core sample 96A.

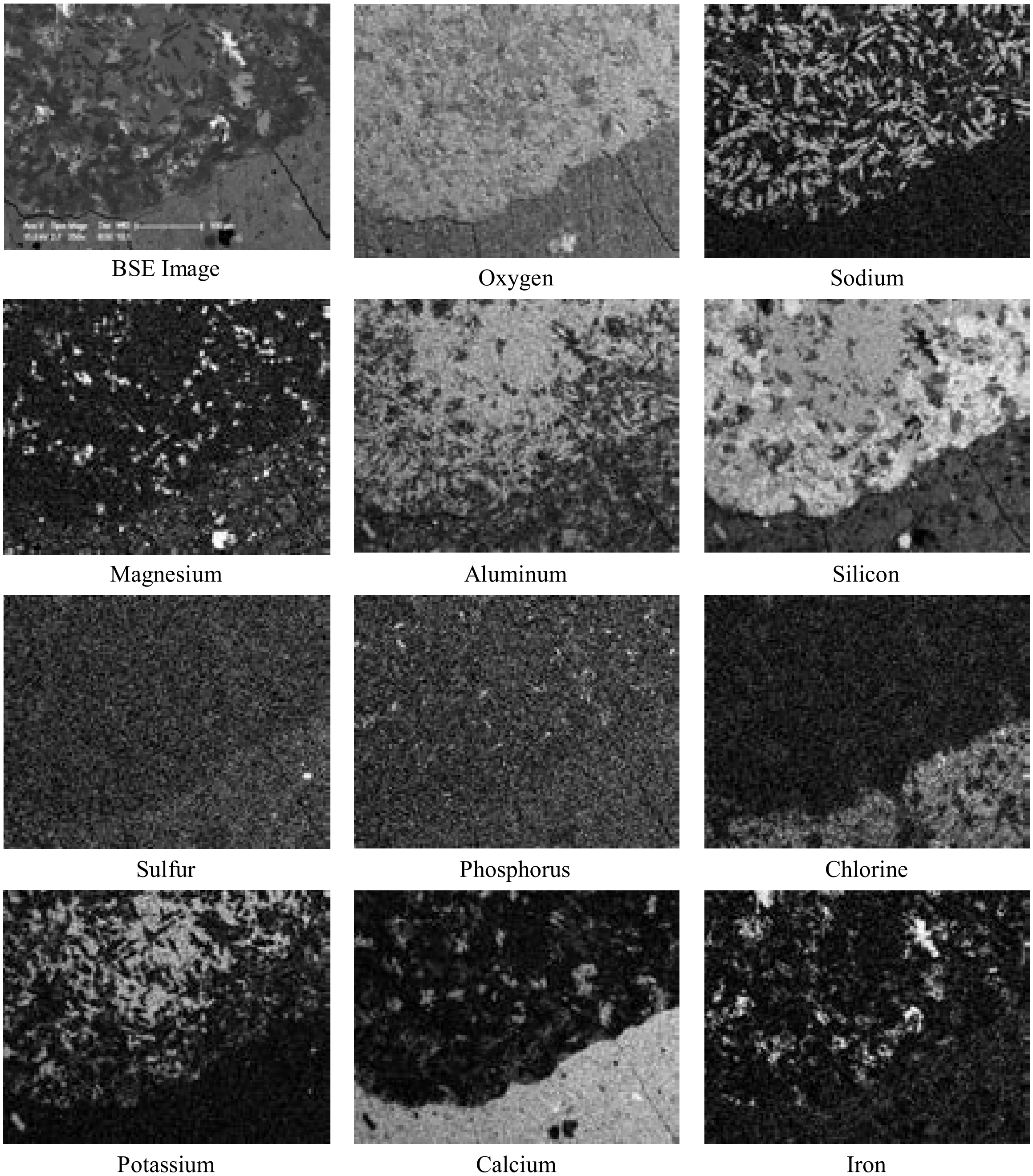


Figure 44. X-ray intensity maps of the same area shown in Figure 43(b).

R	Al
G	Ca
B	Si
Yellow	Al + Ca
Purple	Al + Si
Cyan	Ca +Si

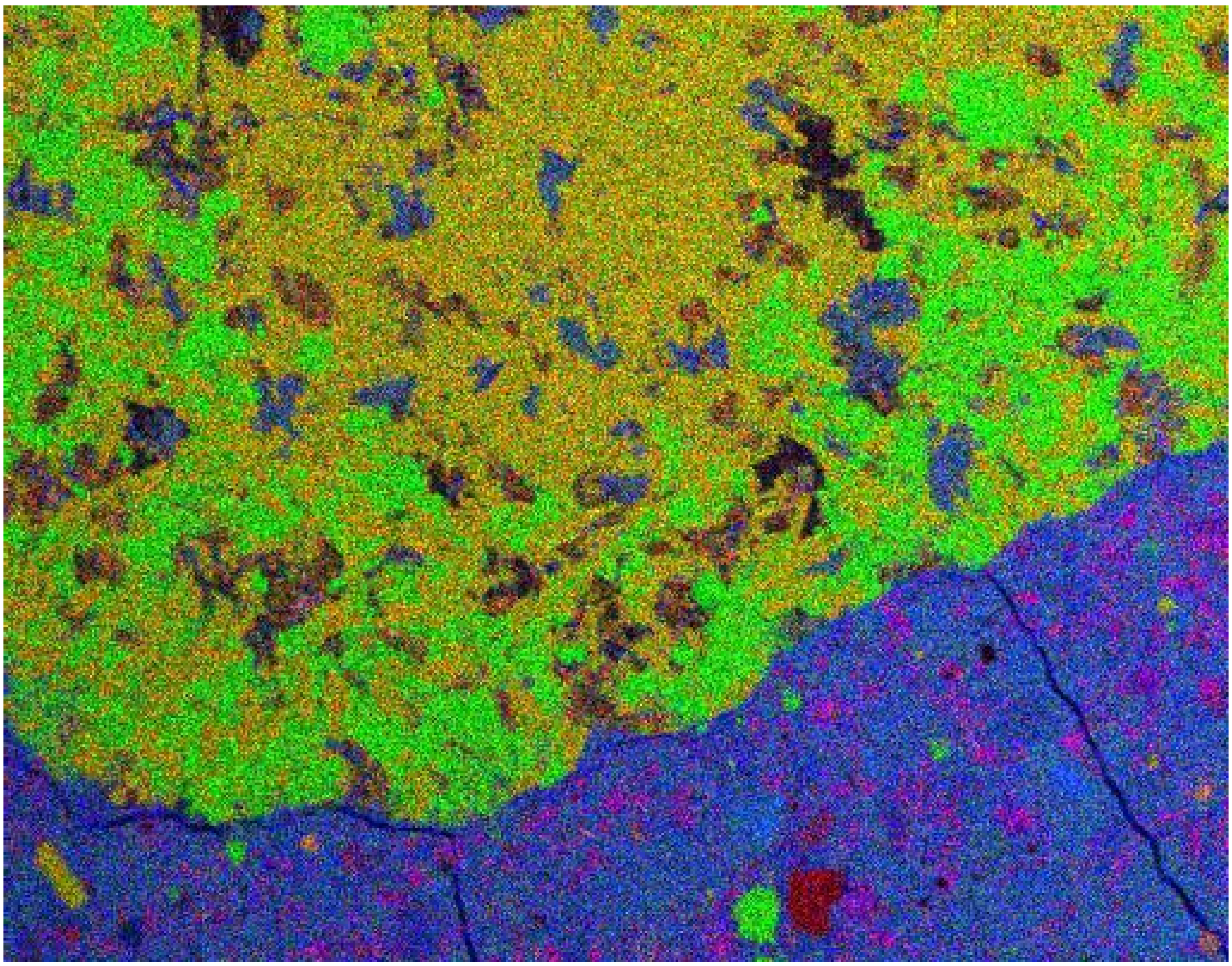


Figure 45. Combined x-ray intensity maps from the area shown in Figure 43(b) where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	K
G	Si
B	Na
Yellow	K + Si
Purple	K + Na
Cyan	Si + Na
R	K

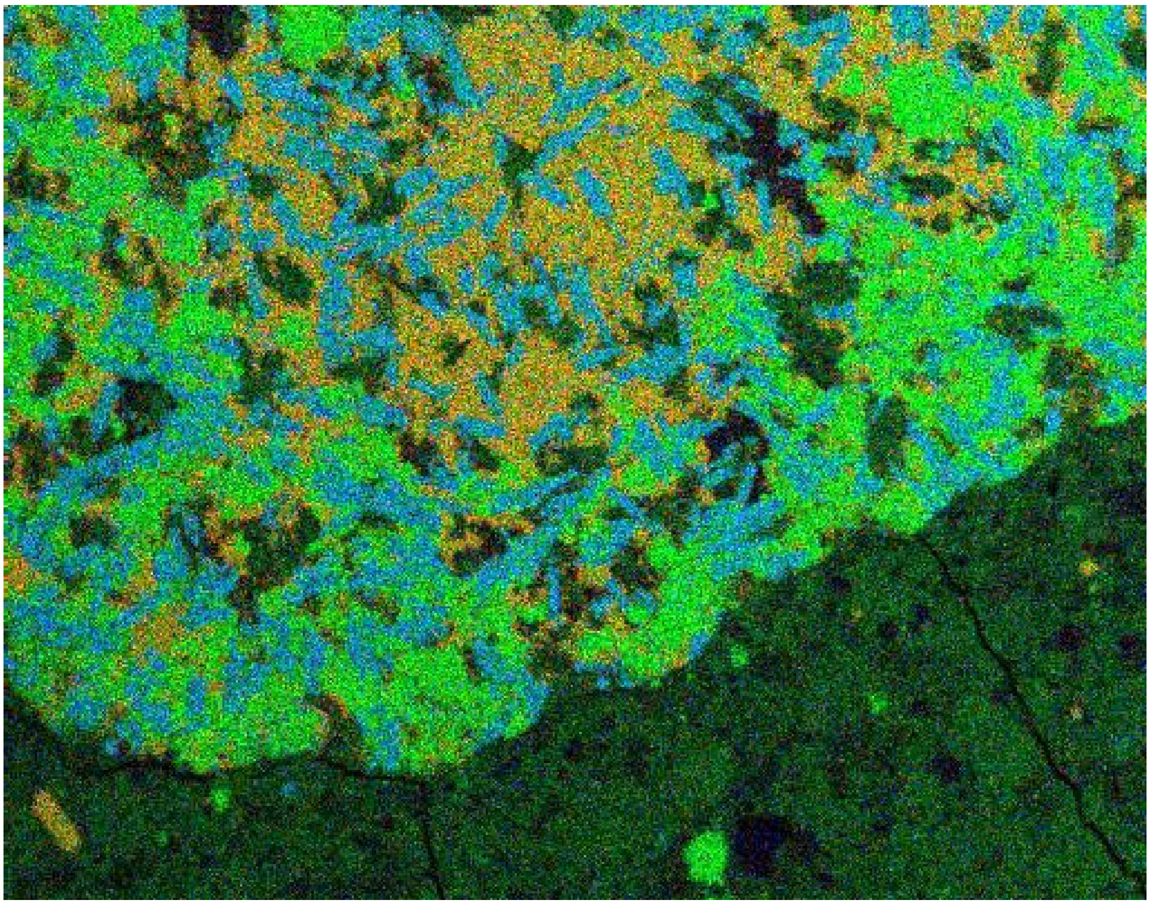


Figure 46. Combined x-ray intensity maps from the area shown in Figure 43(b) where maps for potassium (red color), silicon, (green color), sodium (blue color), and iron (magenta) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange or cyan) indicate varying ratios of the elements combined to form that color.

R	Cl
G	Fe
B	Mg
Yellow	Cl + Fe
Purple	Cl + Mg
Cyan	Fe +Mg

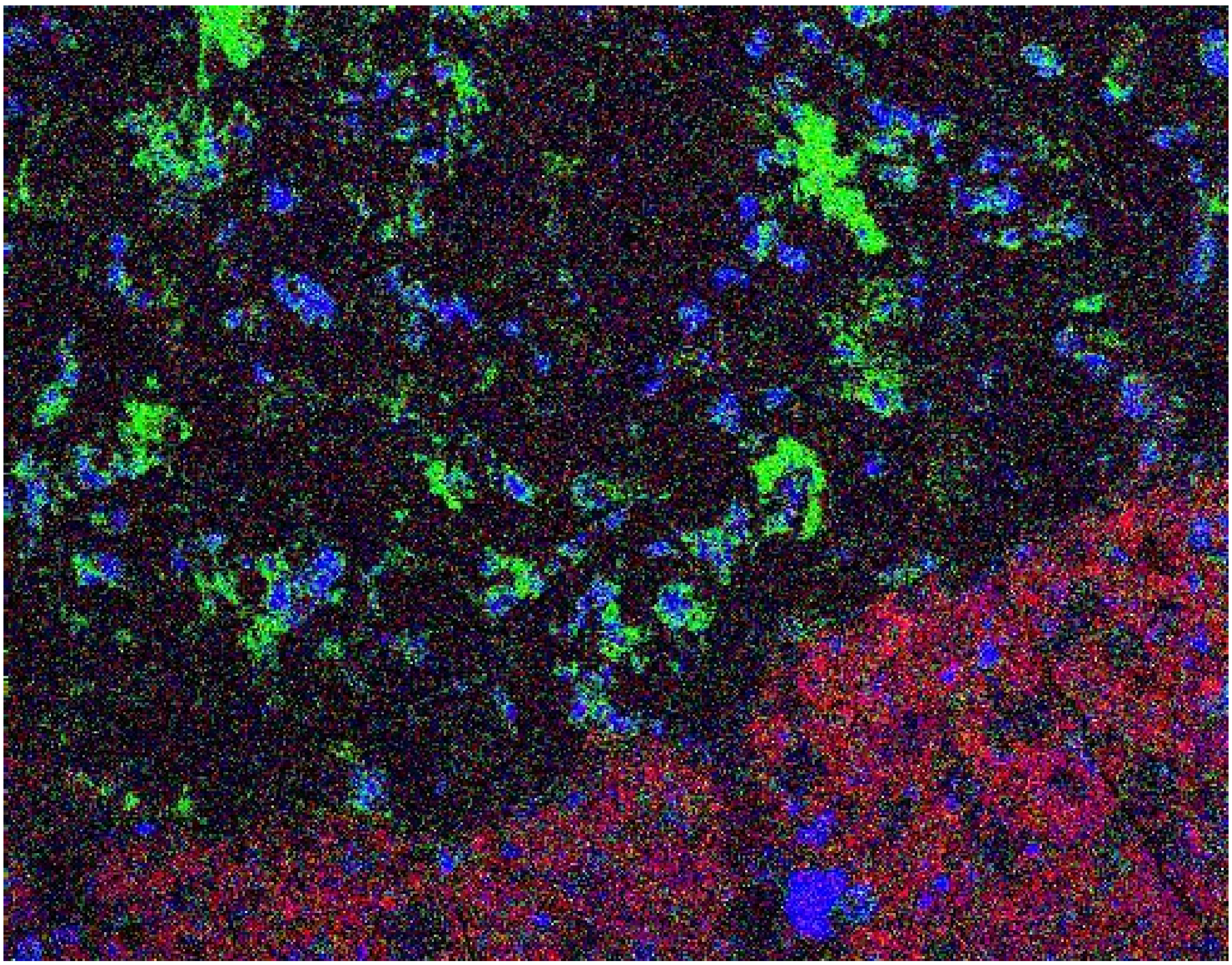


Figure 47. Combined x-ray intensity maps from the area shown in Figure 43(b) where maps for chlorine (red color), iron, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	P
G	Ca
B	Mg
Yellow	P + Ca
Purple	P + Mg
Cyan	Ca + Mg

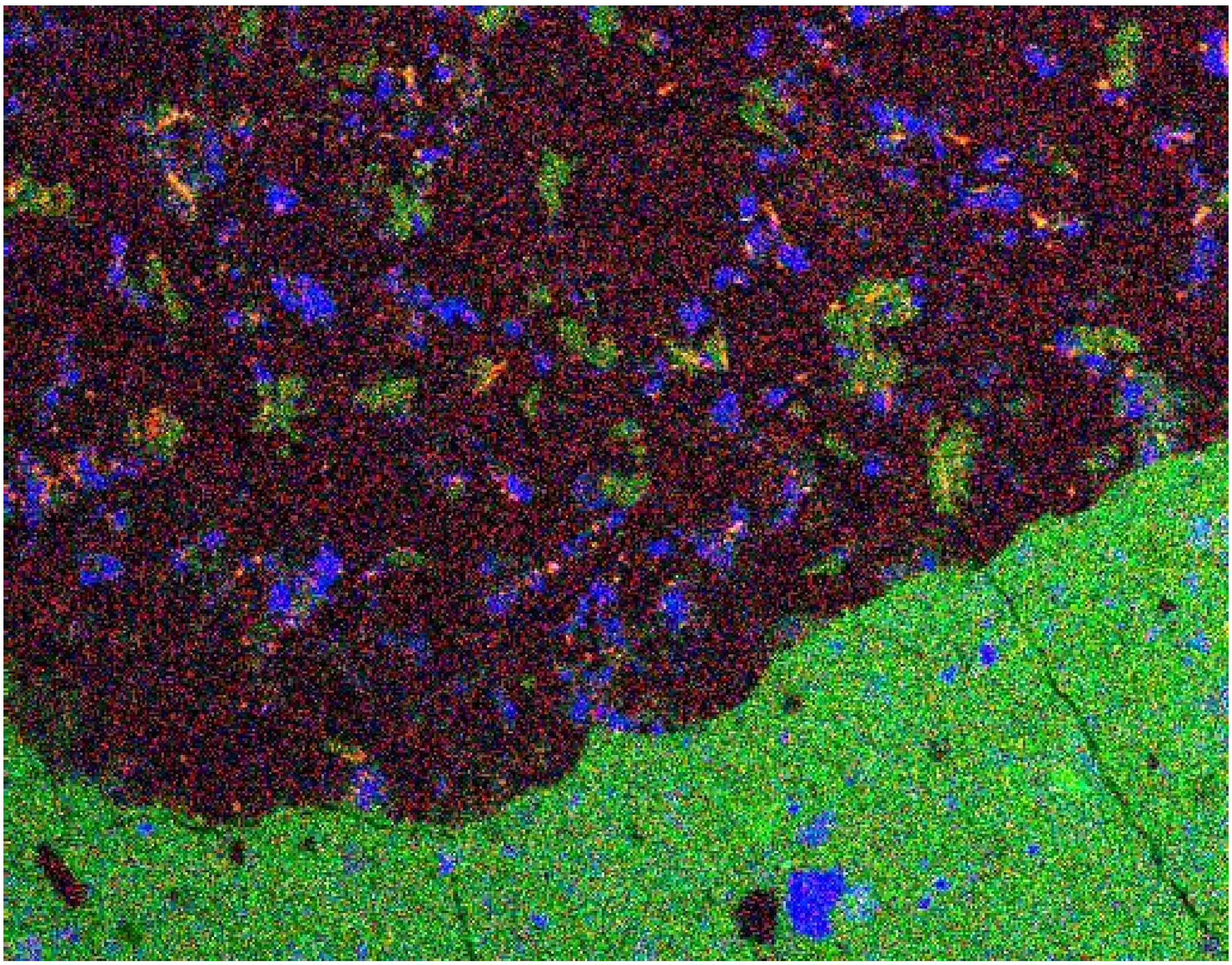


Figure 48. Combined x-ray intensity maps from the area shown in Figure 43(b) where maps for phosphorous (red color), calcium, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

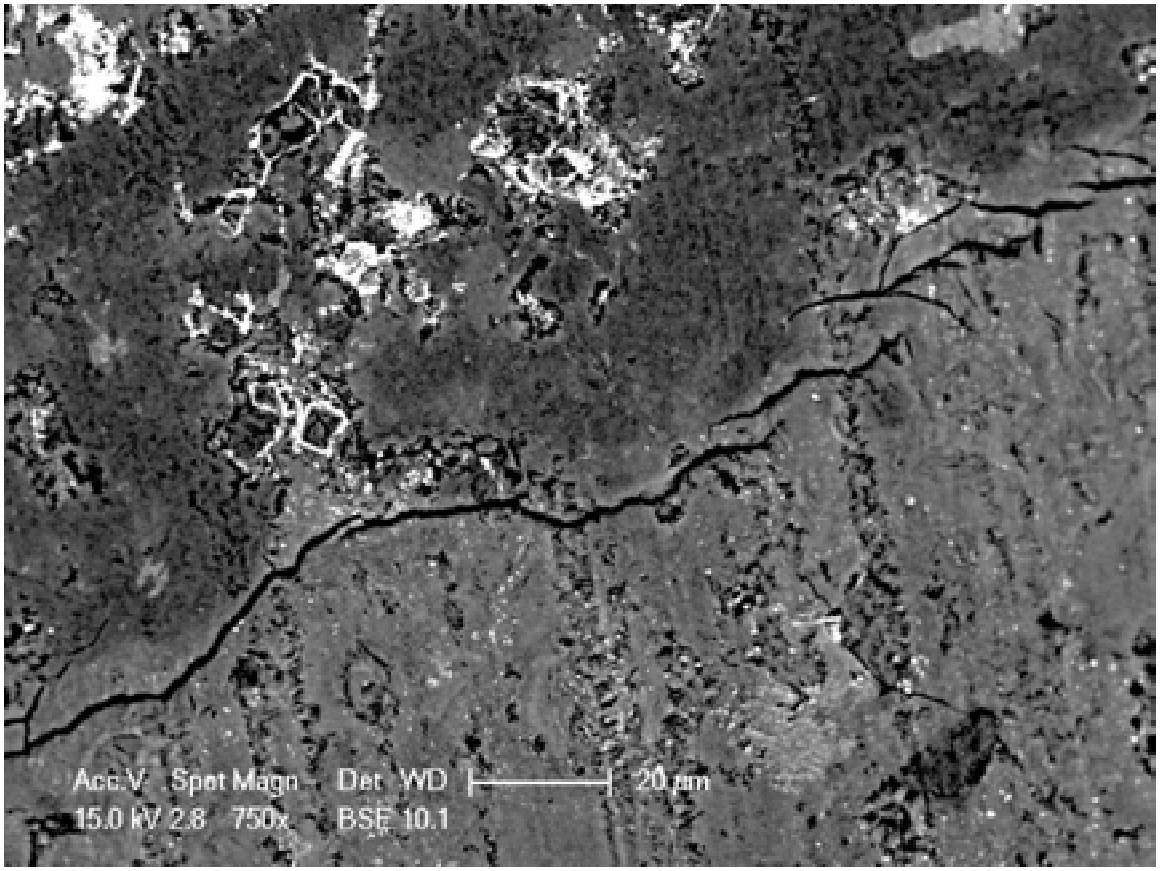


Figure 49. Backscattered electron image of aggregate particle that has undergone partial dissolution. Area shown is the area outlined in blue in Figure 43(b).

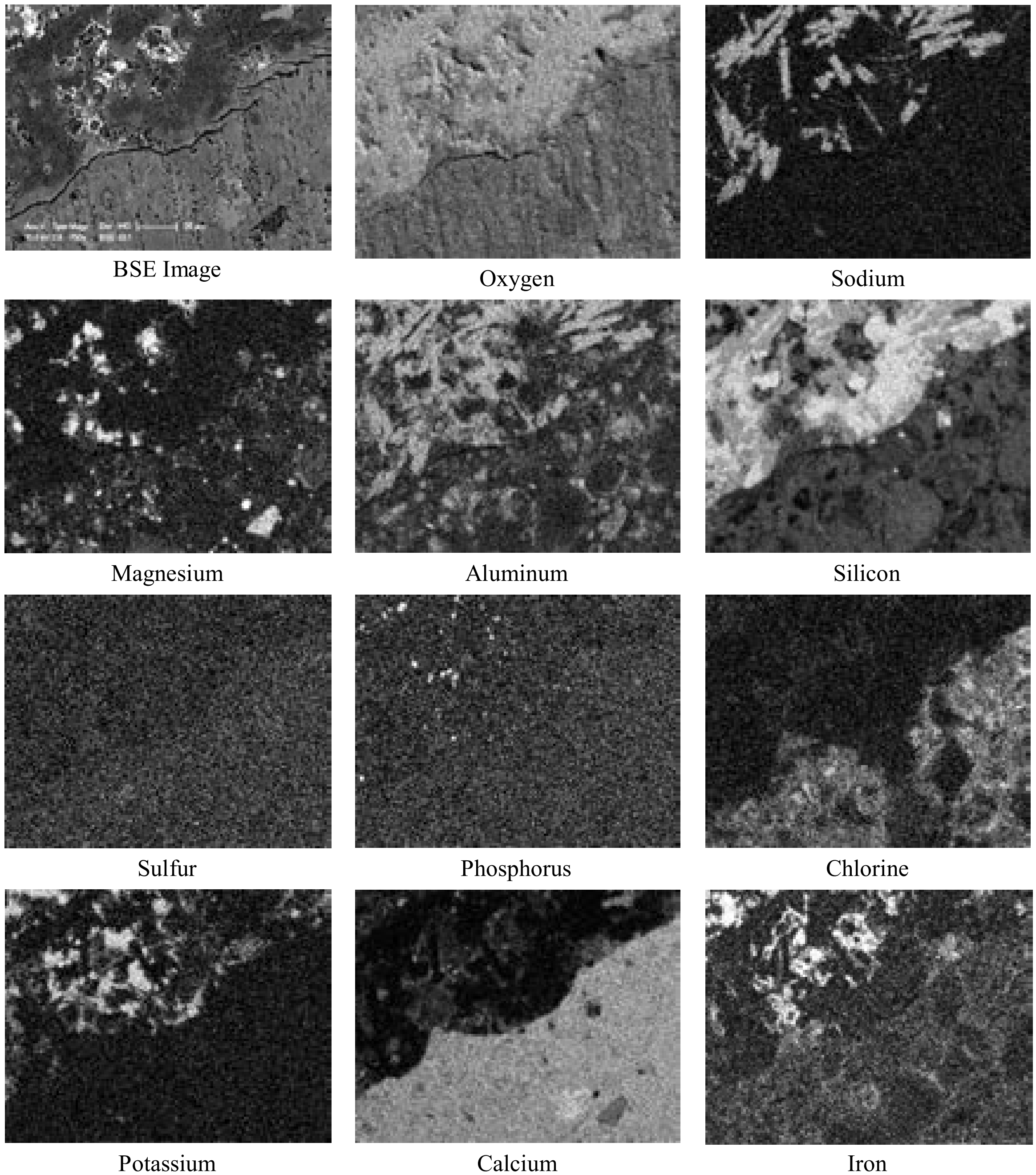


Figure 50. X-ray intensity maps of the same area shown in Figure 49.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

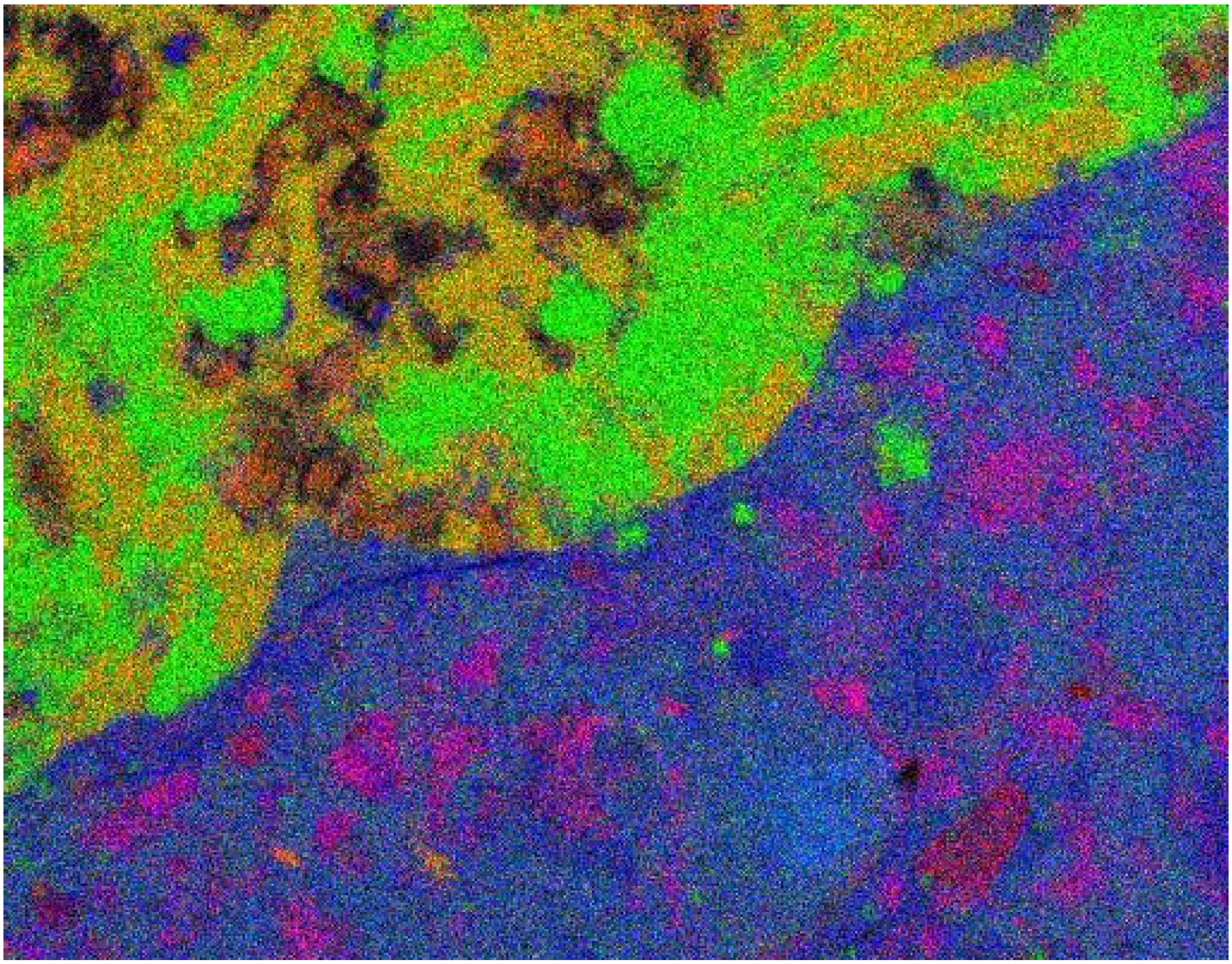


Figure 51. Combined x-ray intensity maps from the area shown in Figure 49 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	K
G	Si
B	Na
Yellow	K + Si
Purple	K + Na
Cyan	Si +Na

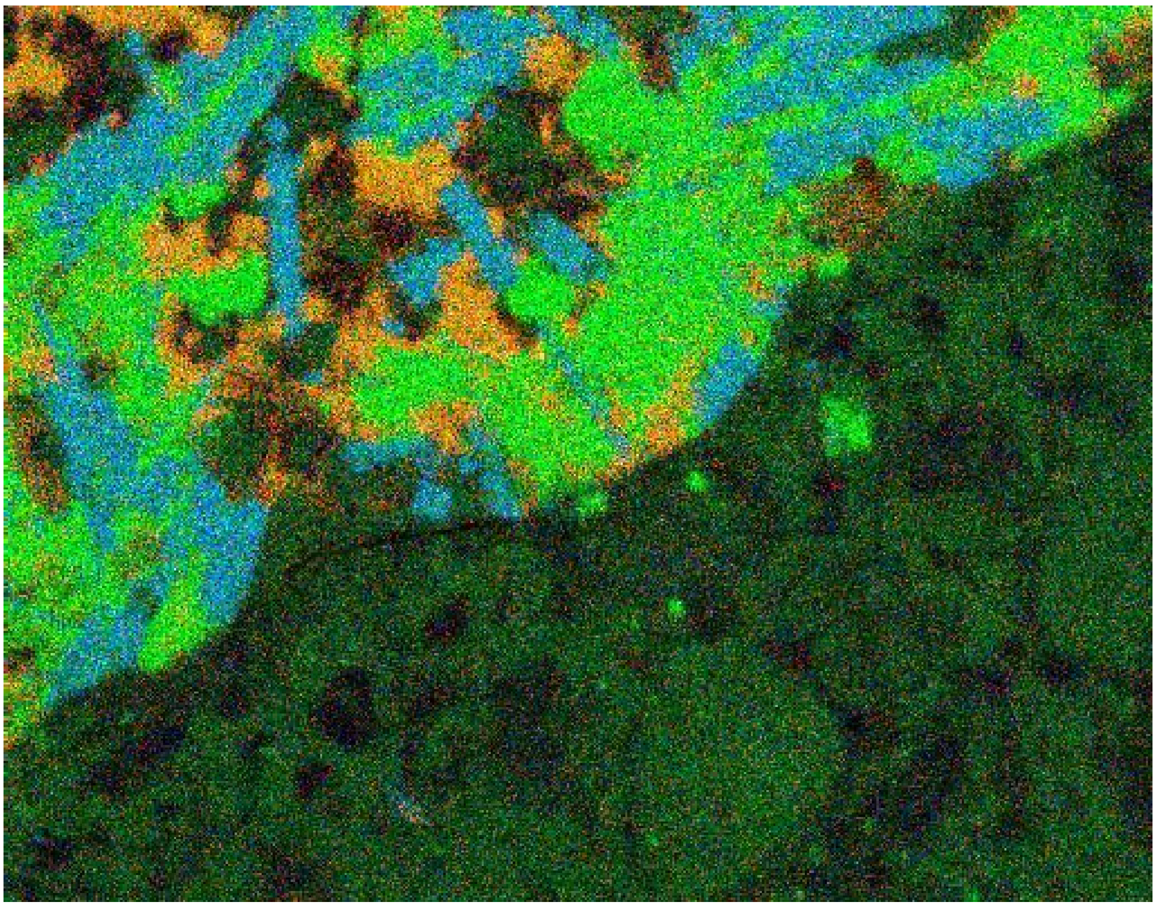


Figure 52. Combined x-ray intensity maps from the area shown in Figure 49 where maps for potassium (red color), silicon, (green color), sodium (blue color), and iron (magenta) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange or cyan) indicate varying ratios of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

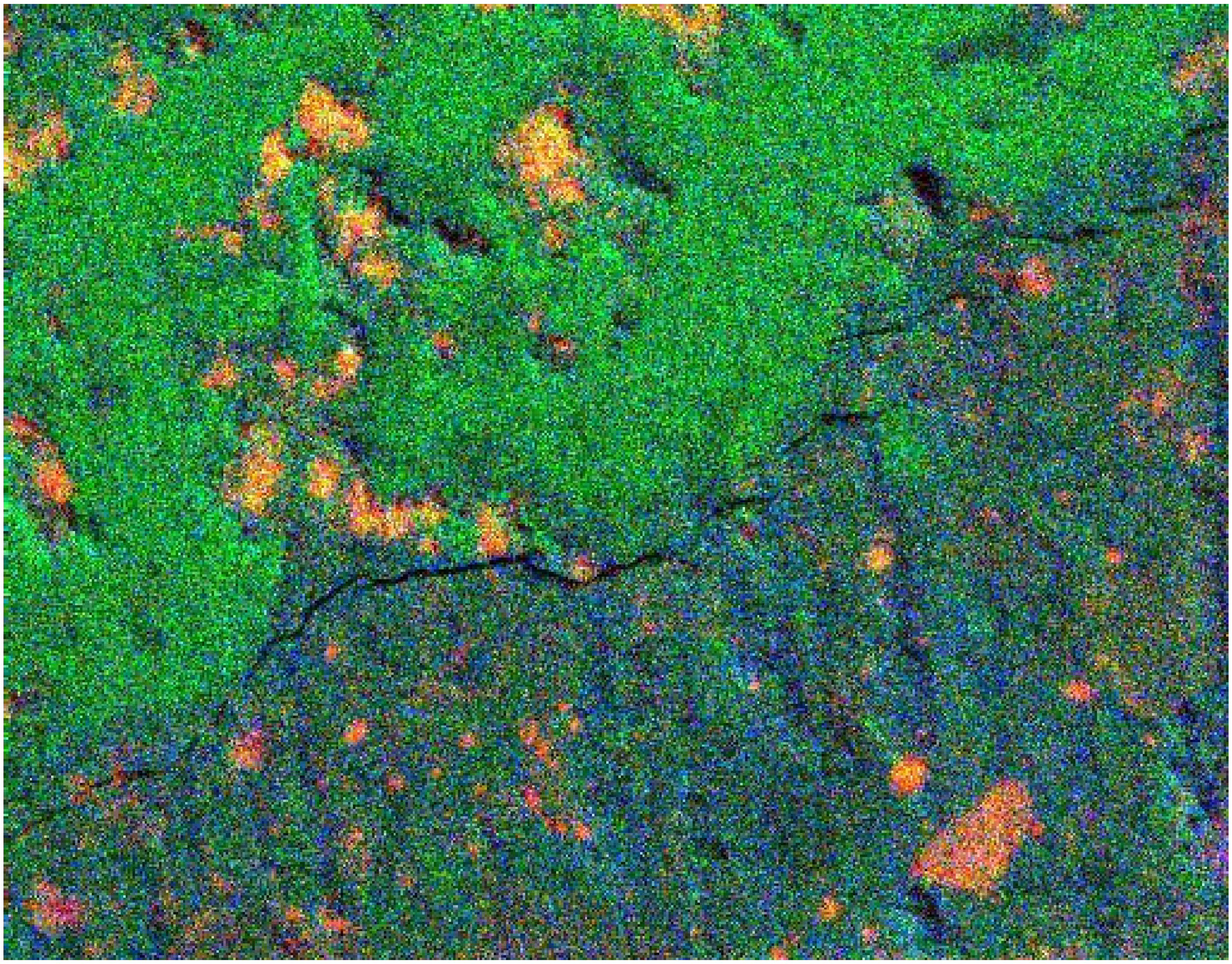


Figure 53. Combined x-ray intensity maps from the area shown in Figure 49 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange) indicate varying ratios of the elements combined to form that color.

R	K
G	Fe
B	Mg
Yellow	K + Fe
Purple	K + Mg
Cyan	Fe + Mg

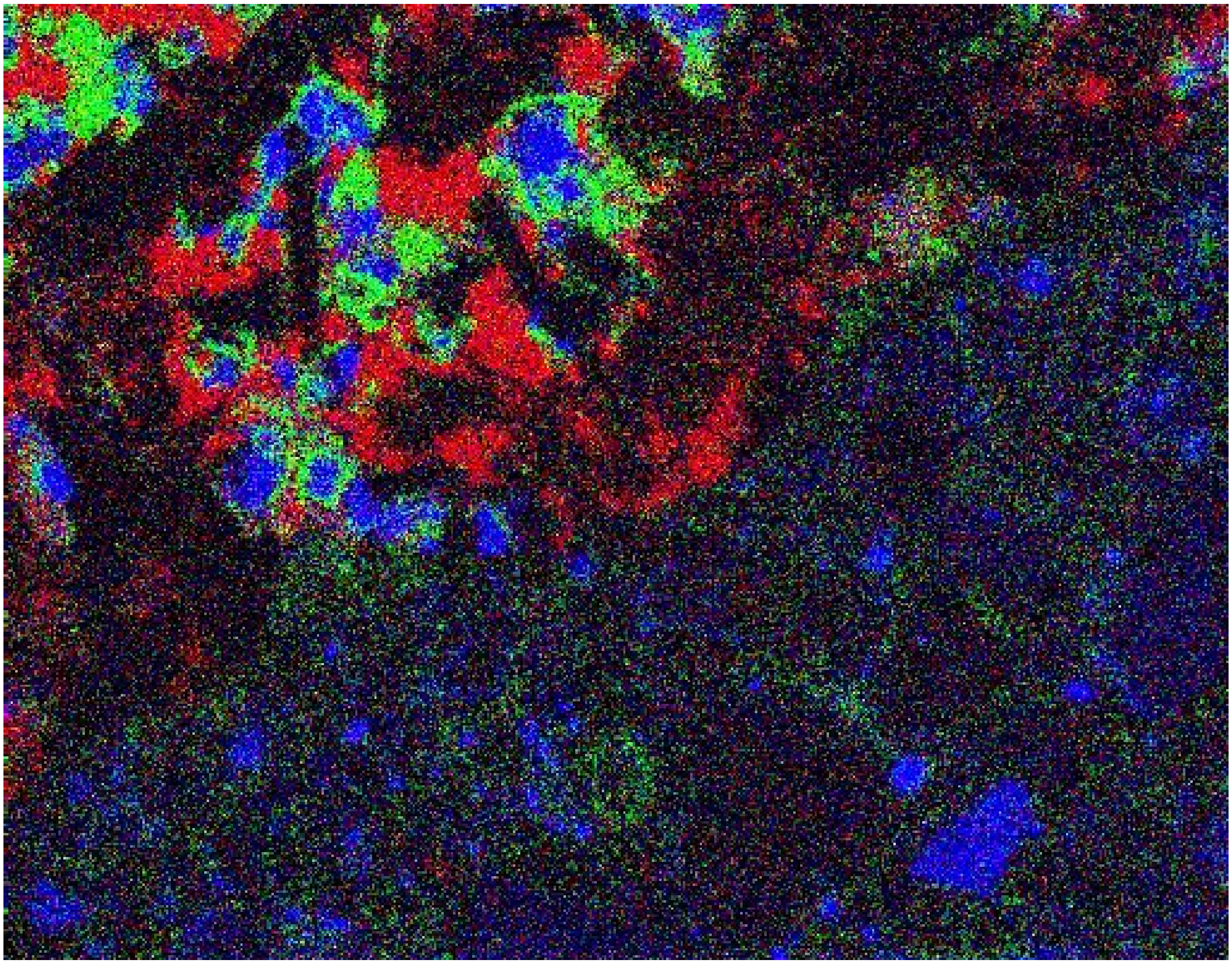


Figure 54. Combined x-ray intensity maps from the area shown in Figure 49 where maps for potassium (red color), iron, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	P
G	Ca
B	Mg
Yellow	P + Ca
Purple	P + Mg
Cyan	Ca + Mg

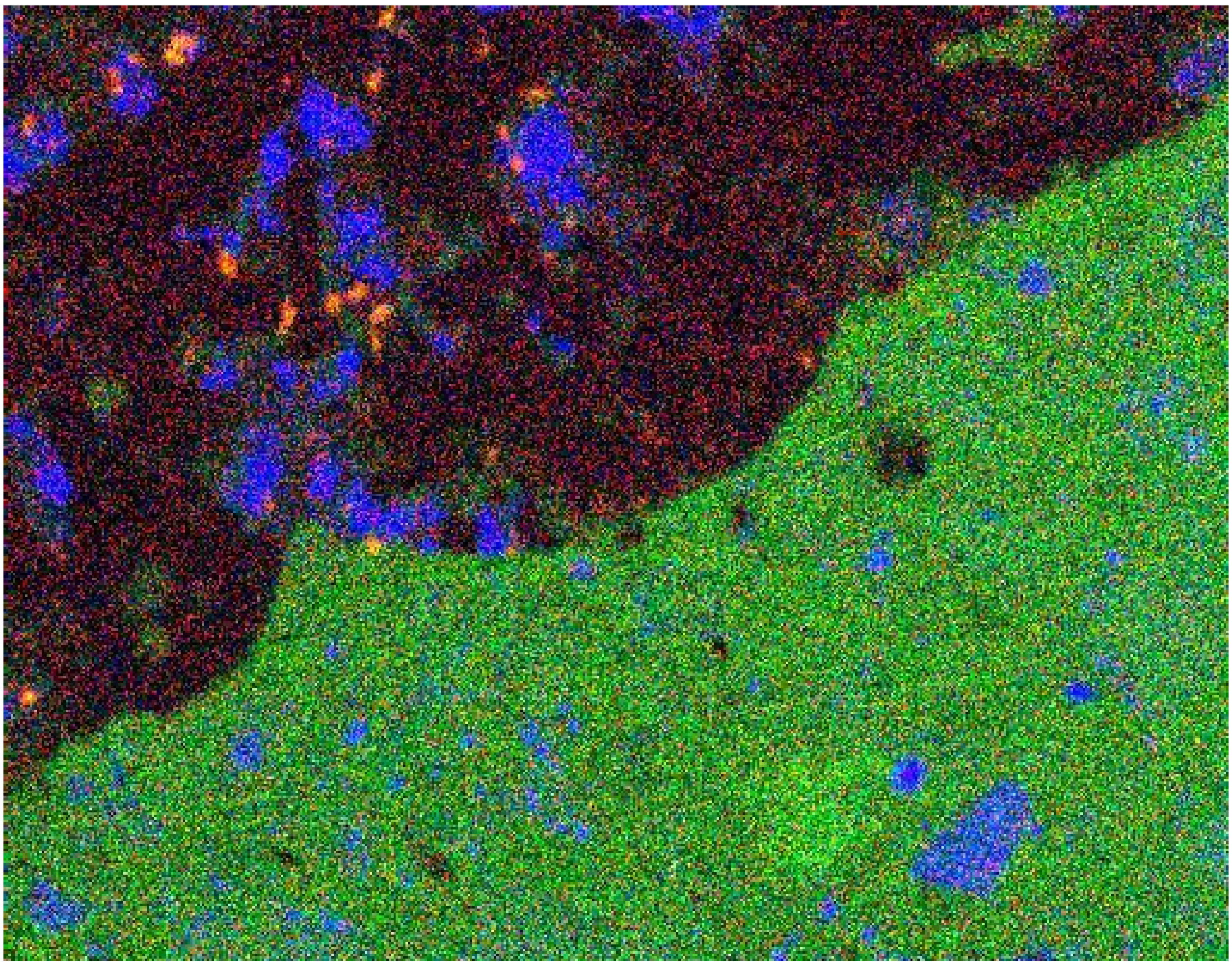


Figure 55. Combined x-ray intensity maps from the area shown in Figure 49 where maps for phosphorous (red color), calcium, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

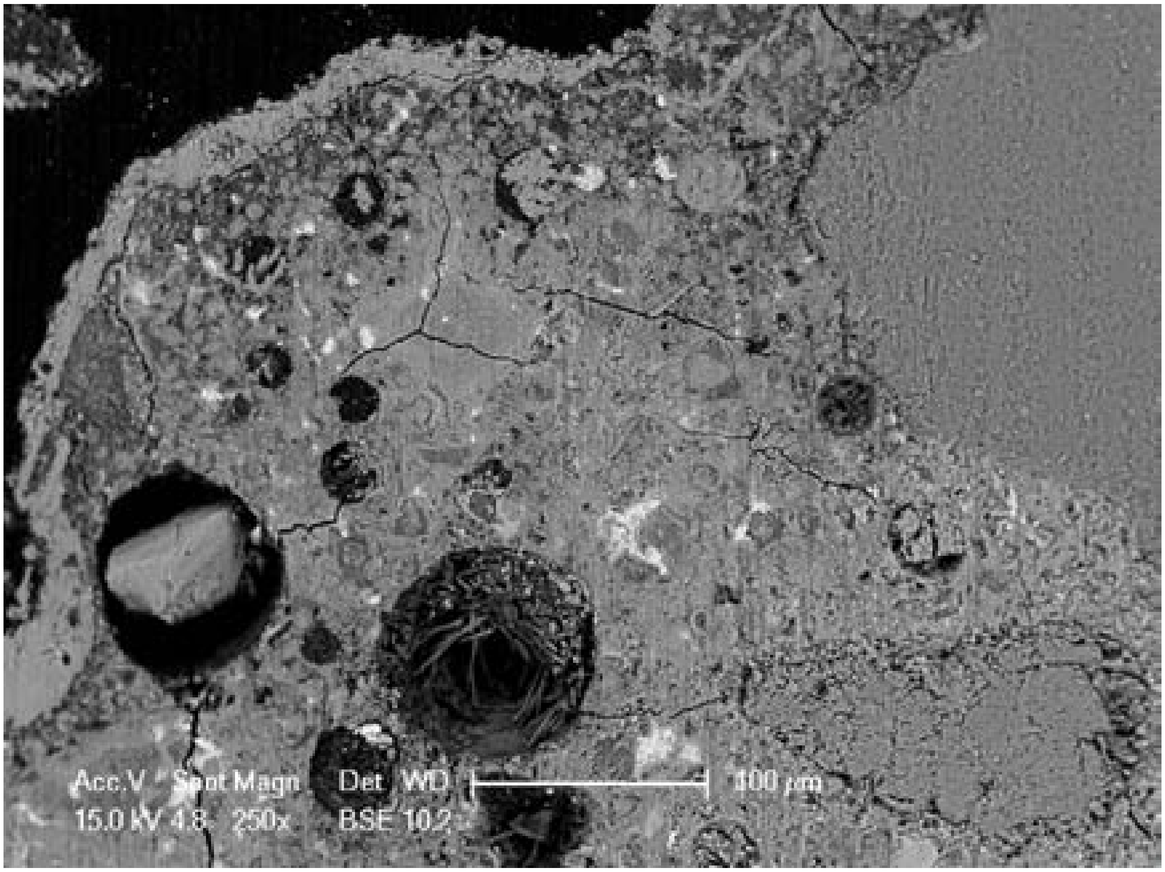


Figure 56. Backscattered electron image of showing the joint surface and cement paste matrix near the joint surface. Specimen prepared from core sample L&F C.

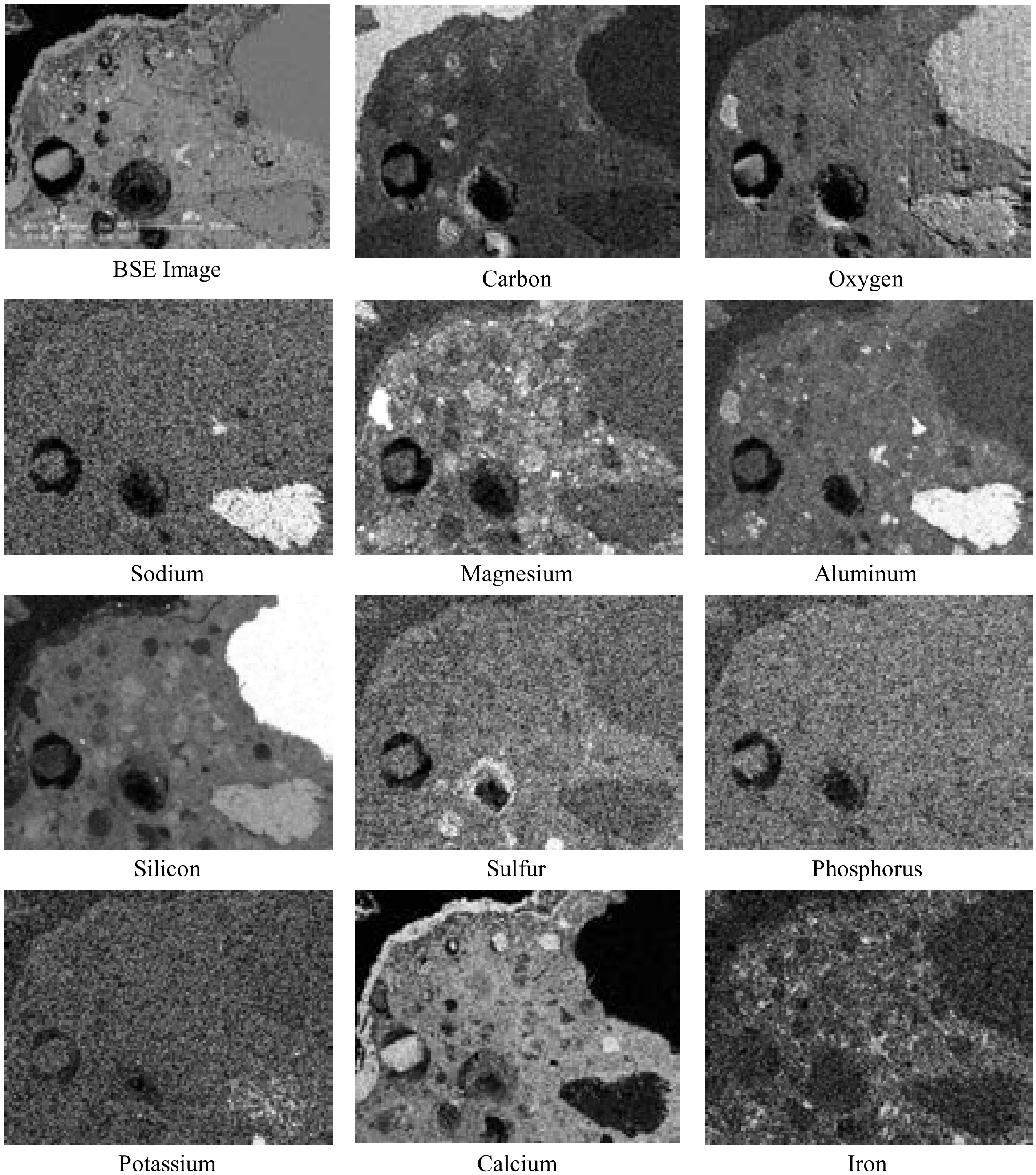


Figure 57. X-ray intensity maps of the same area shown in Figure 56.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

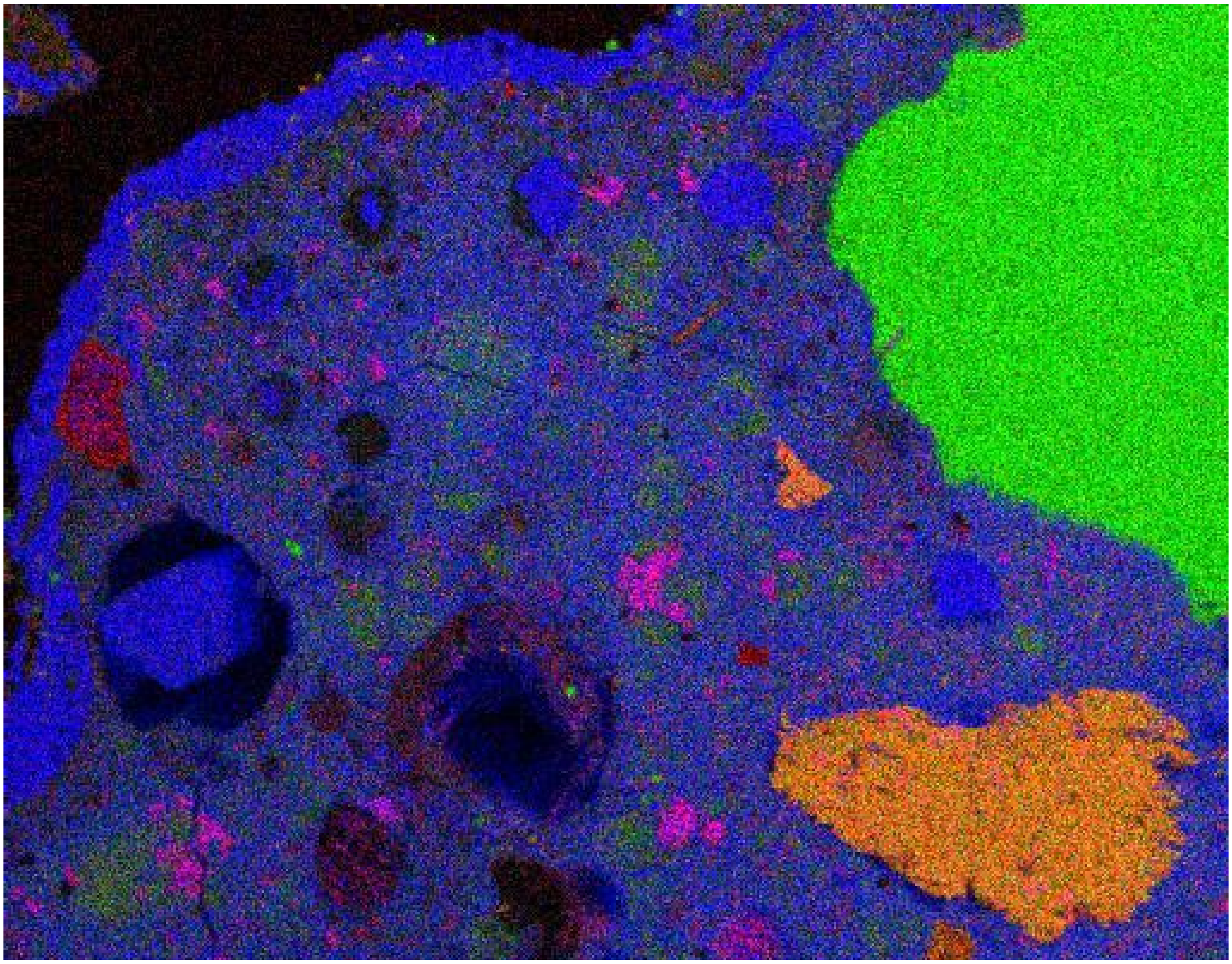


Figure 58. Combined x-ray intensity maps from the area shown in Figure 56 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

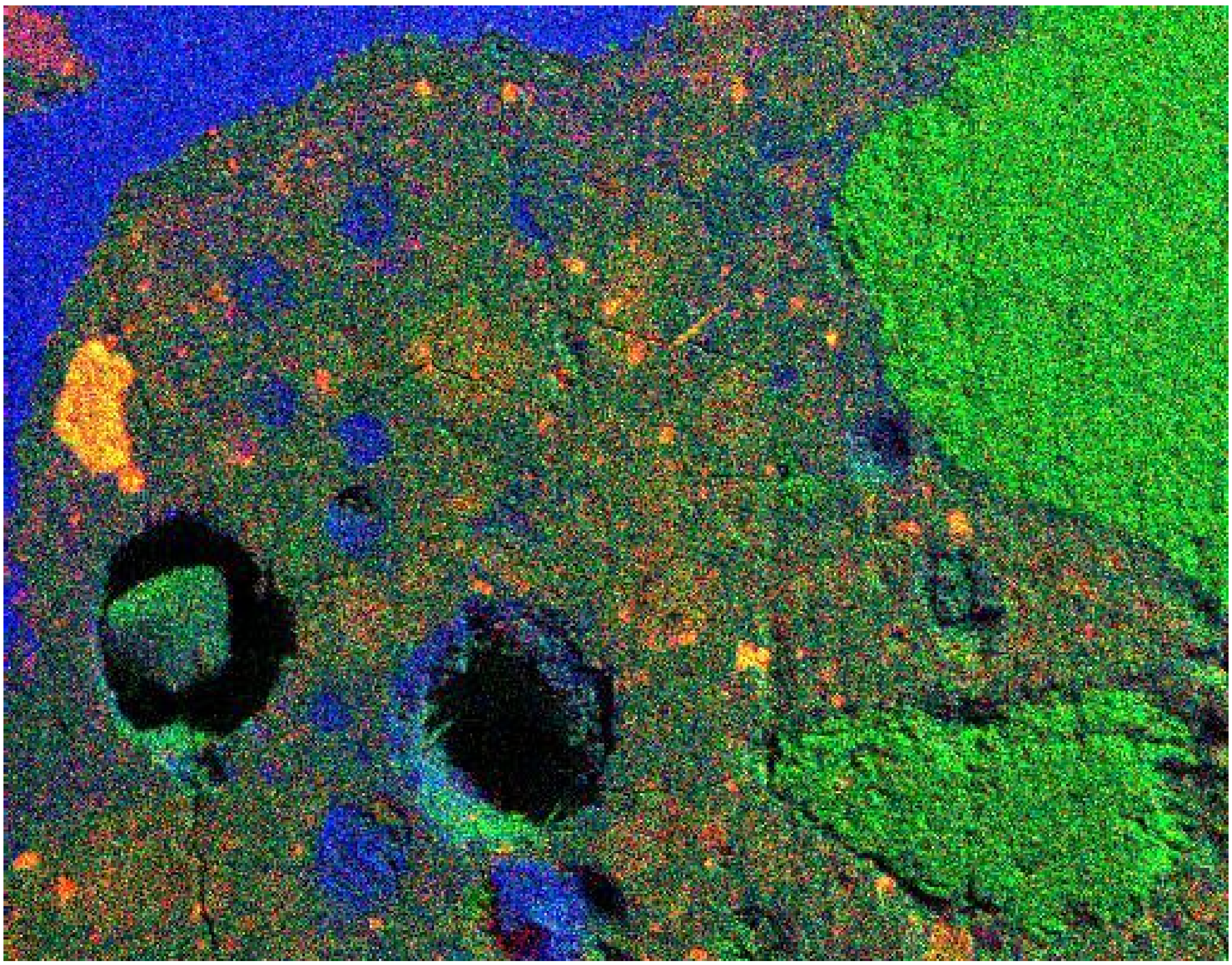


Figure 59. Combined x-ray intensity maps from the area shown in Figure 56 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange) indicate varying ratios of the elements combined to form that color.

R	Al
G	S
B	Ca
Yellow	Al + S
Purple	Al +Ca
Cyan	S + Ca

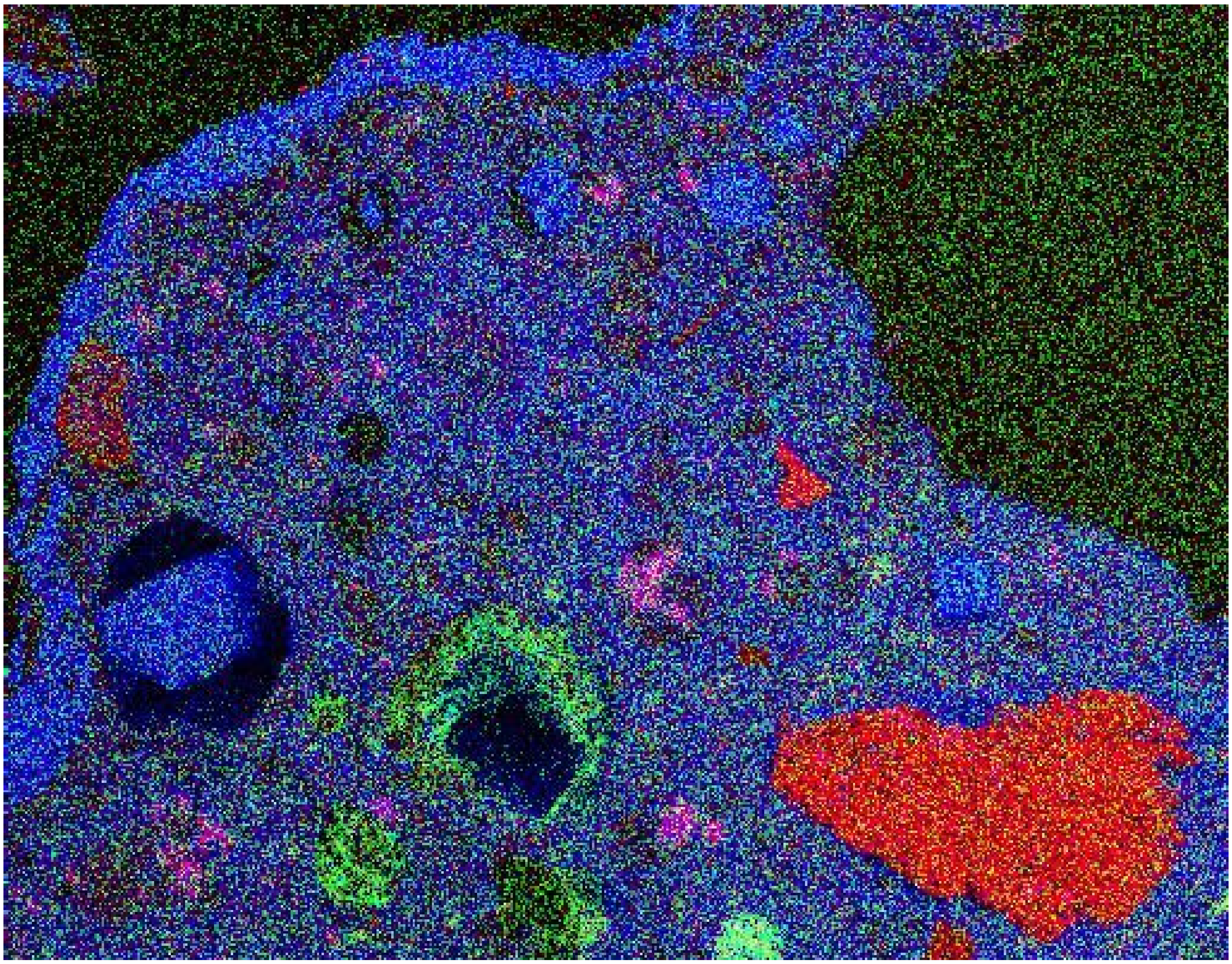


Figure 60. Combined x-ray intensity maps from the area shown in Figure 56 where maps for aluminum (red color), sulfur, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	P
G	Ca
B	Mg
Yellow	P + Ca
Purple	P + Mg
Cyan	Ca + Mg

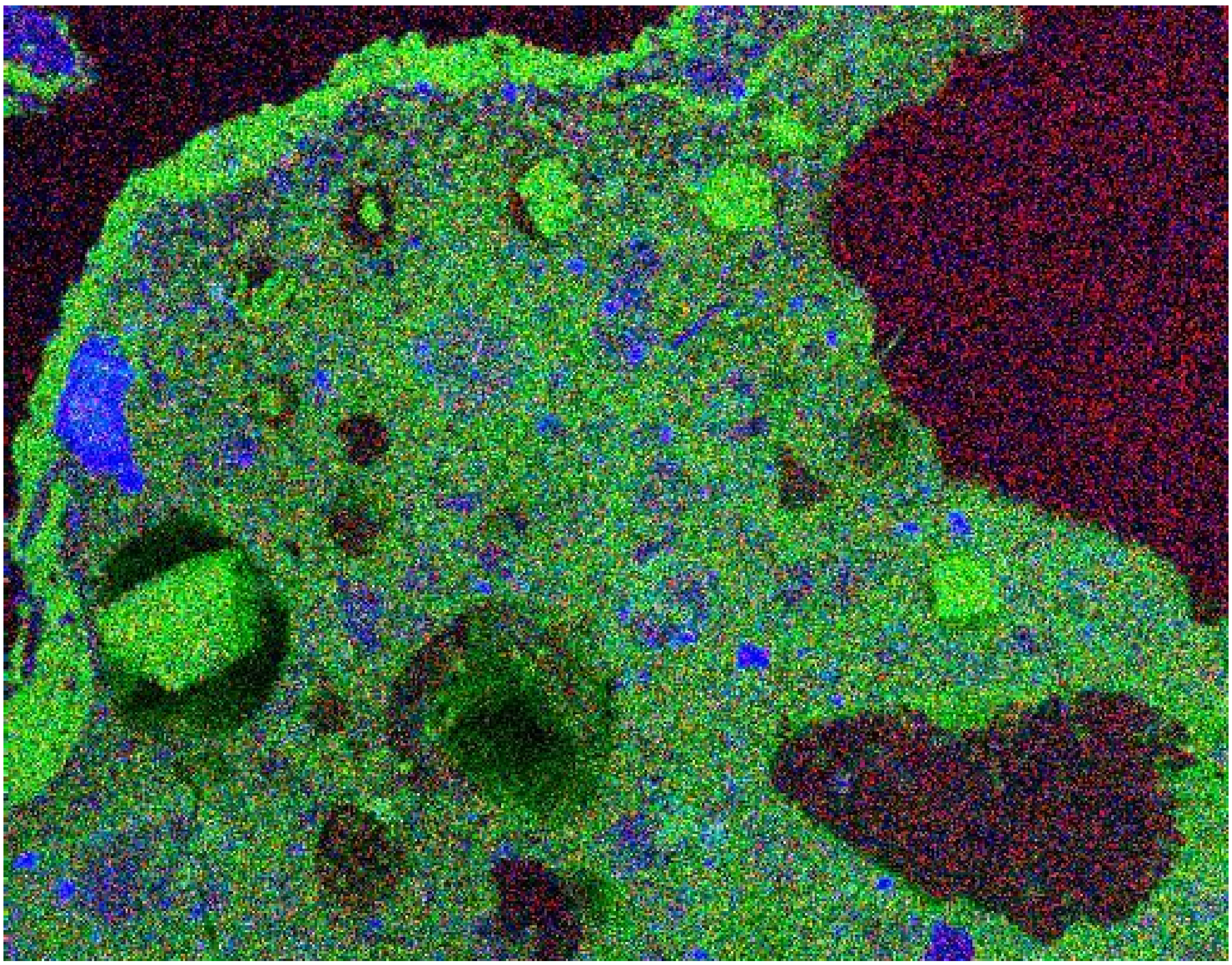


Figure 61. Combined x-ray intensity maps from the area shown in Figure 56 where maps for phosphorous (red color), calcium, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	
G	Fe
B	Mg
Cyan	Fe + Mg

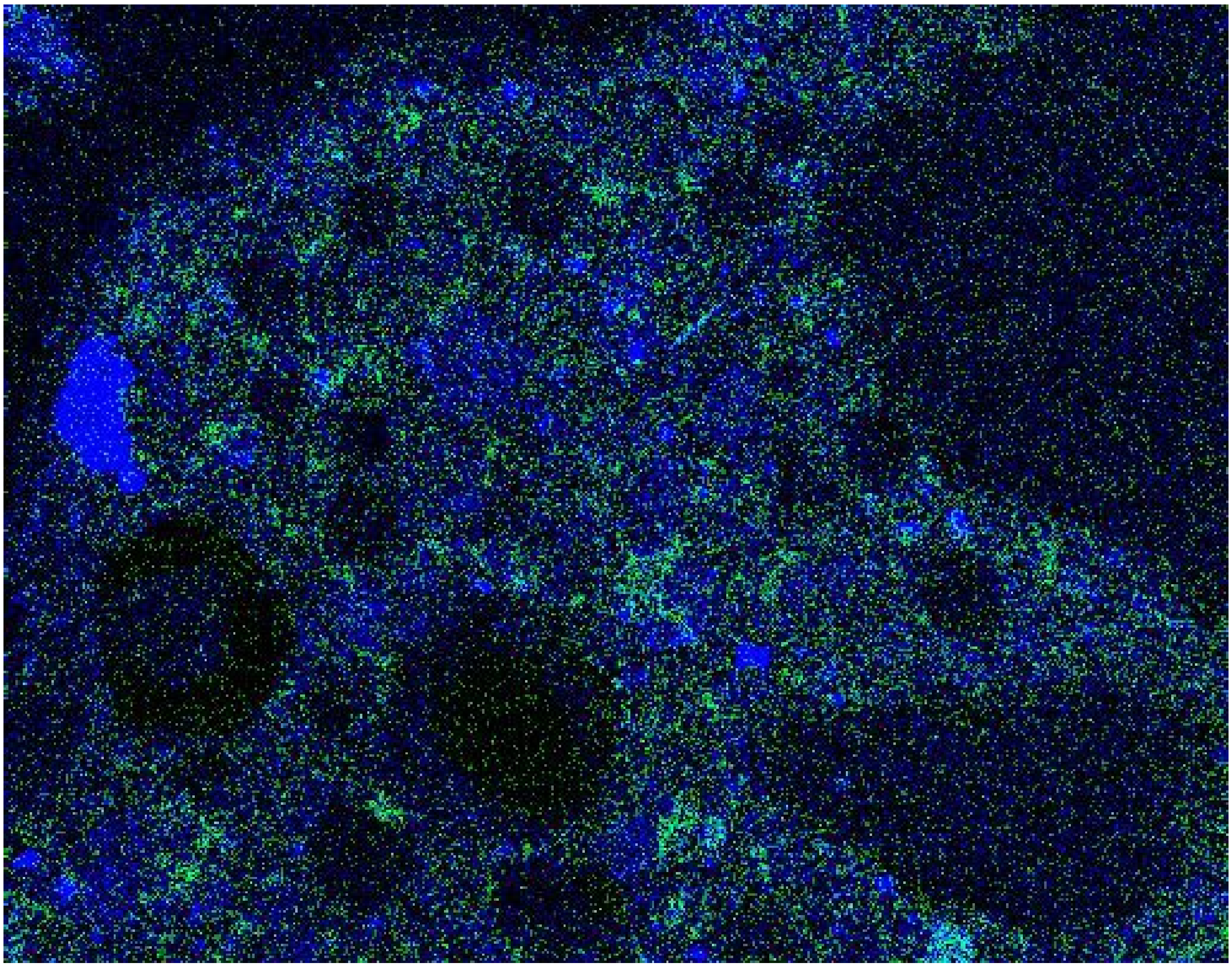


Figure 62. Combined x-ray intensity maps from the area shown in Figure 56 where maps for iron (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., cyan) indicate varying ratios of the elements combined to form that color.

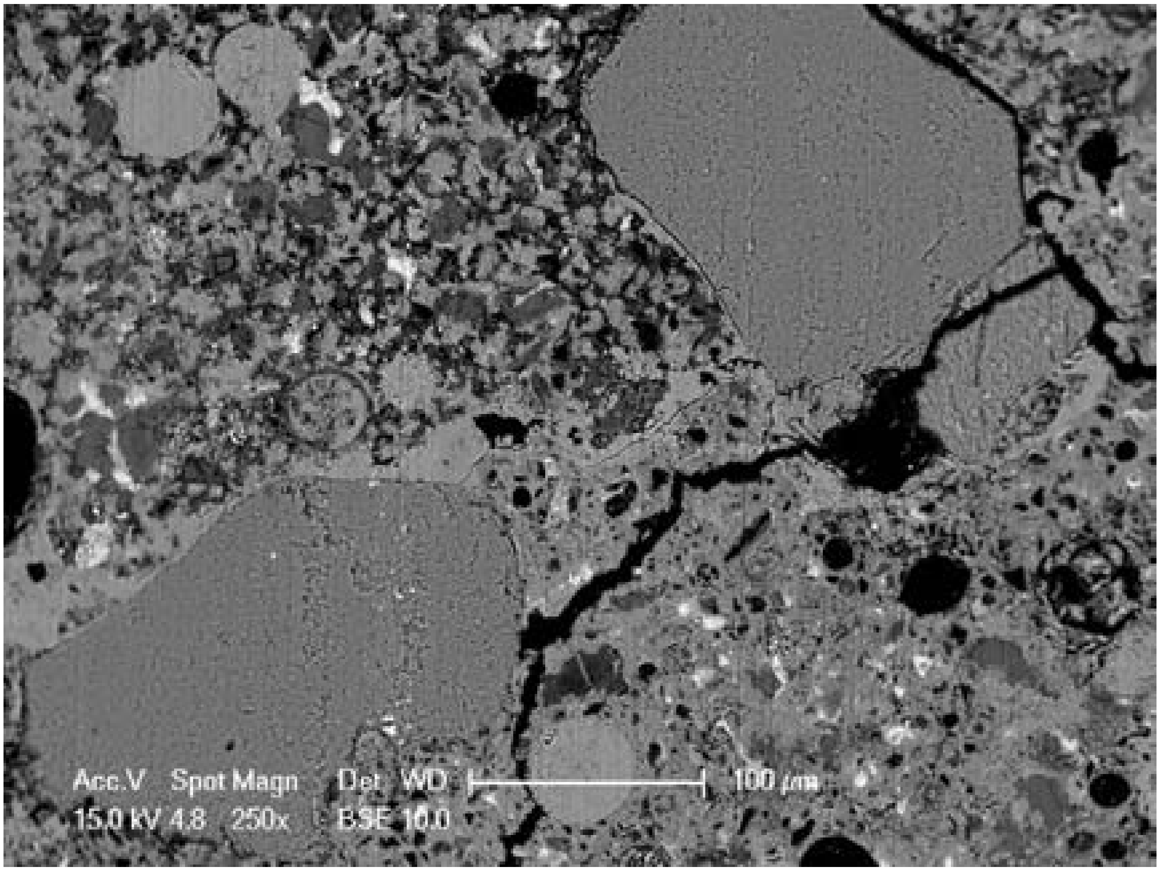


Figure 63. Backscattered electron image showing the cement paste matrix near the joint surface. Specimen prepared from core sample L&F C.

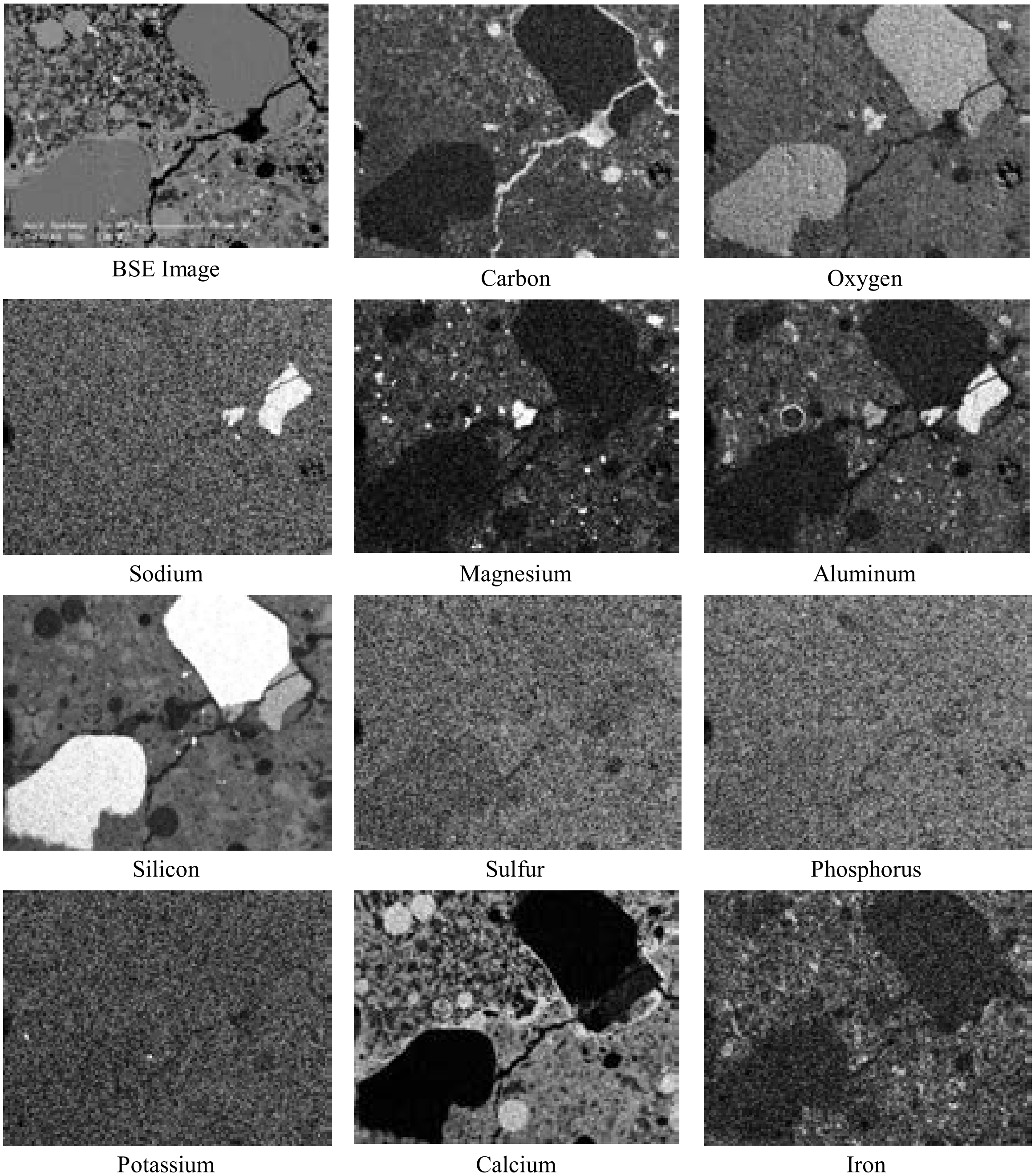


Figure 64. X-ray intensity maps of the same area shown in Figure 63.

R	Al
G	Si
B	Ca
Yellow	Al + Si
Purple	Al + Ca
Cyan	Si + Ca

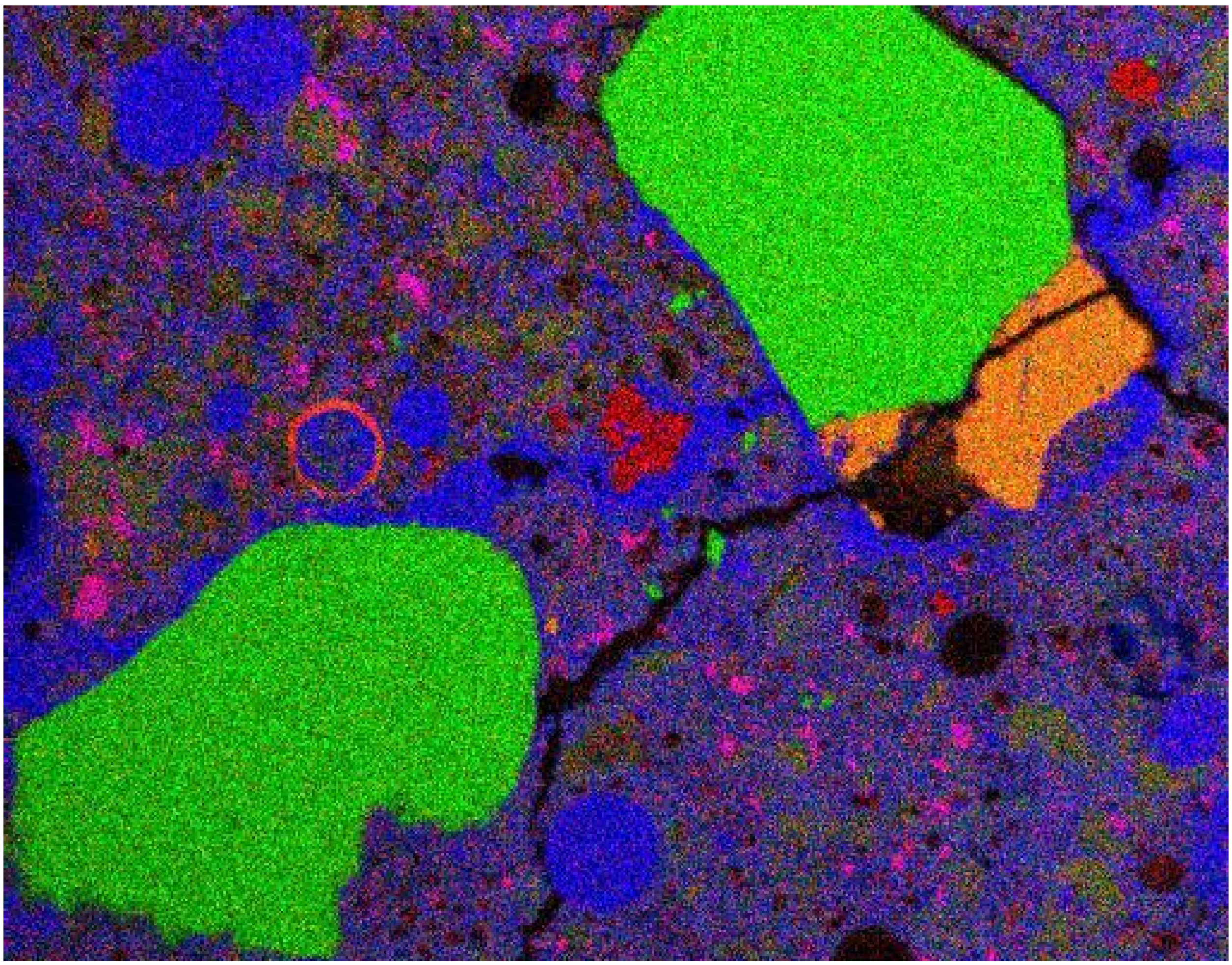


Figure 65. Combined x-ray intensity maps from the area shown in Figure 63 where maps for aluminum (red color), silicon, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	Mg
G	O
B	C
Yellow	Mg + O
Purple	Mg + C
Cyan	O + C

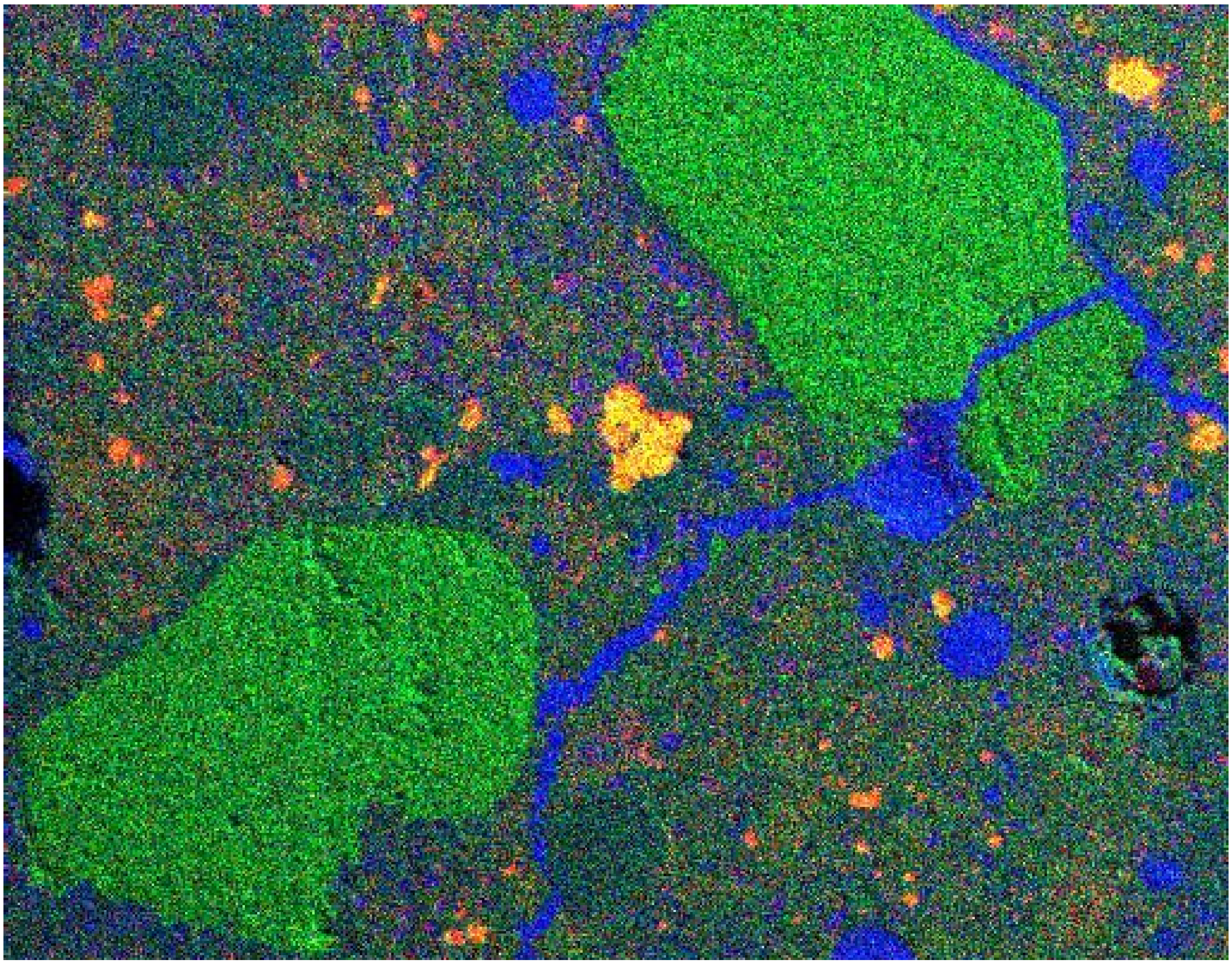


Figure 66. Combined x-ray intensity maps from the area shown in Figure 63 where maps for magnesium (red color), oxygen, (green color) and carbon (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of yellow/orange) indicate varying ratios of the elements combined to form that color.

R	Al
G	S
B	Ca
Yellow	Al + S
Purple	Al +Ca
Cyan	S + Ca

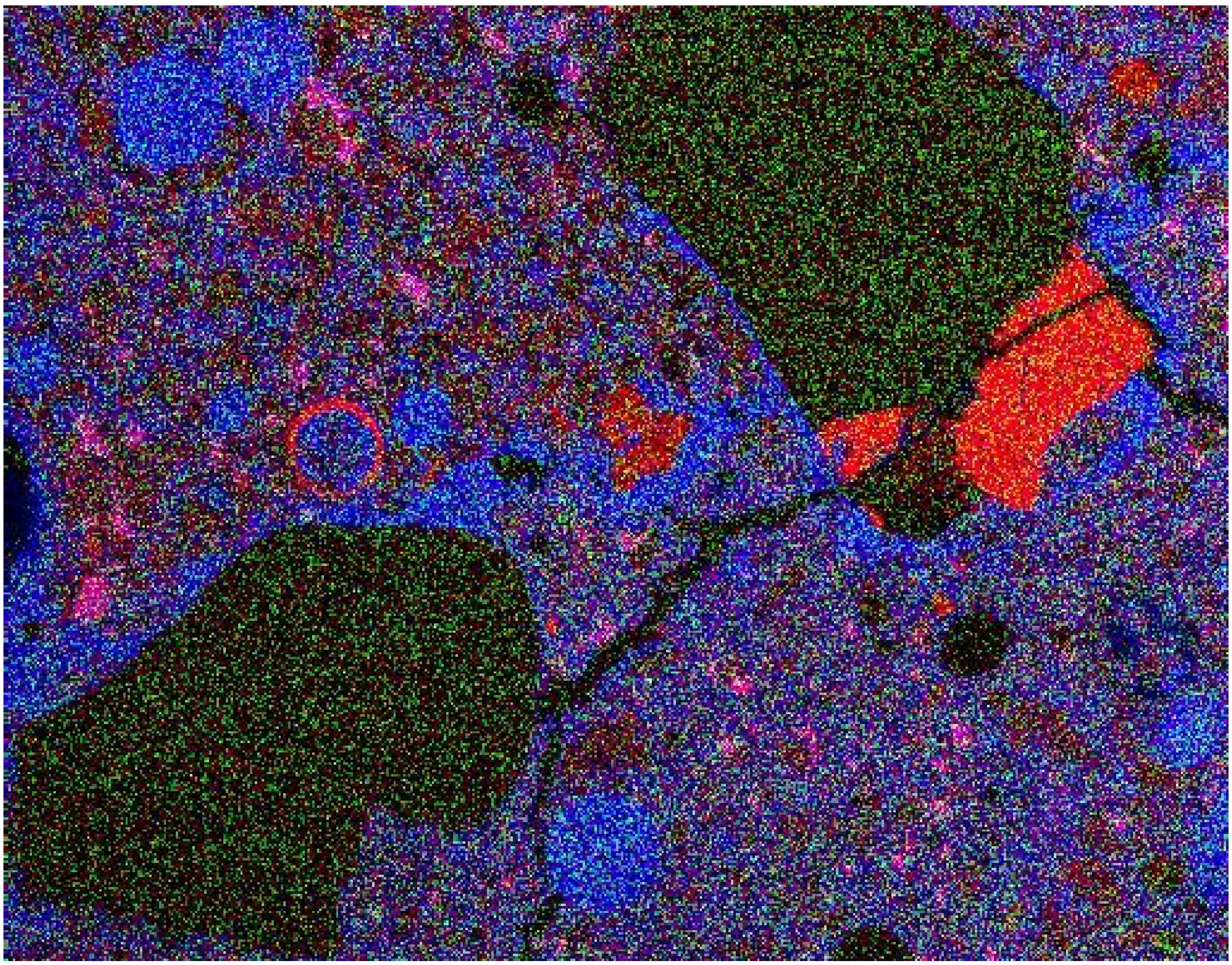


Figure 67. Combined x-ray intensity maps from the area shown in Figure 63 where maps for aluminum (red color), sulfur, (green color) and calcium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	P
G	Ca
B	Mg
Yellow	P + Ca
Purple	P + Mg
Cyan	Ca + Mg

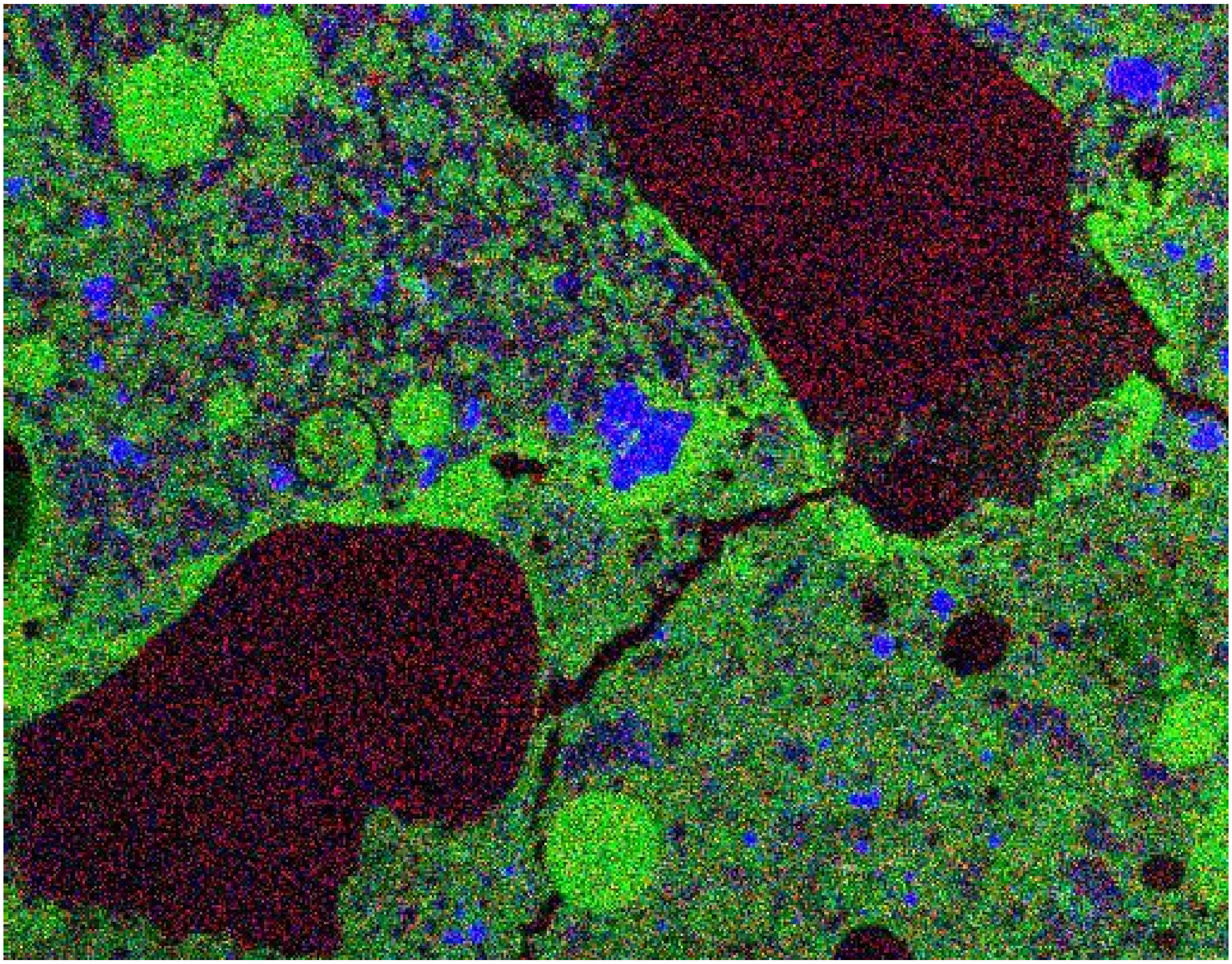


Figure 68. Combined x-ray intensity maps from the area shown in Figure 63 where maps for phosphorous (red color), calcium, (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., shades of purple) indicate varying ratios of the elements combined to form that color.

R	
G	Fe
B	Mg
Cyan	Fe + Mg

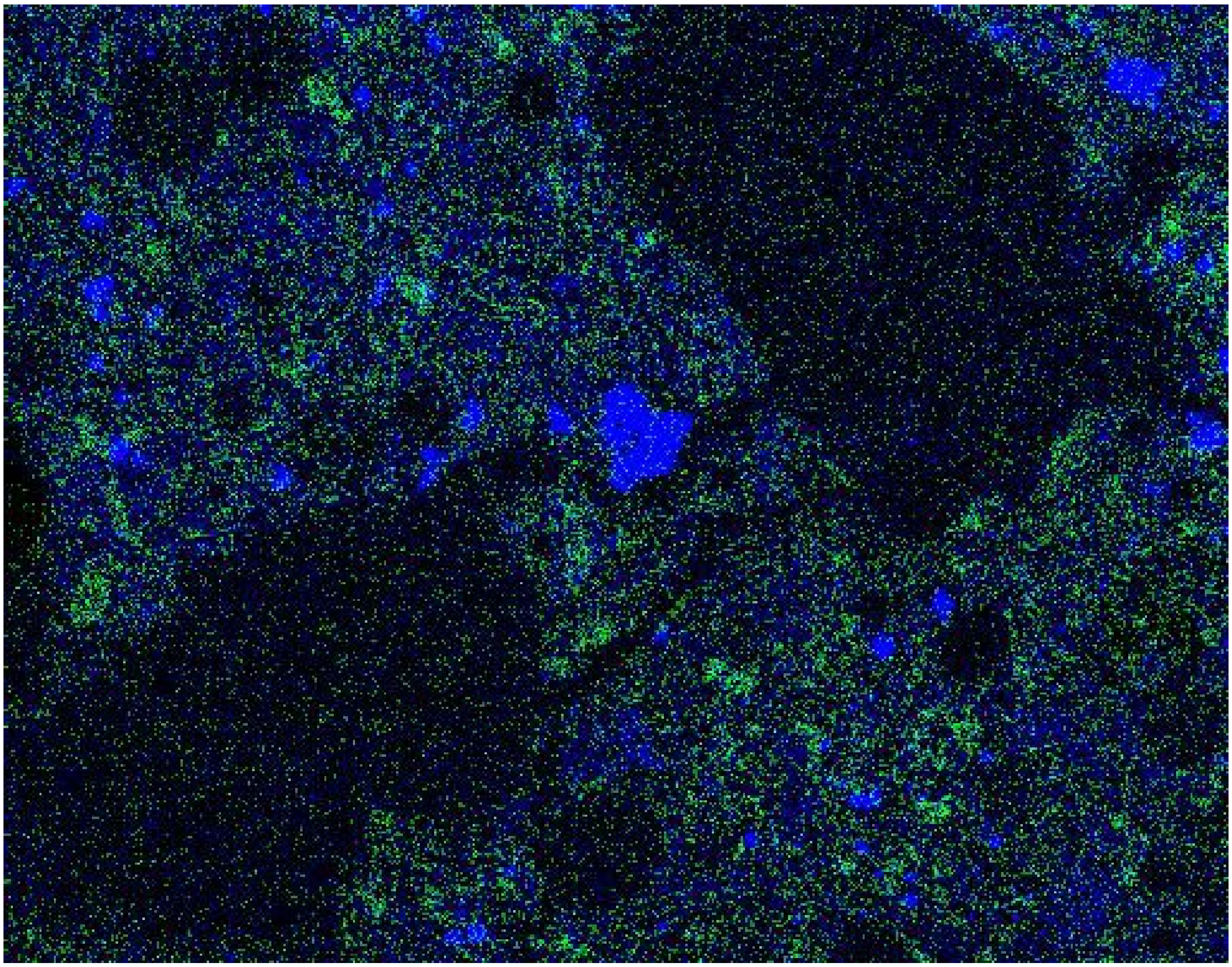


Figure 69. Combined x-ray intensity maps from the area shown in Figure 63 where maps for iron (green color) and magnesium (blue color) are combined to show discrete and coincident locations of elements. Other colors result from the addition of colors as shown in the key at the top of the image. Shades of color (e.g., cyan) indicate varying ratios of the elements combined to form that color.

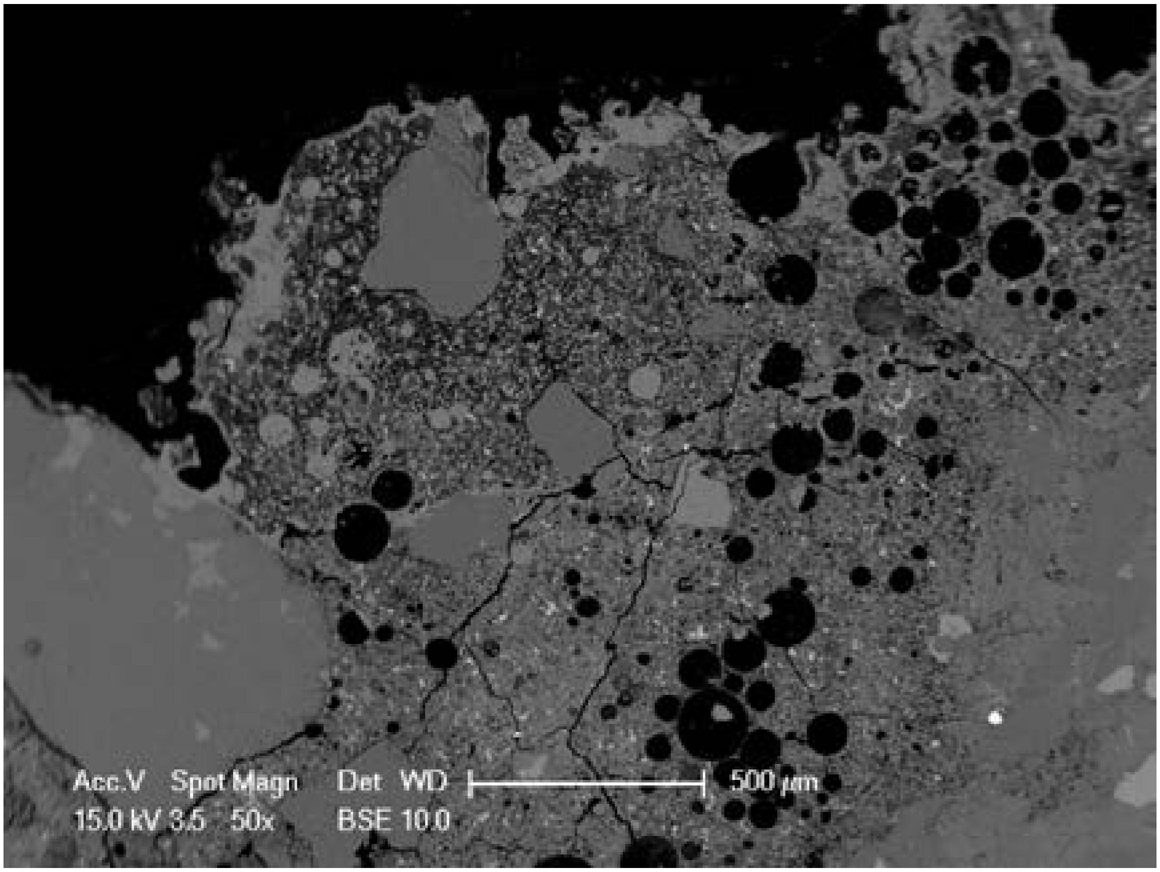


Figure 70. Backscattered electron image showing the joint surface and cement paste matrix near the joint surface. Specimen prepared from core sample L&F C.

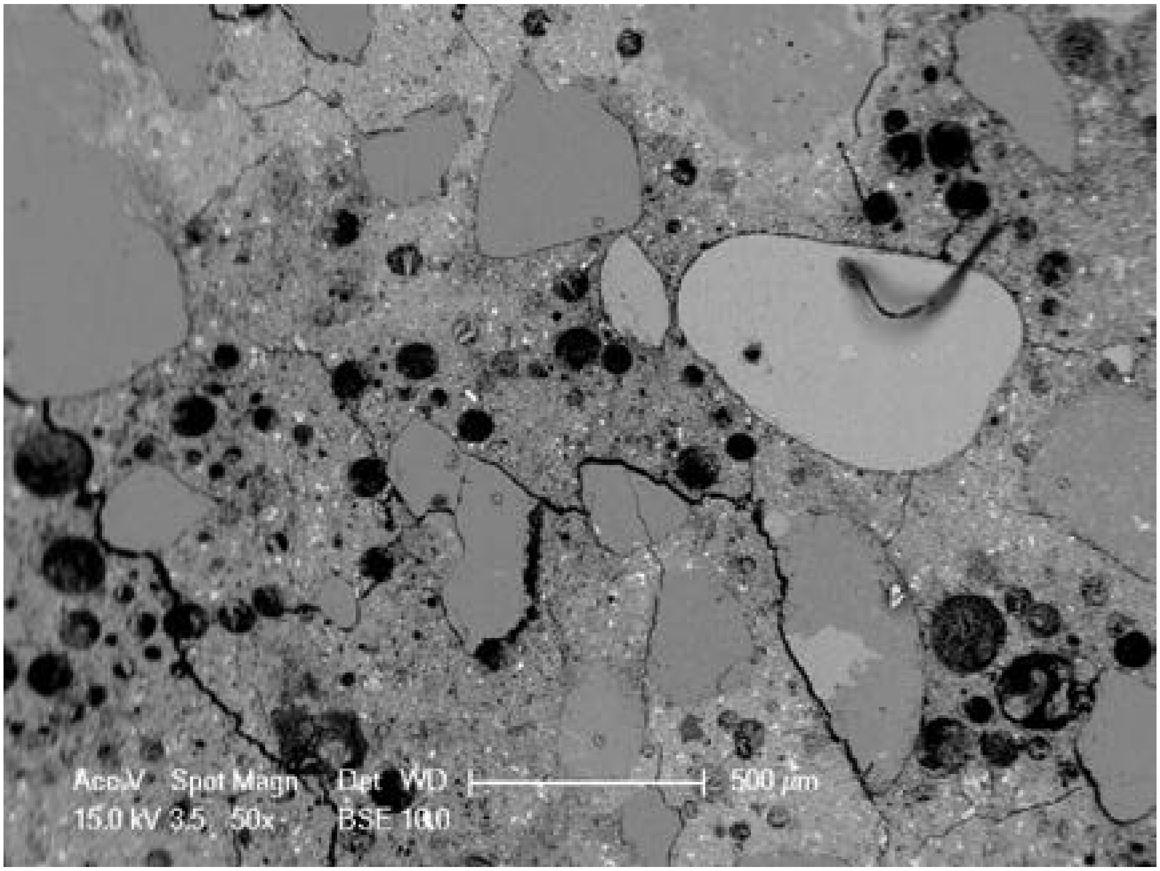


Figure 71. Backscattered electron image showing the cement paste matrix near the joint surface. Regions of the cement paste, as shown here, appear to be altered. Specimen prepared from core sample L F C.

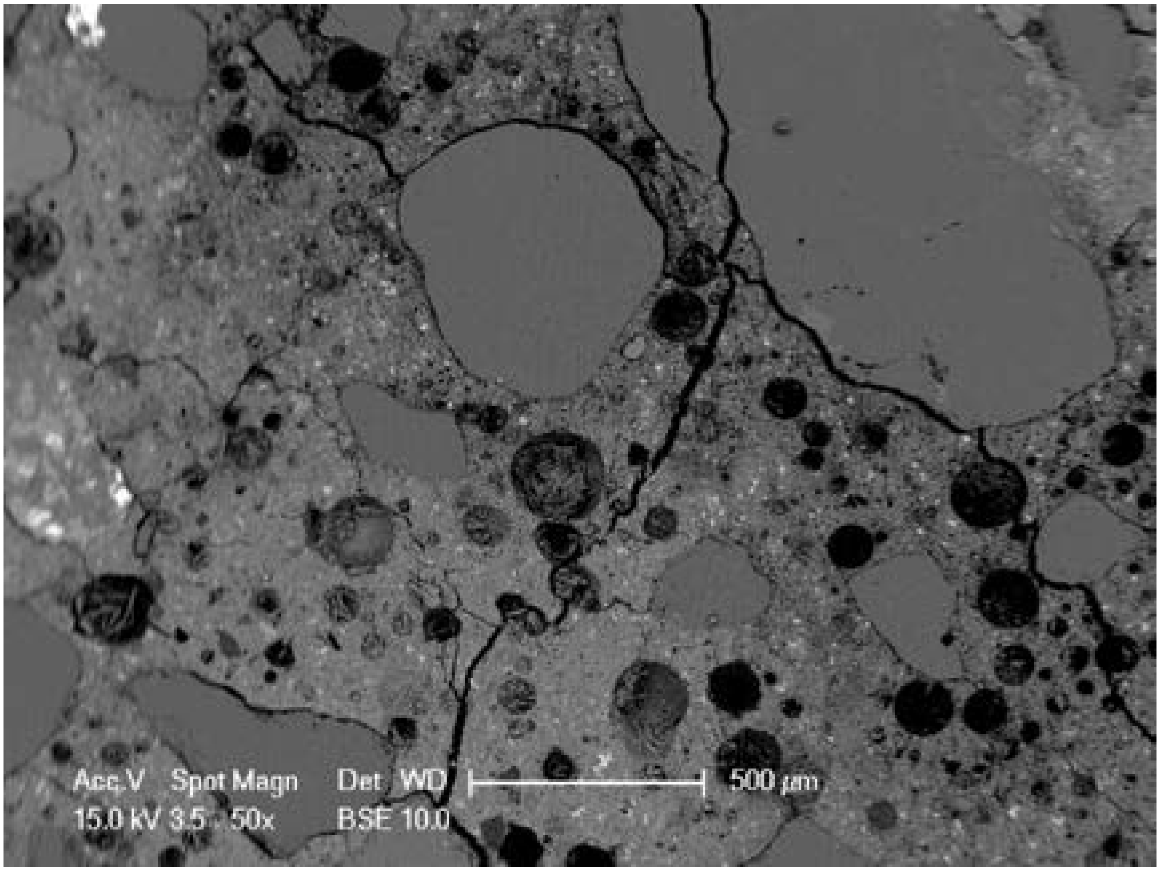


Figure 72. Backscattered electron image showing the cement paste matrix near the joint surface. Regions of the cement paste, as shown here, appear to be altered. Specimen prepared from core sample L F C.

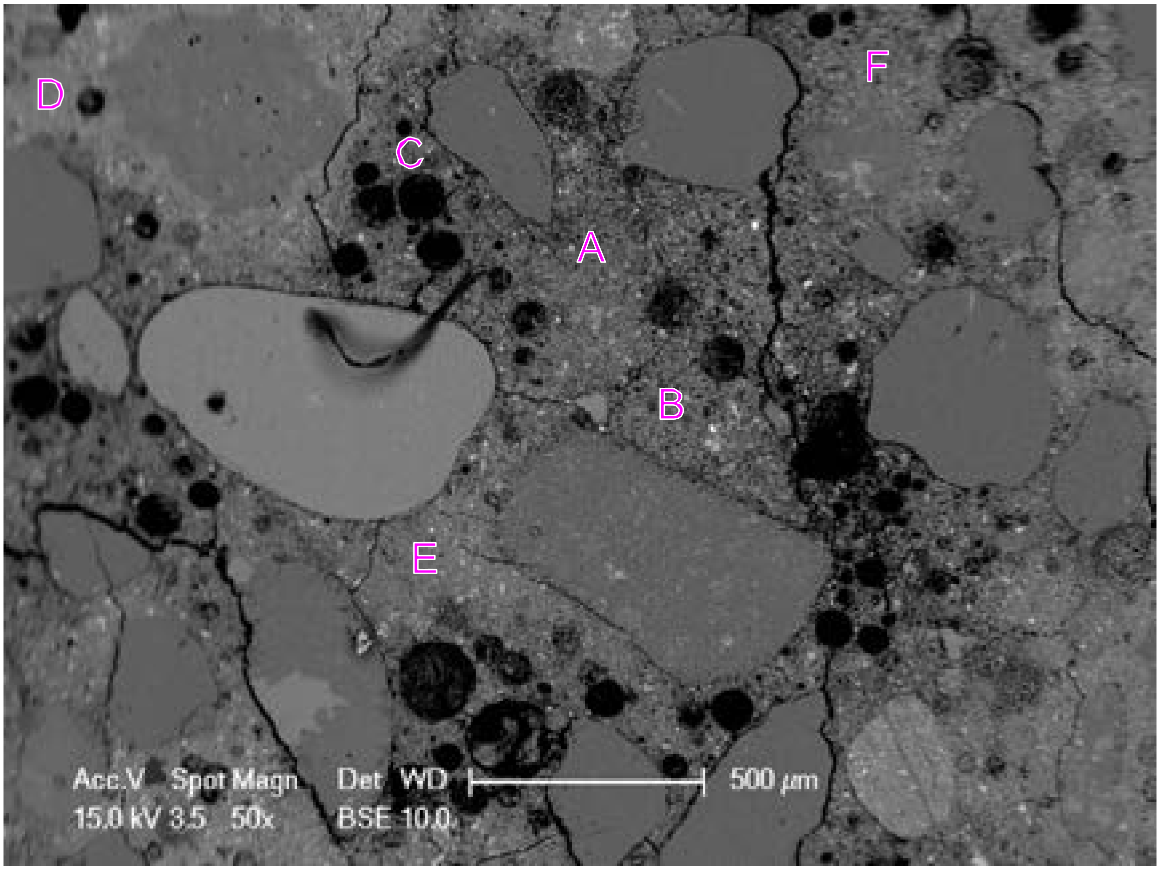


Figure 73. Backscattered electron image showing the cement paste matrix near the joint surface. Regions of the cement paste, as shown here, appear to be altered. Specimen prepared from core sample L F C.

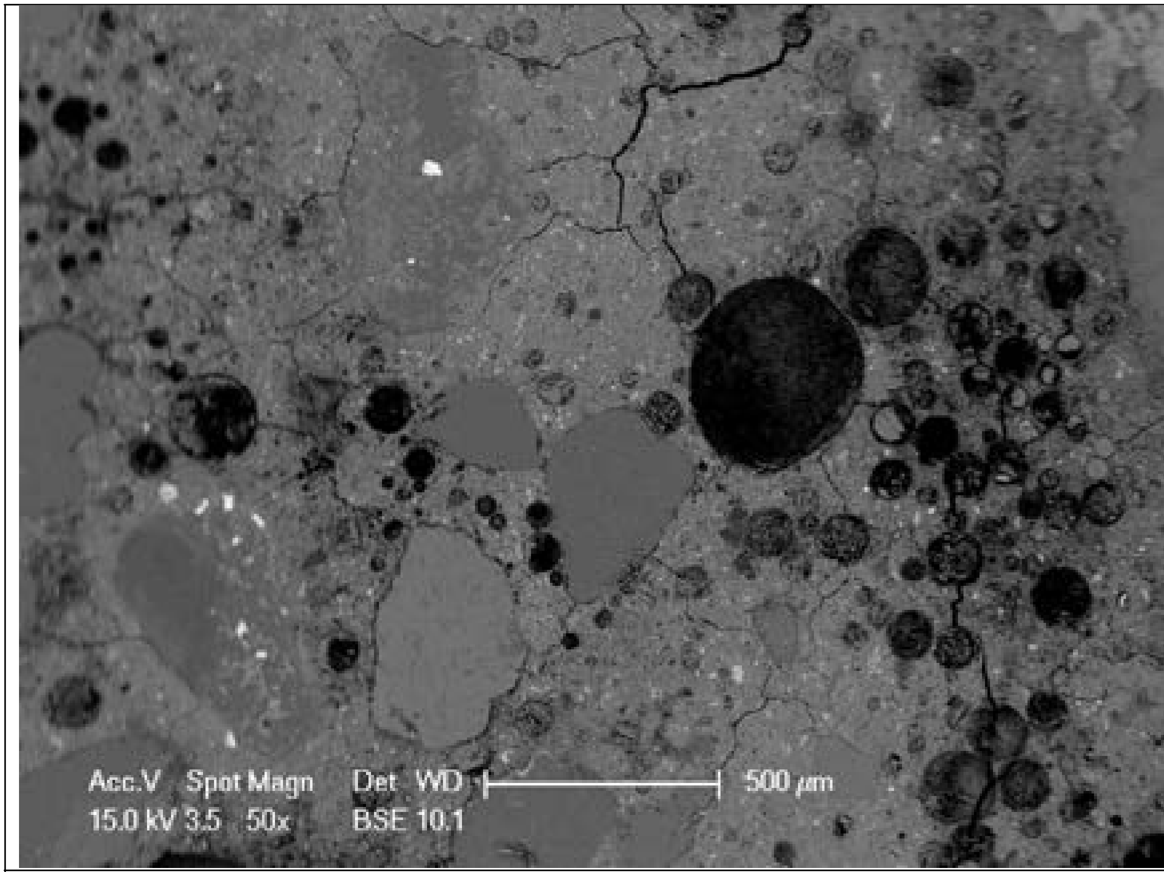


Figure 74. Backscattered electron image showing the cement paste matrix near the joint surface. Regions of the cement paste, as shown here, appear to be altered. Note the clustering of air voids. Specimen prepared from core sample L F C.

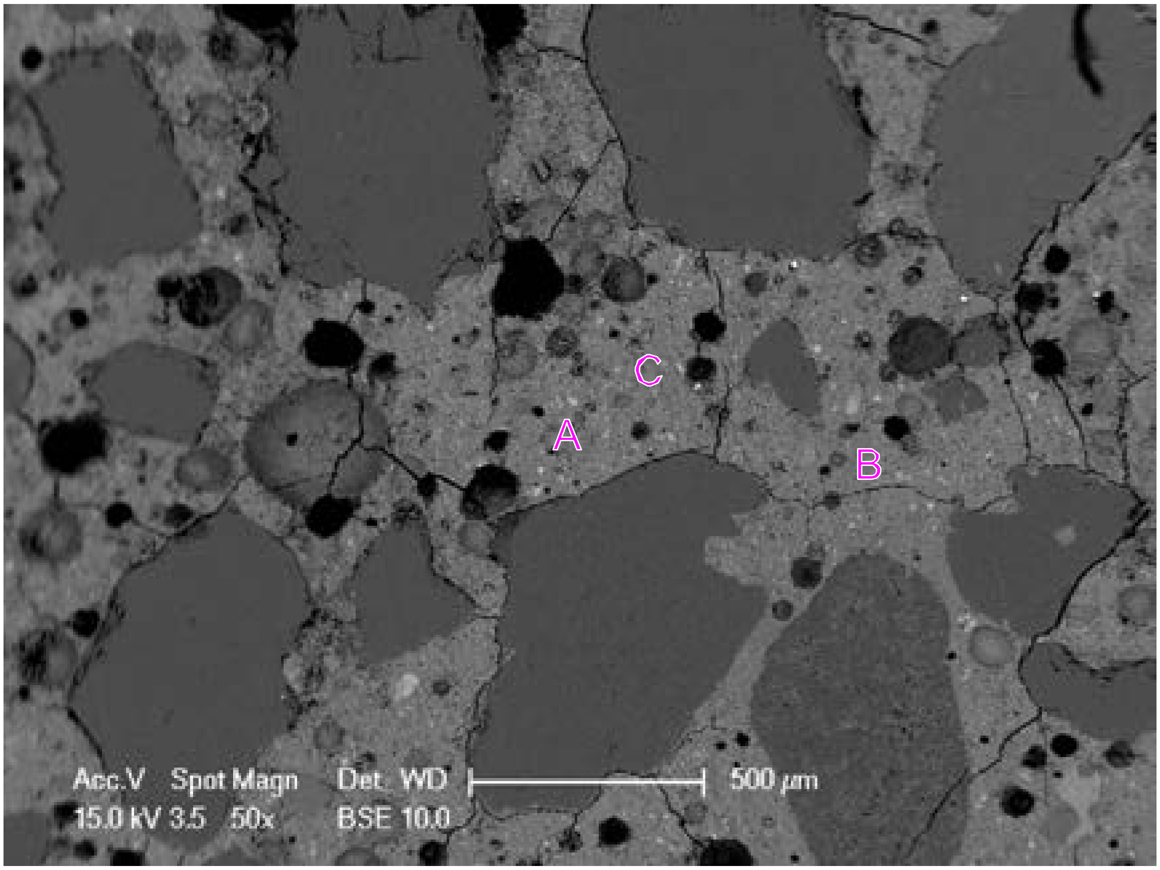


Figure 75. Backscattered electron image showing the cement paste matrix away from the joint surface. Regions of the cement paste, as shown here, do not appear to be altered. Specimen prepared from core sample L F C.

APPENDIX C: FREEZE-THAW AND ASR TESTING SUMMARIES

Investigation and Assessment of Colored "
Concrete Pavement "

LRRB Inv. 929 "

Amendment No. 1 to MnDOT Contract No. "
01219 "

Submitted by

W. Morrison !
AET Project Manager !

January 24, 2014

American Engineering Testing, Inc.

Table C-1. Freeze-Thaw Testing Summary (ASTM C666) "

Lab Mix, SSD (pcy) [1]	Mix #1-Control-No pigment - 0.43 w/cm	Mix #2-Pigment 4%-0.43 w/cm	Mix #3-Pigment 4%-0.40 w/cm	Mix #4-Pigment 6%-0.43 w/cm
Lafarge Davenport (lbs)	592	592	592	592
Portage Fly Ash (lbs)	104	104	104	104
Lakeville +3/4", Coarse Aggregate. (lbs)	742	742	757	742
Lakeville -3/4", Coarse Aggregate. (lbs)	823	823	839	823
Lakeville -1/2", Coarse Aggregate. (lbs)	274	274	280	274
Lakeville Fine Aggregate (lbs)	966	966	985	966
Water (lbs)	299.0	299.0	278.4	299.0
Vinsol Resin, Air Entrainer (oz/cwt)	0.8	0.8	0.9	0.8
Pigment, % by weight of cementitious	---	4.0	4.0	6.0
Water to Cementitious Ratio	0.43	0.43	0.40	0.43
Fresh Properties				
Unit Weight, pcf	144.0	145.2	144.8	146.0
Slump (in)	4.00	4.00	3.25	3.75
Air Content (%)	7.0	6.2	6.8	6.0
Average [2] **ASTM C666, Rapid Freezing and Thawing, Proc. A, Relative dynamic modulus, %**				
300 Cycles	94	89	97	92

Notes:

(1) Mix design provided by MnDOT. Mix identified as "Mix 3A21 HEF" July 2000. Mix adjusted for higher water to cementitious requirements of this study.

(2) Average of three 3x3x11-1/4-in beams.

Table C-2. Materials for ASTM C1567 "

Lakeville Fine Aggregate	100%
LaFarge Davenport Cement	85%
Portage Fly Ash	15%

Table C-3. ASR Testing Summary for Fine Aggregate (ASTM C1567) "

Fine Aggregate	**Mix #1 Control**	**Mix #2**	**Mix #3**	**Mix #4**
w/c	0.43	0.43	0.40	0.43
Pigment, % by weight of cement	None	4	4	6
ASTM C1567, Alkali Silica Reactivity, % Average Expansion				
4 days	0.032	0.022	0.020	0.022
7 days	0.035	0.056	0.040	0.046
11 days	0.041	0.125	0.074	0.111
14 days	0.048	0.194	0.102	0.175
21 days	0.056	0.265	0.253	0.245
28 days	0.061	0.320	0.309	0.295

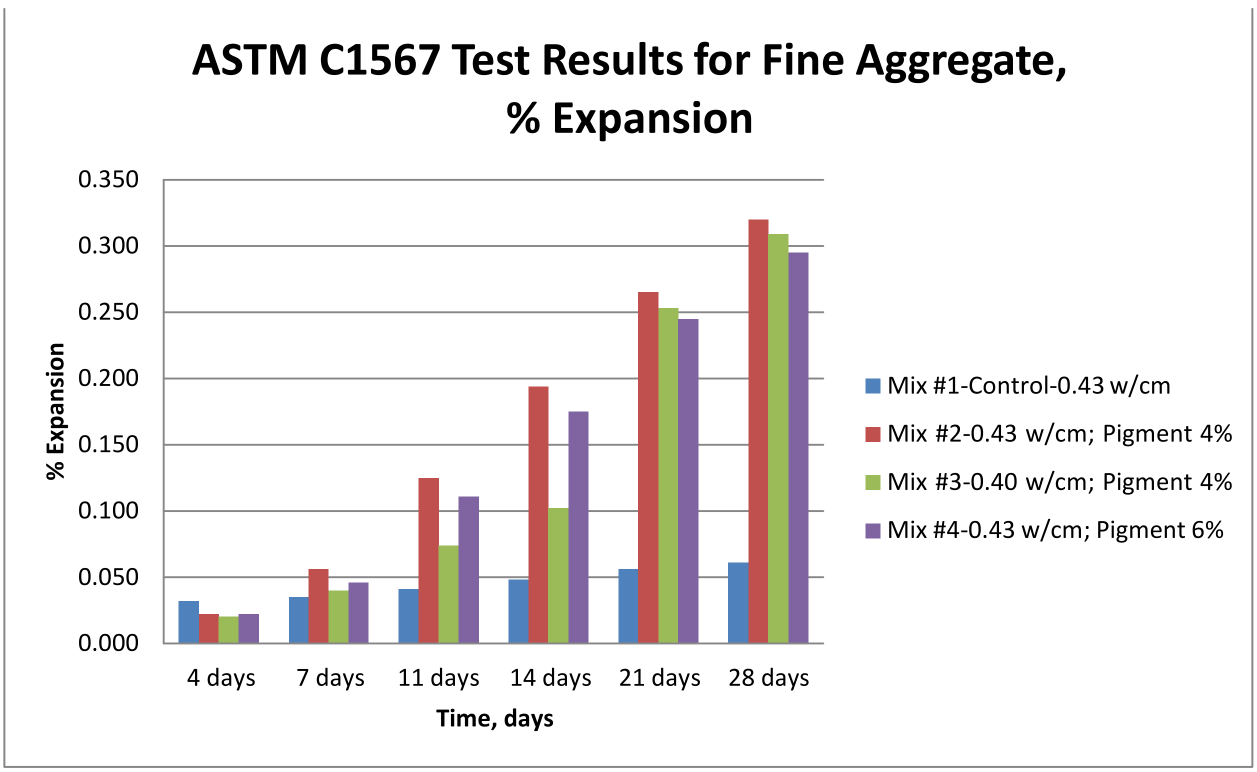


Figure C-1 Plot of results from Table C-3 (ASTM C1567)

Table C-4. Materials for ASTM C1567

Lakeville Coarse Aggregate	100%
LaFarge Davenport Cement	85%
Portage Fly Ash	15%

Table C-5. ASR Testing Summary for Coarse Aggregate (ASTM C1567)

Coarse Aggregate	Mix #1 Control	Mix #2	Mix #3	Mix #4
w/c	0.43	0.43	0.40	0.43
Pigment, % by weight of cement	None	4	4	6
ASTM C1567, Alkali Silica Reactivity, % Average Expansion				
4 days	0.023	0.031	0.022	0.027
7 days	0.036	0.044	0.033	0.041
11 days	0.065	0.076	0.056	0.078
14 days	0.083	0.098	0.065	0.099
21 days	0.121	0.144	0.109	0.144
28 days	0.144	0.170	0.132	0.165

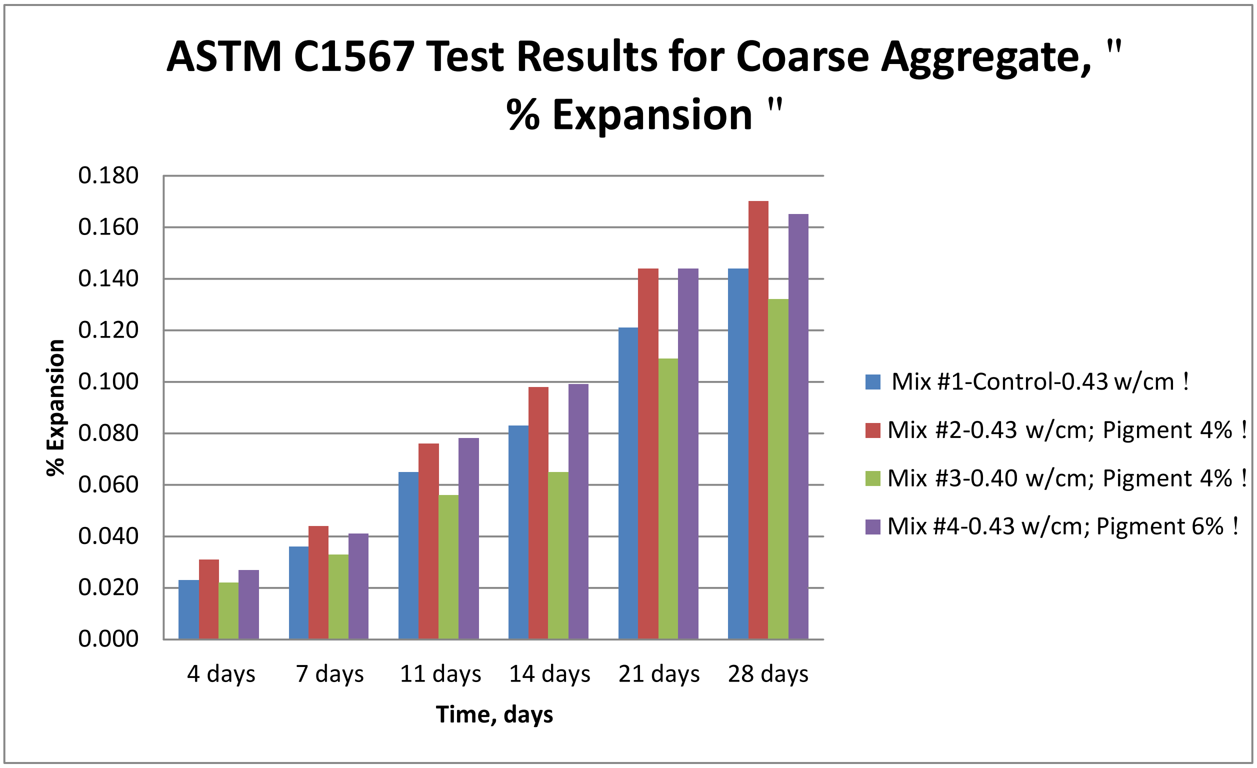


Figure C-2 Plot of results from Table C-5 (ASTM C1567)