



**PERVIOUS CONCRETE EVALUATION
MATERIALS INVESTIGATION
DENVER, COLORADO**

Prepared for:

**URBAN DRAINAGE AND FLOOD CONTROL DISTRICT
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Suite #156-B
Denver, Colorado**

Attention: Mr. Ken MacKenzie, P.E.

Project No. CT14,571-356

November 6, 2008



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SCOPE

CTL | Thompson Materials Engineers, Inc. was requested to perform a materials evaluation of select pervious concrete parking lots in the Denver Metro area as described in our Proposal No. CT08-092 (dated June 10, 2008). Our proposed scope of services included field observations and sample collection, laboratory testing and analysis and providing a report with our findings.

BACKGROUND

In June, 2008 the Urban Drainage and Flood Control District (UDFCD) issued a temporary moratorium on the Best Management Practice (BMP) use of porous concrete pavement due to poorly performing pervious concrete in the Denver Metro area. Speculation as to the causes of the failures included chemical interaction with magnesium chloride, mechanical shearing and/or abrasion by tires, freeze-thaw conditions, improper concrete mix design and improper placement and/or curing techniques.

Four sites were selected by UDFCD for investigation. Each of the sites had a portion of their parking lots recently constructed with pervious concrete and each was displaying various stages of distress. All of the sites were constructed between 2005 and 2007. We were not supplied with any additional information regarding the mix designs, testing procedures or construction practices for any of the sites.

SITE A (Photos 7 & 8)

Site A is the control site for this evaluation. The pervious concrete was not displaying any significant distress or deterioration at the time of our investigation.

SITE B (Photos 1 & 2)

The pervious concrete at Site B was experiencing significant deterioration and servicability was impacted. Select repairs had been performed due to deterioration of the surface.



SITE C (Photos 3 & 4)

The pervious concrete at Site C was experiencing minimal deterioration and servicability was not impacted.

SITE D (Photos 5 & 6)

The pervious concrete at Site D was experiencing significant deterioration and servicability was impacted.

INVESTIGATION

We visited each of the four sites to visually evaluate the performance of the pervious concrete and to select sample locations. We returned to the sites on June 27, 2008 to collect samples. Three samples of non-distressed pervious concrete were collected at Site A. At each of the remaining sites, four samples were collected, consisting of three from distressed areas and one from a non-distressed area. Full depth samples were removed by saw cutting an area approximately 15 to 18 inches square (Photo 9). Samples locations were patched back with a non-shrink grout prior to our leaving each site.

Once the samples were returned to our laboratory, initial measurements on pavement thickness and depth of surface erosion were made. The samples were then trimmed down to workable size pieces (Photos 10-17) to perform laboratory tests, including: compressive strength, unit weight, % voids, chemical analysis, freeze-thaw testing and petrographic analysis. A summary of our laboratory data is presented in Tables I-III and summarized below.

Pavement Thickness and Surface Erosion

The full depth pavement samples were measured for thickness and ranged



from 5.0 inches to 8.1 inches (Table I). Measurements of deterioration depth of the wearing surface ranged from no erosion (Site A, control site) to ½” to 2” for the distressed sites. Two of the distressed sites exhibited significant surface erosion (e.g., potholes, Photo 4) and select patching/repairs were in progress (Photos 1 & 2).

Compressive Strength

Cube shaped samples of material were cut from the bulk samples and tested for compressive strength. According to the National Ready Mixed Concrete Association, compressive strength for pervious concrete can range from 2,500 psi to 3,000 psi. However, strengths of 600 psi to 1,500 psi are more common.

Compressive strengths of the samples ranged from 420 psi to 3,240 psi (Table I). At each of the three distressed sites (B, C and D), the compressive strength of the sample collected from the non-distressed area was higher than the sample from a distressed area.

Unit Weight

Prior to breaking the cube samples for compressive strength, the samples were tested to determine the unit weight (Table I). Additional samples were trimmed and prepared to analyze the unit weight in full depth profile for the pavement section to examine the potential differences due to consolidation during construction (Table II). The data does not indicate a significant pattern to the variation in the unit weight densities for the samples in bulk or in profile, indicating that unit weight of the material may not a large influence factor on performance.

Void Analysis

Unlike traditional concrete, pervious concrete is not specified by strength. More important to the performance of the material is the void content. Void



content for pervious content can range from 15-25% (3/8" size aggregate) to 30-40% (1/2" size aggregate). Void contents for the samples ranged from 5.9% to 28.3% (Table I).

For comparison purposes, void contents were also collected on the unprepared bulk samples using a Troxler nuclear density gage (Table 1). The correlation of the void contents using the Troxler gage verses volumetric measurements demonstrated significant variation in select samples, and the Troxler gage does not appear to be a reliable tool to measure in-situ void content.

Drainage Analysis

A modified falling head permeability test was performed on one sample from each site to evaluate drainage conditions of the as-constructed pavement. Samples from each site were trimmed to the same size (approximately 5.1" x 5.1" surface area by 5" thick) and placed in a 5 gallon bucket with a 5.1" x 5.1" square cut out of the bottom. Samples that were thicker than 5 inches were trimmed along the bottom surface as not to disturb the void conditions in the upper portion of the sample. The prepared sample was placed directly over the opening in the bottom of the bucket and then hydrocal plaster was poured into the bucket to the top surface of the sample. The purpose of the plaster was to hold the sample in place over the opening and to only allow the water to drain through the sample. A Thirty pounds of water (3.6 gallons) was then poured into the bucket and allowed to drain through the sample. The draindown time for each sample was recorded and is presented below in Table A.

**TABLE A
PERMEABILITY TESTS**

Site A	Sample began to drain in 11 secs	Total time = 16 mins 51 secs
Site B	Sample began to drain in 28 secs	Total time = 59 mins 58 secs
Site C	Sample began to drain in 12 secs	Total time = 27 mins 02 secs
Site D	Sample began to drain in 15 secs	Total time = 1 hr 33 mins 02 secs



Chemical Analysis

Chemical testing was performed on samples to indicate the presence of chloride ions which could have been introduced into the pervious concrete from municipal deicing agents (magnesium chloride, calcium chloride, etc.) tracked from public roadways. Full depth profile samples were collected from our samples and sent to Wyoming Analytical Laboratories for testing to determine chloride penetration (Table II). Our data indicates elevated chloride concentrations in the bottom portion of the samples for two of the sites. The other two sites exhibit the elevated chloride concentrations near the surface of the sample.

Deicing salts (e.g., chlorides) are deleterious to concrete. They are absorbed into the concrete as it dries, and the absorbed salt strongly attracts water during subsequent wet weather events. If the ambient temperature is cold enough, and the sample does not have sufficient drainage capabilities, the water freezes in spite of the deicer, and will contribute to accelerated deterioration from freeze-thaw conditions.

Freeze-Thaw Durability

Four samples were was subjected to freeze-thaw abrasion durability testing (modified ASTM D560 and ASTM D559) for a total of 50 cycles. The mass of the sample was tracked during testing to measure percent loss over the testing period (Photos 18-20). All four samples exhibited complete failure after 6 to 41 cycles (Table III).

To examine the effect of the freeze-thaw condition, four additional samples were subjected to abrasion durability testing without the freeze-thaw conditioning (modified ASTM D560 and ASTM D559). Sample mass loss ranged from 0.1% to 0.3% over 50 test cycles. These data clearly demonstrate that the freeze-thaw condition is



very detrimental to the performance of the material if the sample does not exhibit significant drainage capabilities. Pervious concrete in freeze-thaw environments must not become fully saturated.

Petrographic Analysis

One representative sample of distressed material (Sample D-1) and one sample of non-distressed material (Sample D-4) were submitted to DRP Petrographic Services in Boulder, Colorado for additional analysis. A copy of the petrographic report is attached and the conclusions are summarized below.

“The deterioration of the concrete represented by the samples is from cracking due to freeze-thaw damage. The concrete does not drain effectively due to the high paste content of the concrete below the pervious zone (PZ). The cracking observed in the upper PZ is consistent with frost wedging. This is a process that can fracture rocks and occurs when water pools in a crack or void and then freezes. The lack of air entrainment in the paste below the PZ is problematic for the durability of the material in an environment of cyclic freezing and thawing. Although there is no evidence of cracking related to freeze-thaw damage below the PZ in the samples examined for this study it is the likely explanation for the failure for the specimens in the ASTM freeze-thaw testing.”

DISCUSSION

Our investigation indicated several possible factors that may likely influence the performance of pervious concrete, including;

- Variation in compressive strength. Our data indicated relative higher compressive strengths for the non-distressed areas in the three problematic parking lots (Sites B, C and D).
- Larger aggregate size. We did not have any information regarding the mixes used on these sites, however, our data indicates that the non-distressed



control site (Site A) was constructed with a larger aggregate mix. Sites B, C and D were constructed with smaller aggregate mixes and experienced surface deterioration.

- **Maintaining uniformity in void content.** Our data indicates that the measured void space in the samples for each site was inconsistent, likely indicating constructability issues.
- **Permeability of the material is critical for drainage.** Drainage results of the as-constructed pavements exhibited significant variability. As expected, the larger aggregate size mix (Site A) exhibited the best drainage performance. Site D, which was identified to have consolidation of the material in the bottom of the pavement, exhibited the poorest drainage.
- **Chlorides.** Varying amounts of chloride were found in each of the sites. Deicing salts (e.g., chloride) in the pavement material are deleterious to concrete and will accelerate deterioration due to freeze-thaw cycling.
- **Freeze-thaw durability.** Samples from all four sites exhibited short-term complete failure during freeze-thaw testing. Abrasion durability testing (excluding the freeze-thaw conditioning) demonstrated less than 0.5% loss of the sample for the testing cycle. Maintaining drainage of the pavement system and not allowing the material to become saturated from surface water appears to be the key influence factor associated the lack of performance at the sites included in this investigation.


LIMITATIONS

The locations of our samples were spaced to obtain a reasonably accurate indication of pavement conditions. The data are representative of conditions encountered only at the exact location of the sample. Variations in the conditions not indicated by our data are always possible.



We believe this investigation was conducted with that level of skill and care ordinarily used by material engineers practicing in this area at this time. No warranty, express or implied, is made. We appreciate the opportunity to work with you on this project. If we can be of further service in discussing the contents of this report, please call.

CTL | THOMPSON MATERIALS ENGINEERS, INC.


Michael S. Skinner, P.E.
Project Manager



Reviewed by:


Orville R. Werner, P.E.
President

MSK:ORW/msk/hh

(5 copies sent)



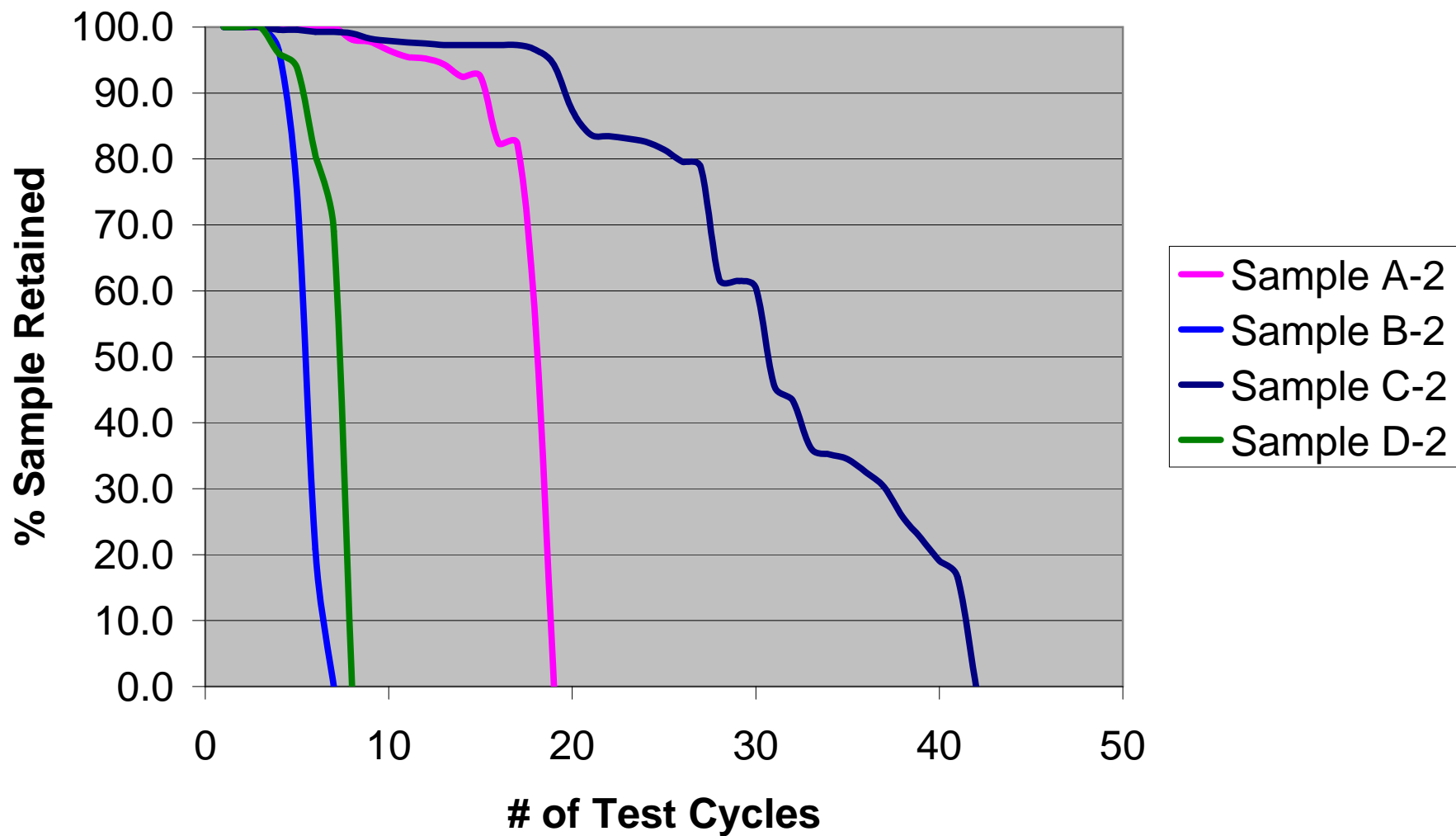
TABLE I
Pervious Concrete Sample Data

Sample	Condition	Thickness (in.)	Depth of Surface Erosion (in.)	Compressive Strength (psi)	Unit Wt. (pcf)	% Voids	% Voids (nuc gage)
A-1	non-distressed	5.1	0.0		147.8	16.0	12.2
A-2	non-distressed		0.0	3,240	147.8	10.9	11.9
A-3	non-distressed	4.8	0.0	1,820	149.1	13.8	13.9
B-1	distressed	6.0	1.0		142.0	11.3	11.4
B-2	distressed		0.5		138.5	28.2	19.1
B-3	distressed		1.0	420	139.3		30.9
B-4	non-distressed	8.1	0.0	811	142.4	15.2	
C-1	distressed		2.0				
C-2	distressed		0.5	600	150.8	24.4	28.8
C-3	distressed	5.0	0.5	2,180	146.8	28.3	17.1
C-4	non-distressed	5.0	0.0		141.4	11.6	
D-1	distressed	5.3	0.5	1,760	143.4	22.5	24.8
D-2	distressed		1.0		140.1	14.9	17.5
D-3	distressed		0.8		140.9	10.3	43.1
D-4	non-distressed	5.8	0.0	1,930	138.1	5.9	

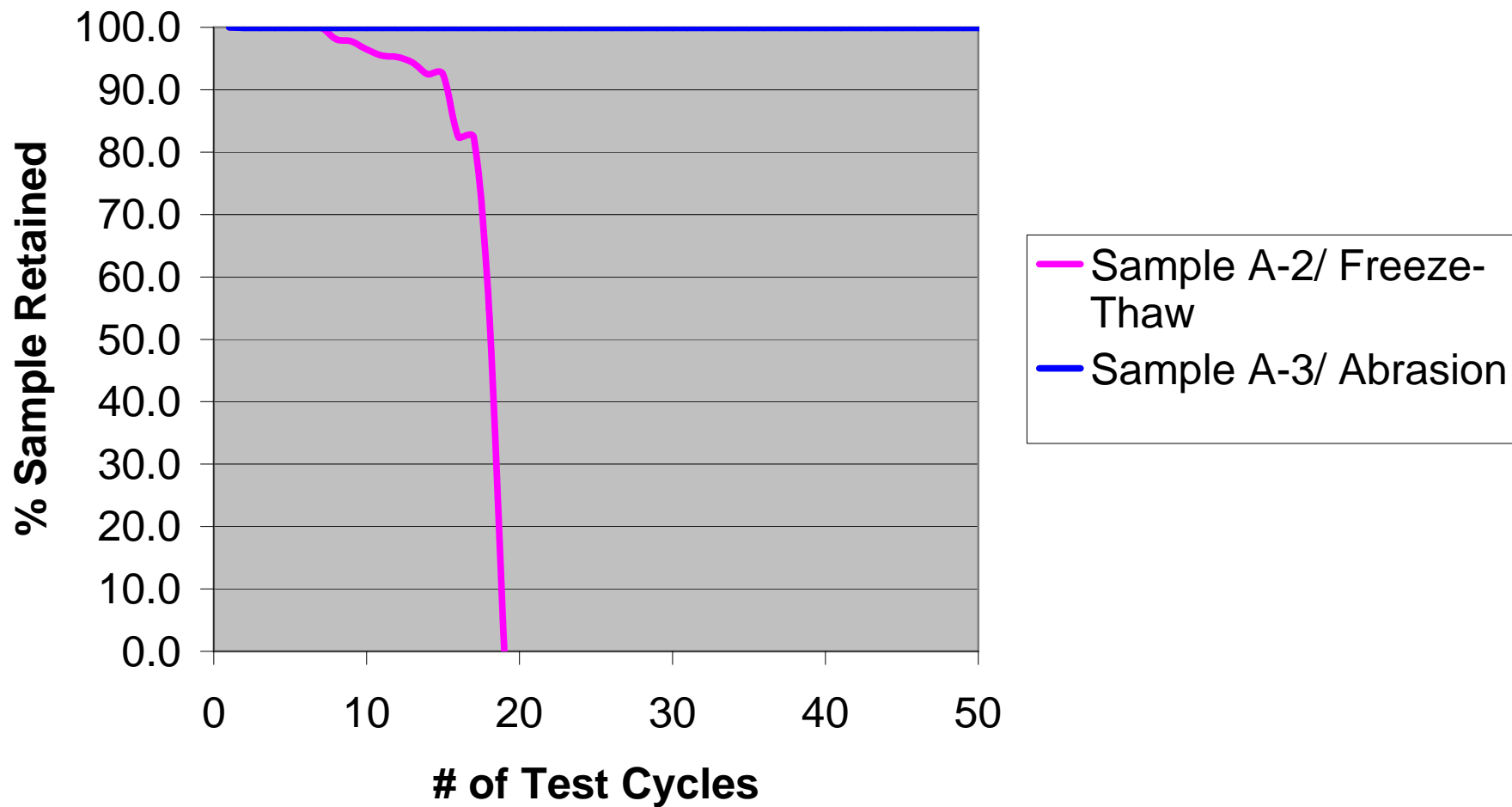
TABLE II
Pervious Concrete Profile Data

Sample	Depth	Unit Wt. (pcf)	Total Chloride (% wt)
A-1	top	154.2	0.011
	middle	152.5	0.022
	bottom	149.7	0.032
B-3	top	149.3	0.017
	middle	145.7	0.022
	bottom	144.6	0.034
C-3	top	144.8	0.067
	middle	144.2	0.049
	bottom	145.0	0.049
D-2	top	142.4	0.051
	middle	142.5	0.057
	bottom	142.6	0.009

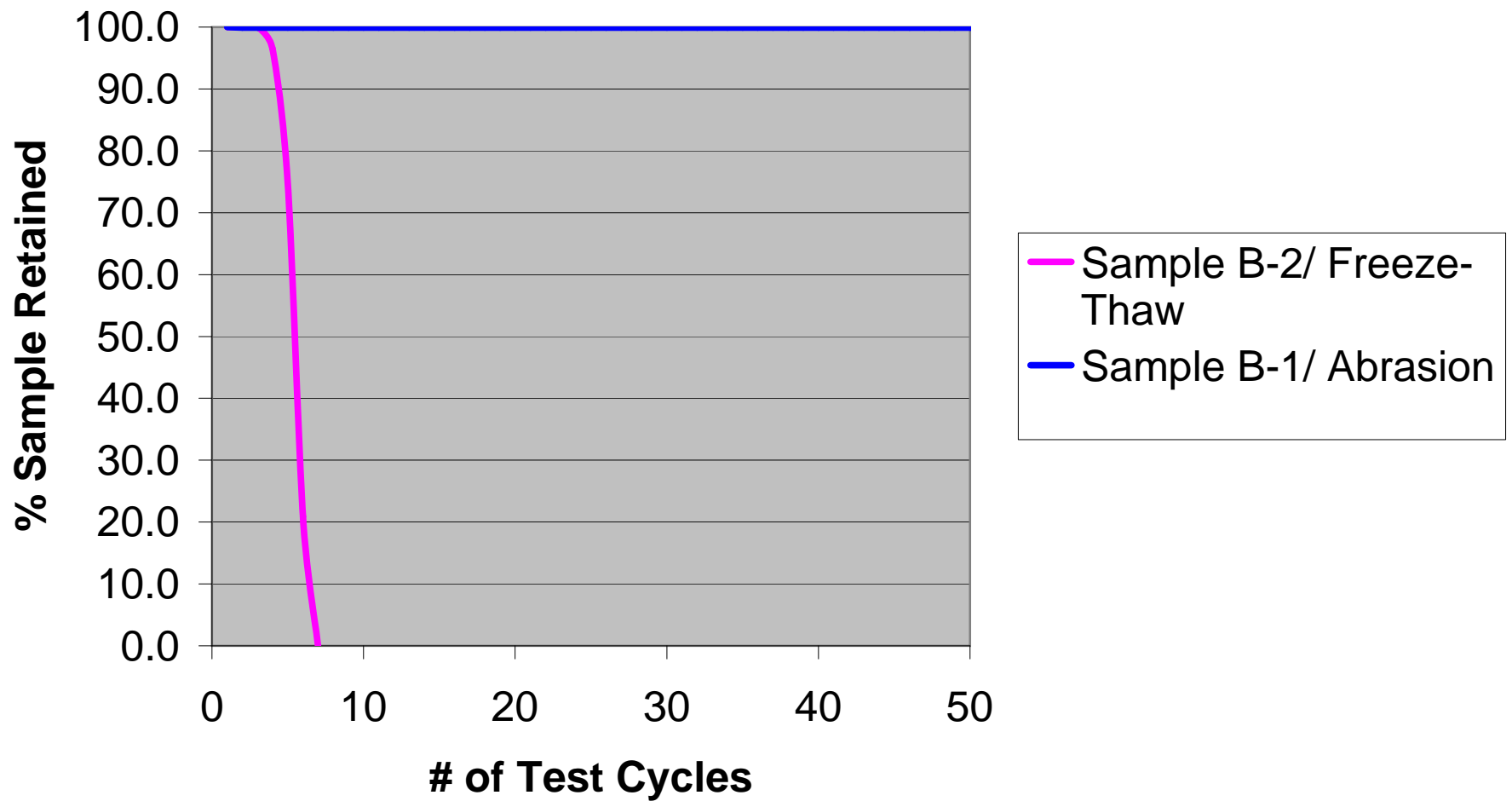
Freeze-Thaw Testing



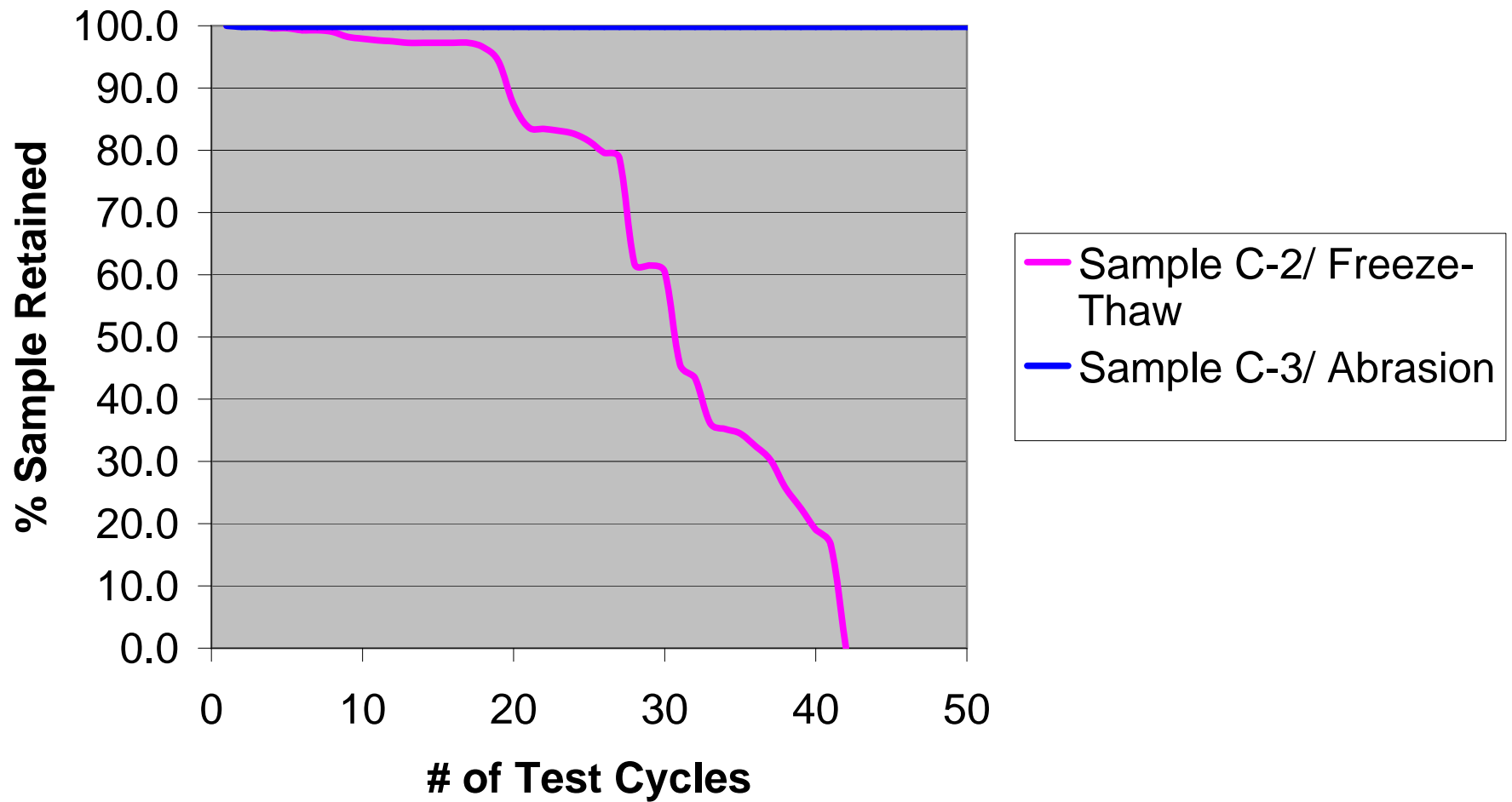
Freeze-Thaw vs. Abrasion Durability Testing Site A



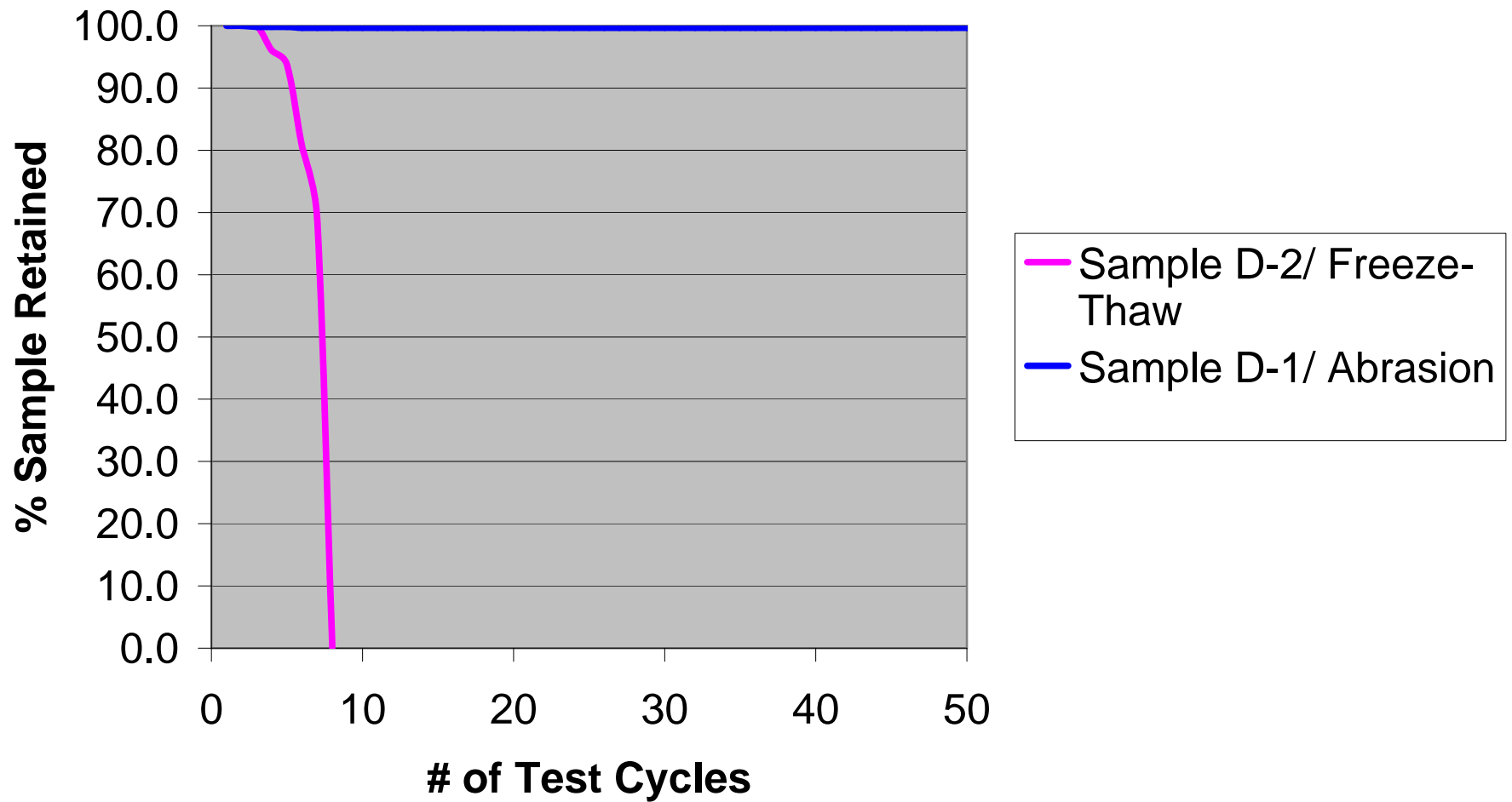
Freeze-Thaw vs. Abrasion Durability Testing Site B



Freeze-Thaw vs. Abrasion Durability Testing Site C



Freeze-Thaw vs. Abrasion Durability Testing Site D

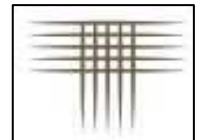




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Photo 1 Site B - distressed areas patched with non-pervious concrete.

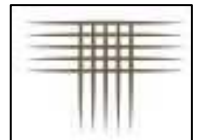


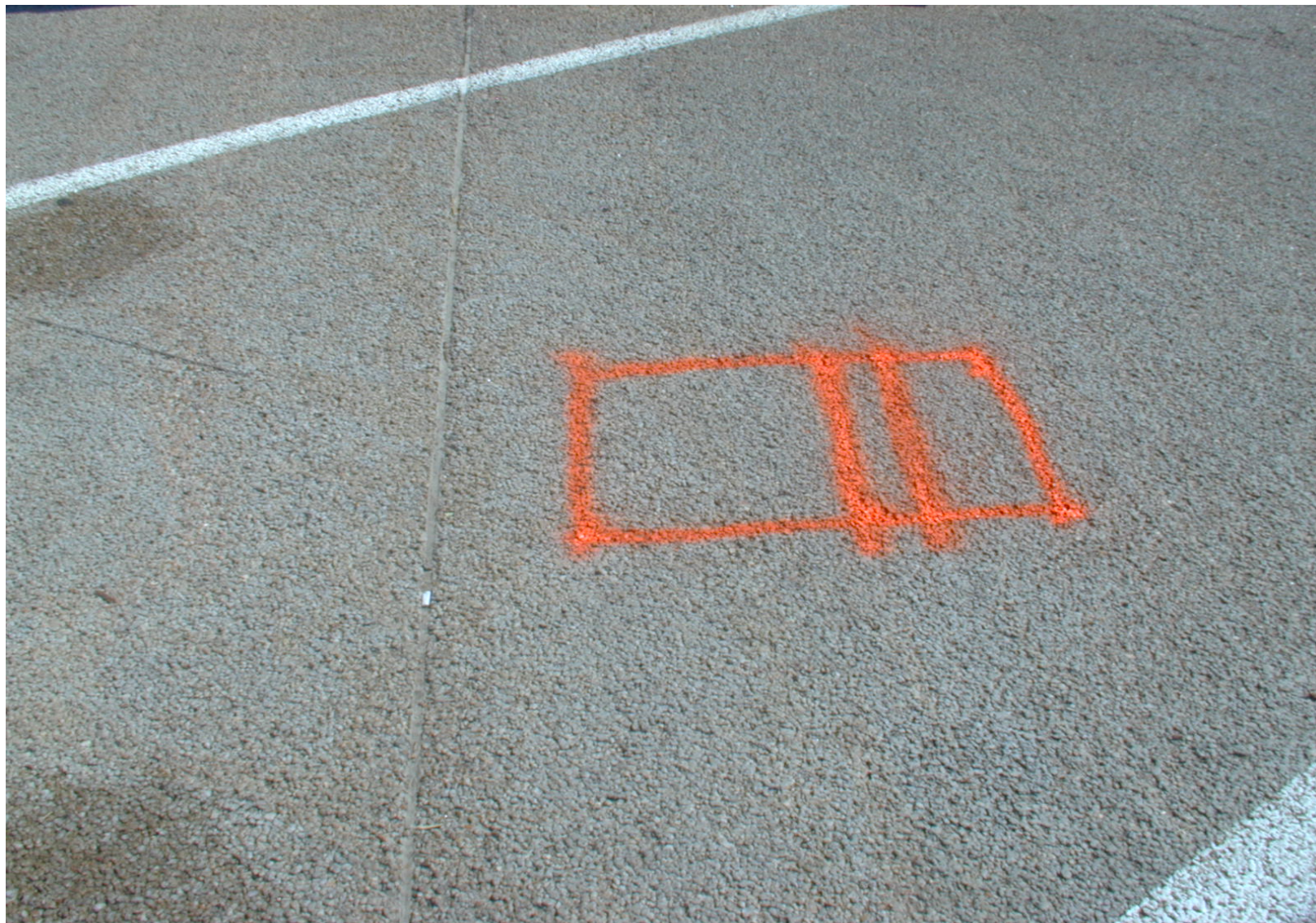


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Photo 2 Site B - distressed pervious concrete.

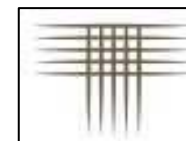




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Photo 3 Site C - non distressed portion of pervious concrete.

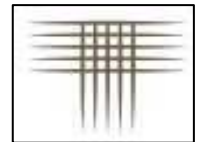




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Photo 4 Site C - distressed pervious concrete.

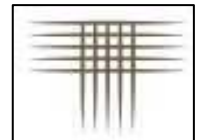




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Photo 5 Site D - surface distress to pervious concrete.

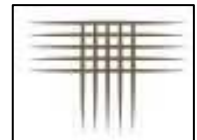




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Photo 6 Site D - non distressed pervious concrete.

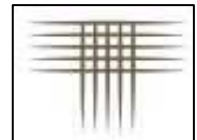


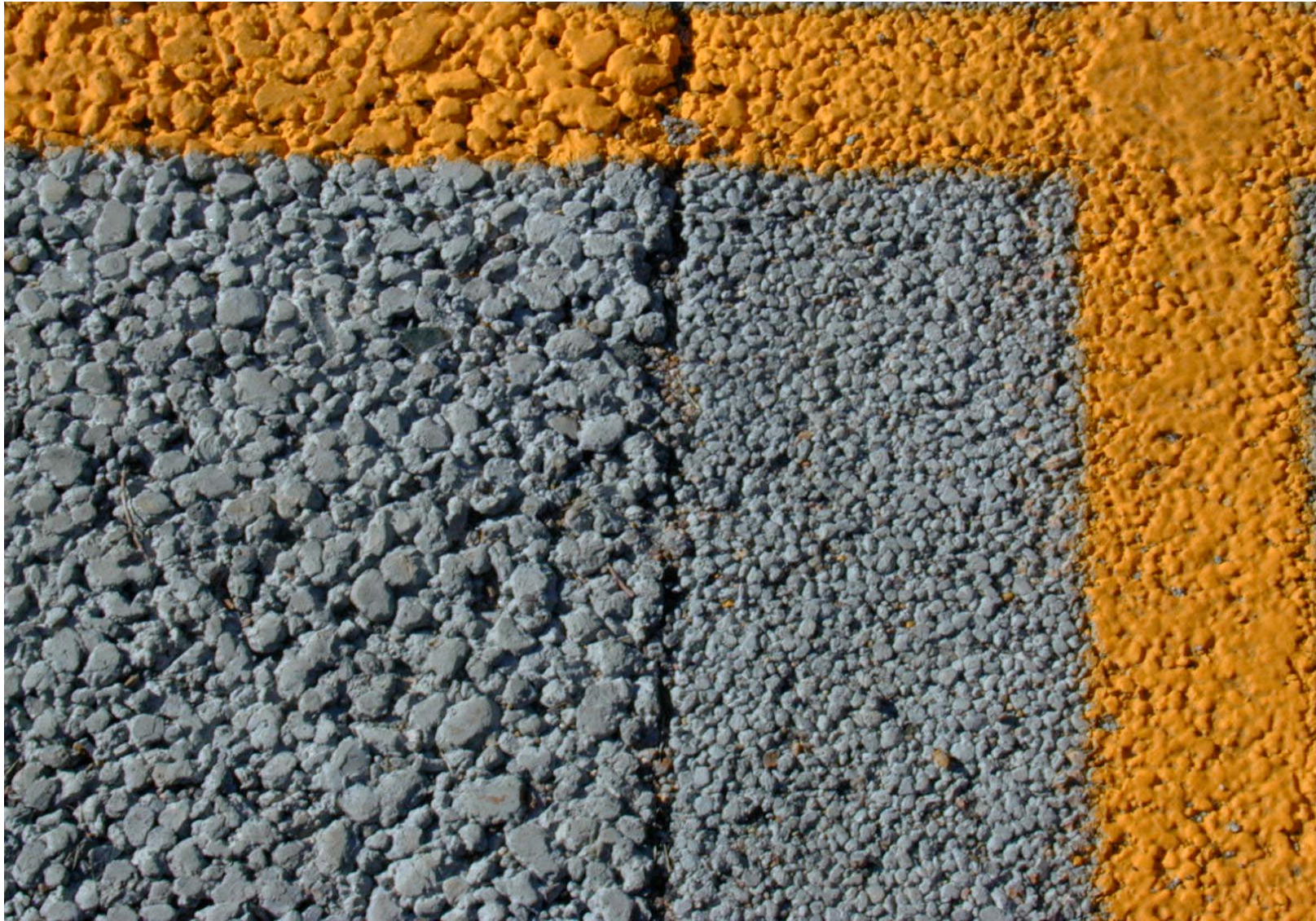


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Photo 7 Site A - non distressed pervious concrete.

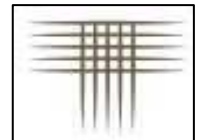




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Photo 8 Site A - two different in-place pervious concrete mixes.

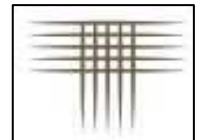




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Photo 9 Saw cut samples returned to CTL Materials Lab for testing.

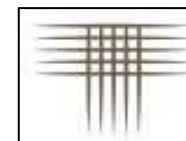




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Photo 10 Site B - sample B-1 (distressed sample).

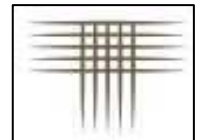




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Photo 11 Site B - sample B-4 (non distressed sample).

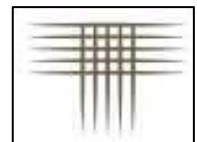




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Photo 12 Site C - sample C-3 (distressed sample).

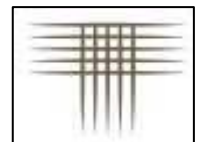




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Photo 13 Site C - sample C-4 (non distressed sample).

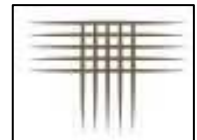




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Photo 14 Site D - sample D-1 (distressed sample).

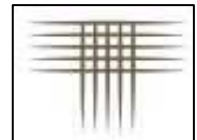




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Photo 15 Site D - sample D-4 (non distressed sample).

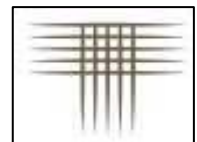




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Photo 16 Site A - sample A-1 (non distressed sample).

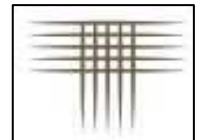




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Photo 17 Site A - sample A-3 (non distressed sample).

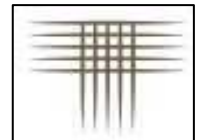




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Photo 18 Deterioration of samples during freeze-thaw testing.

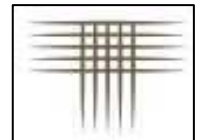




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Photo 19 Deterioration of samples during freeze-thaw testing.

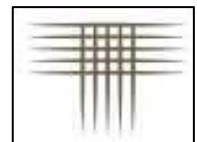




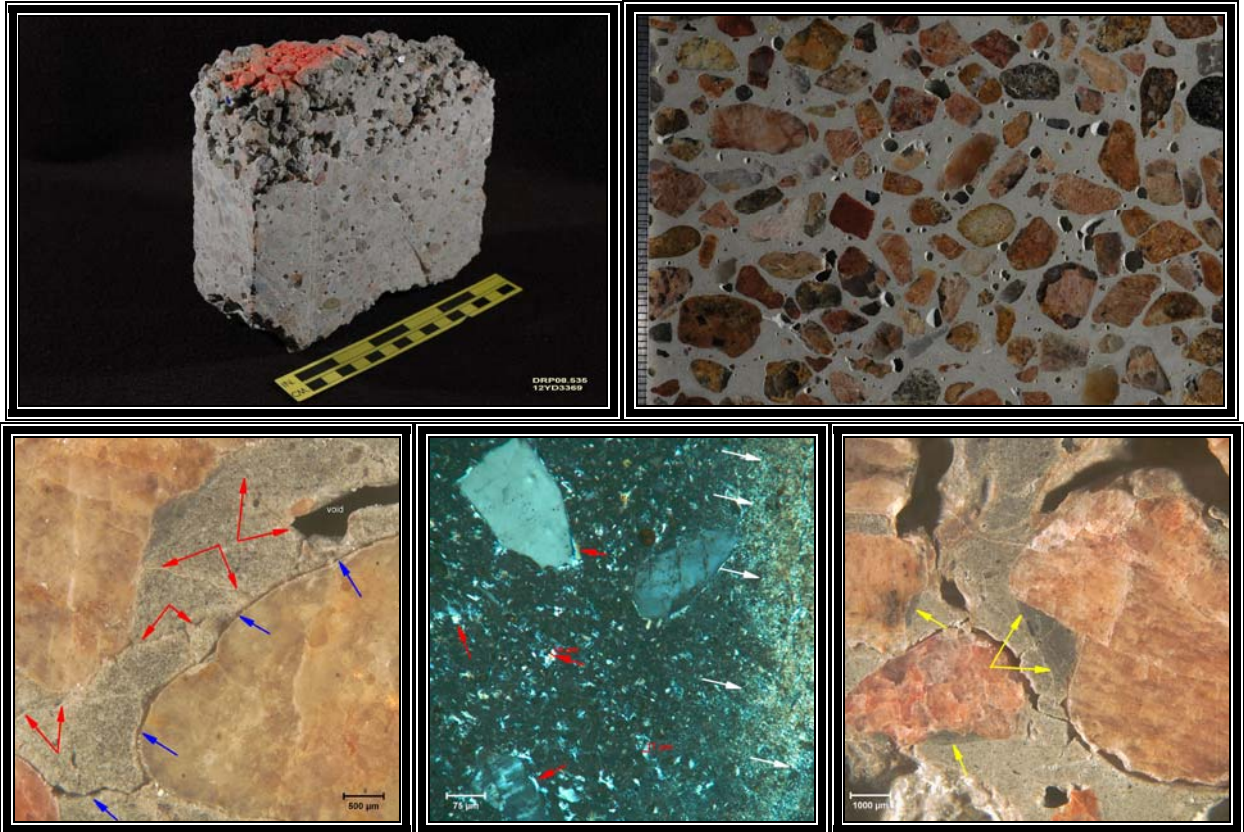
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Photo 20 Deterioration of samples during freeze-thaw testing.



Petrographic Investigation of a Concrete Samples from Commercial Slab on Ground Construction at Site D Located in Denver, Colorado



Prepared for: Mr. Michael Skinner, P.E.
CTL/Thompson, Inc.
Denver, Colorado

Prepared by: David Rothstein, Ph.D., P.G.
Report No.: DRP08.535

22 AUGUST 2008

EXECUTIVE SUMMARY

Two (2) concrete samples extracted from a pervious concrete slab placed for the parking lot at Site D located in Denver Colorado are the subject of petrographic examination to determine the cause (s) of premature deterioration of the concrete. The petrographic examinations indicate that the deterioration of the concrete represented by the samples is from freeze-thaw damage and sub-horizontal cracking.

In both samples the aggregates are in point-to-point contact and the paste content of the concrete is minimal in the top 38-50 mm (1 ½-2 in.) of the slab. This zone is designated as the Pervious Zone (**PZ**). Below the **PZ** the paste content is high and aggregates are not in point-to-point contact. The paste in this zone is not air-entrained.

The concrete does not appear to drain effectively due to the high paste content of the concrete below the **PZ**. The cracking observed in the upper **PZ** is consistent with frost wedging. This is a process that can fracture rocks in nature and occurs when water pools in a crack or void and then freezes. The lack of air entrainment in the paste below the **PZ** is problematic for the durability of the material in an environment of cyclic freezing and thawing. Although there is no evidence of cracking related to freeze-thaw damage below the **PZ** in the samples examined for this study it is the likely explanation for the failure of specimens in the ASTM freeze-thaw testing.

1.0 INTRODUCTION

Mr. Michael Skinner, P.E. of CTL|Thompson (**CTL|T**) located in Denver, Colorado requested DRP Consulting, Inc. (**DRP**) to conduct petrographic examinations to determine the causes (s) of degradation of concrete taken from slab on ground construction at the parking lot at Site D located in Denver Colorado. On 30 July 2008 **DRP** received two (2) concrete samples from **CTL|T**. The cores were labeled #D-1 (from distressed area) and #D-4 (non-distressed area) and were assigned **DRP** sample numbers 12YD3369 and 12YD3370 respectively.

Mr. Skinner provided the following information regarding other testing performed on concrete from the parking lot. Cube samples were cut from larger saw-cut blocks and tested for compressive strength. Mr. Skinner reported highly variable test results with average compressive strengths of 1760 psi for sample D-1 and 1930 psi for sample D-4. **CTL|T** also tested a sample for freeze-thaw durability via ASTM C666 and reported complete failure of the sample after the completion of only five cycles.

2.0 SCOPE OF WORK

The testing involved petrographic analysis in accordance with ASTM C856 [1]. This report summarizes the findings of the examination. *Appendix A* and *Appendix B* contain the detailed notes, photographs and micrographs collected from the petrographic examinations.

3.0 PROCEDURES

The samples were measured, inspected visually and with a hand lens, and photographed in their as-received condition. A slab representing a cross section of each core was cut using an oil-lubricated saw. The slabs were oven dried overnight at ~ 40°C (~ 105°F). Sample D-1 was impregnated with and embedded in epoxy after significant material loss occurred during the first saw cut. The slabs were lapped and polished using progressively finer diamond wheels and an aqueous lubricant following procedures in accordance with ASTM C457 [2]. Phenolphthalein was applied to a freshly saw-cut surface to assess the extent of carbonation, along with thin section analysis. Phenolphthalein is an organic stain that colors materials with pH of greater than or equal to 9.5 purple. Portland cement concrete generally has a pH of 12.5. Carbonation lowers the pH of the paste below 9.5, so areas not stained by phenolphthalein are an indicator of carbonation. The polished and saw-cut surfaces of each of the cores were examined visually and via a stereomicroscope with 3-180x magnification capability in accordance with the standard practice set forth in ASTM C856. Petrographic thin sections were prepared by impregnating billets with epoxy, trimming and grinding the samples on a Buehler

1 *Standard Practice for Petrographic Examination of Hardened Concrete*. Annual Book of ASTM Standards, Vol. 4.02., ASTM C856-04.

2 *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*, Annual Book of ASTM Standards, Vol. 4.02, ASTM C457-06.

Petro-Thin device and polishing to a final thickness of $\sim 20 \mu\text{m}$ on a Buehler Beta-Vector machine. All of these preparations were done in a non-aqueous environment. The thin sections were examined with a petrographic microscope with 50-500x magnification capability.

4.0 FINDINGS

The following findings are relevant to the concrete represented by the samples:

- 4.1. The concrete is proportioned with Portland cement, fly ash, and natural siliceous aggregate with a nominal top size of 9.5 mm ($\frac{3}{8}$ in.). The concrete is not air-entrained. The hydration of the cement is normal.
- 4.2. The aggregate consists primarily of granitic rocks with some metamorphic and volcanic rocks as well. The aggregates are sub-equant to oblong in shape and well-rounded to sub-angular. The gradation of the aggregate is typical for pervious concrete with no significant quantity of sand or fine materials. Most of the materials appear to sit on the 9.5 mm ($\frac{3}{8}$ in.) sieve with some material sitting on the 4.75 (No. 4) to 2.36 mm (No. 8) sieves.
- 4.3. In both samples there is a striking change in the void and paste structure of the concrete that occurs about 50 mm (2 in.) below the top surface of sample D-1 and about 38-50 mm (1 $\frac{1}{2}$ -2 in.) below the top surface of sample D-4. In the top 38-50 mm (1 $\frac{1}{2}$ -2 in.) of the slabs there is little paste and large voids are present between interconnected aggregate particles that often display point-to-point contacts. This zone is hereafter designated as the Pervious Zone (**PZ**). The color of the paste in the **PZ** is gray to dark gray. Below the **PZ** the aggregates do not show point-to-point contacts and cementitious paste occurs between isolated aggregate particles. The color of the paste in this region is light gray to white.
- 4.4. Both samples show cracking and microcracking. In the **PZ** sub-horizontal cracks are present. These cracks are mostly free of secondary deposits and cut around aggregates. Microcracks occur within the paste below the **PZ** that show no preferred orientation. These microcracks are range up to 50 μm (2 mil) in width and are both free of secondary deposits and filled with calcium carbonate.
- 4.5. Traces of ettringite are present in voids in the **PZ**. There is no evidence that the ettringite mineralization is a cause of distress.

5.0 CONCLUSIONS

Based on the observations described above, the deterioration of the concrete represented by the samples is from cracking due to freeze-thaw damage. The concrete does not drain effectively due to the high paste content of the concrete below the **PZ**. The cracking observed in the **PZ** is consistent with frost wedging. This is a process that can fracture rocks in nature and occurs when water pools in a crack or void and then freezes. The lack of air entrainment in the paste below the **PZ** is problematic for the durability of the material in an environment of cyclic freezing and thawing. Although there is no evidence of freeze-thaw damage in the concrete below the **PZ** in the samples examined for this study, it is the likely explanation for the failure of specimens in the ASTM freeze-thaw testing.

This concludes work performed on this project to date.



David Rothstein, Ph.D., P.G.

1. RECEIVED CONDITION	
ORIENTATION	Vertical block cut from concrete slab measures 160 mm (~ 6 ½ in.) long, 50 mm (~ 2 in.) wide, and 163 mm (~ 6 ½ in.) deep (Figure A1, A2).
SURFACES	Top surface has float finish; bottom surface is a fracture. The block does not represent the full thickness of the pavement.
GENERAL CONDITION	Concrete is relatively compact and hard. The material was somewhat fragile for sample preparation with aggregates dislodged easily from the top of the core. In the main body of the concrete no aggregate tears or unusual crumbling was reported.

2. EMBEDDED OBJECTS	
GENERAL	None observed

3. CRACKING	
MACROSCOPIC	In the as-received block no macroscopic cracks were observed. Sub-horizontal cracks are present in the top 50 mm (2 in.); these cracks are sites of the aggregate tears and crumbling during sample preparation (Figure A3). These cracks are similar to adhesion cracks and wrap around aggregate particles.
MICROSCOPIC	Frequent microcracking is observed in the top 50 mm (2 in.) where the microcracks show no preferred orientation (Figure A4). Most of the microcracks are less than 50 µm (2 mil) wide and up to 9.5 mm (¾ in.) long. The deposits are mostly free of secondary deposits but occasional cracks are filled with calcium carbonate or lined with ettringite along segments of the microcrack.

4. VOIDS	
VOID SYSTEM	The concrete is not air-entrained. Large voids are present in the top 50 mm (2 in.); many of these voids are more than 15 mm (5/8 in.) long and are part of the pervious concrete system (Figure A5a). In the lower portion of the core the grading and distribution of air voids is very irregular. Voids most commonly measure less than 1 mm (40 mil) across and are spherical (Figure A5b); rare elongated voids measure up to 6 mm (¼ in.) across as well.
VOID FILLINGS	The luster of interior walls is dull and voids are mostly free of secondary deposits. Traces of ettringite are present in rare voids.

5. COARSE AGGREGATE	
PHYSICAL PROPERTIES	Natural gravel with nominal top size of 9.5 mm (¾ in.; Figure A6). The gradation of the aggregate appears limited to a few sieve sizes with no appreciable amount of sand present. The aggregate particles are typically sub-equant to oblong in shape with well-rounded to sub-angular edges. No preferred orientations were observed.
ROCK TYPES	The aggregate consists predominantly of granitic rocks (> 75%) that range in color from light pink to deep red to light gray. Other rock types that make up minor components (< 10%) of the aggregate include siliceous volcanic rocks, coarse particles of quartz and feldspar that appear derived from pegmatite, metagraywackes, and amphibolites.
OTHER FEATURES	No deleterious coatings or incrustations were observed. There is no significant internal microcracking of the aggregates and no evidence of reaction rims or other evidence of ASR. Low w/cm mortar coatings are present on many aggregate particles.

6. PASTE OBSERVATIONS	
POLISHED SURFACE	Color: Paste color varies significantly between the top 50 mm (2 in.) and the lower section of the core. In the top section the color is gray (Munsell N5-N6) whereas the lower section is light gray to white (2.5Y/6/1 to 2.5Y/7/1; Figure A2, A7). Dark gray mortar coatings are present on aggregate particles throughout the thickness of the polished slab (Figure A8). Texture: Granular Luster: Dull Hardness (Mohs): Medium (2-3); bends when scratched.
THIN SECTION*	Hydration: Advanced hydration with less than 5% RRCG that consists primarily of belite and interstitial ferrite that is fairly fine grained (Figure A9a). SCM: Fly ash is present; no other SCM observed. CH: 15-25% total paste; fine-grained and evenly distributed (Figure A9b).
FRACTURE SURFACE	Color: light gray Texture: Granular Luster: Dull Paste/Aggregate Bonding: cuts exclusively around aggregate

7. SECONDARY DEPOSITS	
PHENOLPHTHALEIN	Stains full depth of slab (Figure A10).
DEPOSITS	Minor carbonation observed around some cracks and microcracks. Traces of ettringite observed in rare voids.

* Abbreviations are as follows: RRCG, relict and residual cement grains (calcium silicates); SCM, supplemental cementitious materials; CH, portlandite or calcium hydroxide; ITZ, interfacial transition zone (thin zone of paste adjacent to aggregate particles). Modal percentages are based on visual estimations, not quantitative measurements.

FIGURES

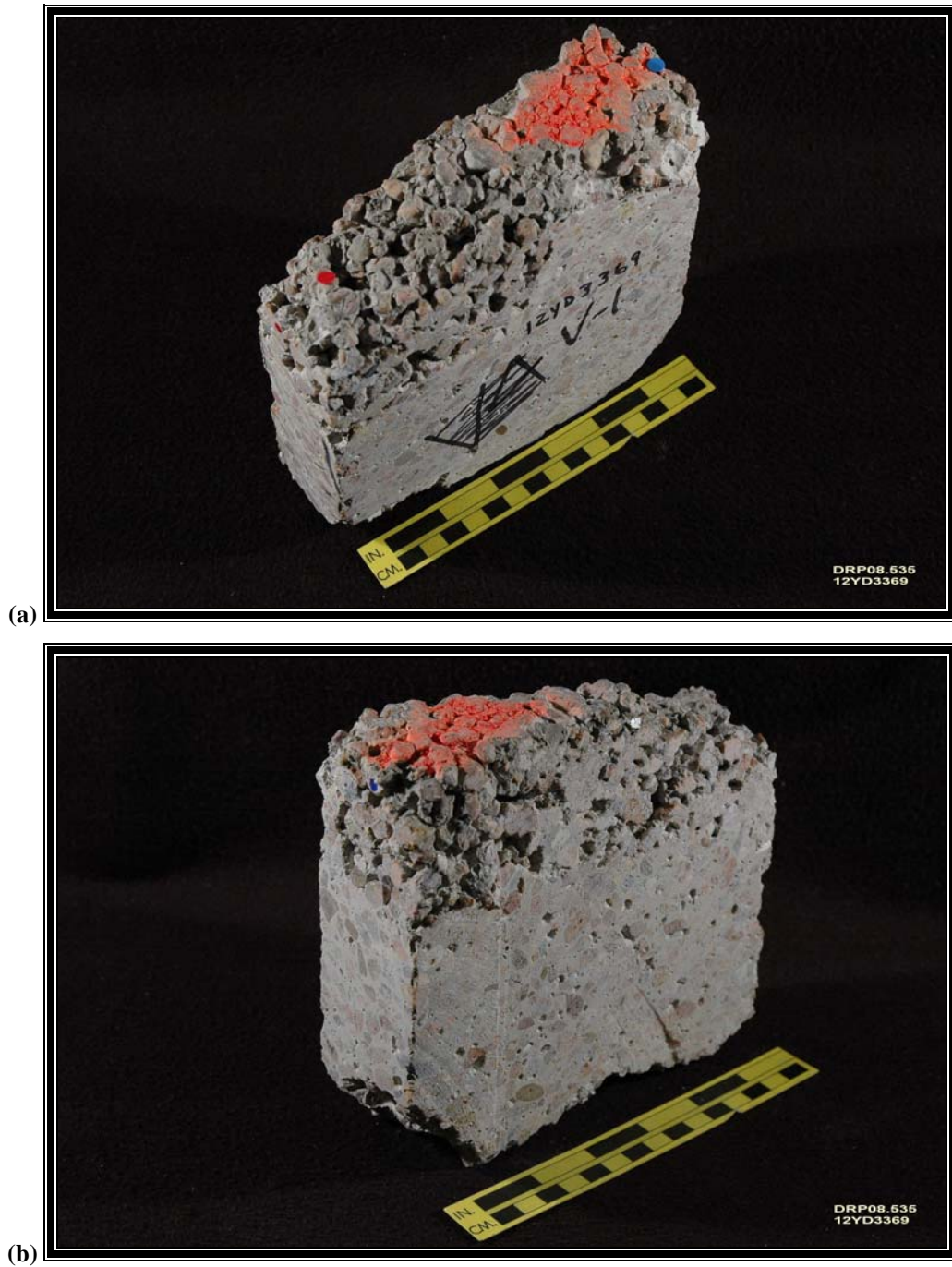


Figure A1. Photographs of sample in as-received condition. The paint marks the top surface and the red and blue dots show the orientation of the saw cut.



(c)



(d)

Figure A1 (cont'd). Photograph of sample in as-received condition.

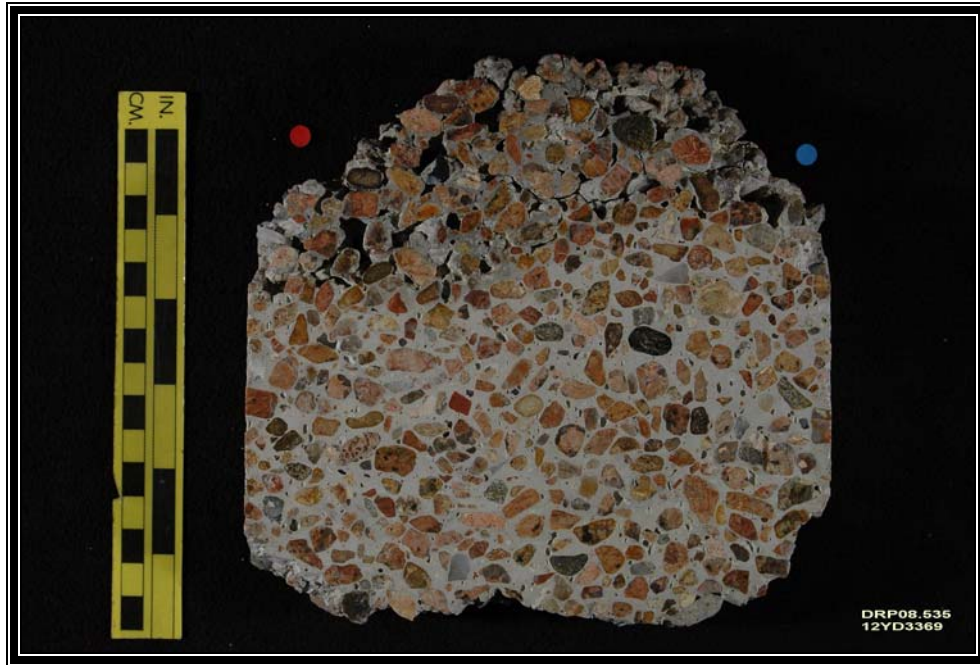


Figure A2. Photograph of polished surface of sample.



(a)

Figure A3. (a) Photograph showing cracks in the paste near the top surface; scale in millimeters.



(b)

Figure A3 (cont'd). (b) Photograph showing cracks in the paste near the top surface; scale in millimeters.

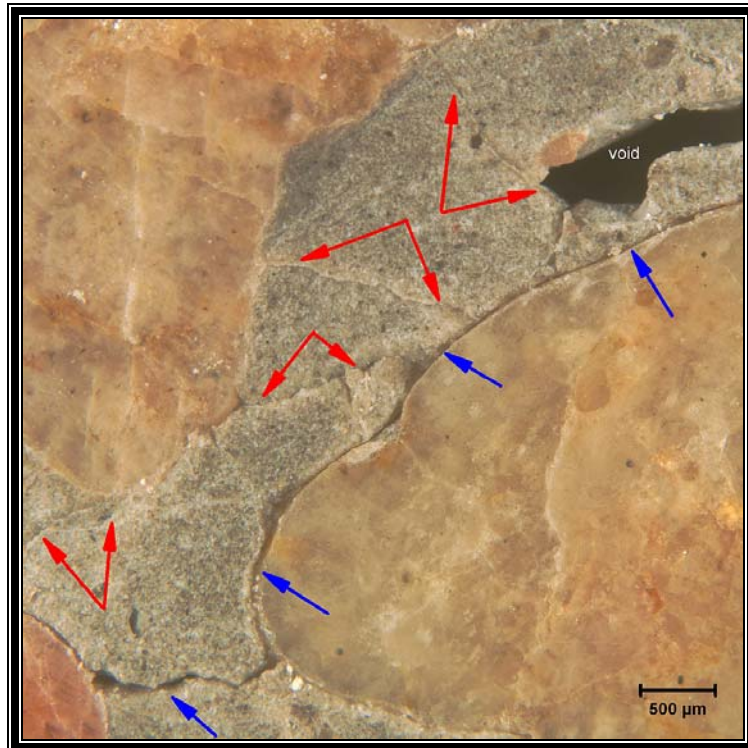


Figure A4. Reflected light photomicrograph showing microcracks (red arrows) and crack near the top of the slab.

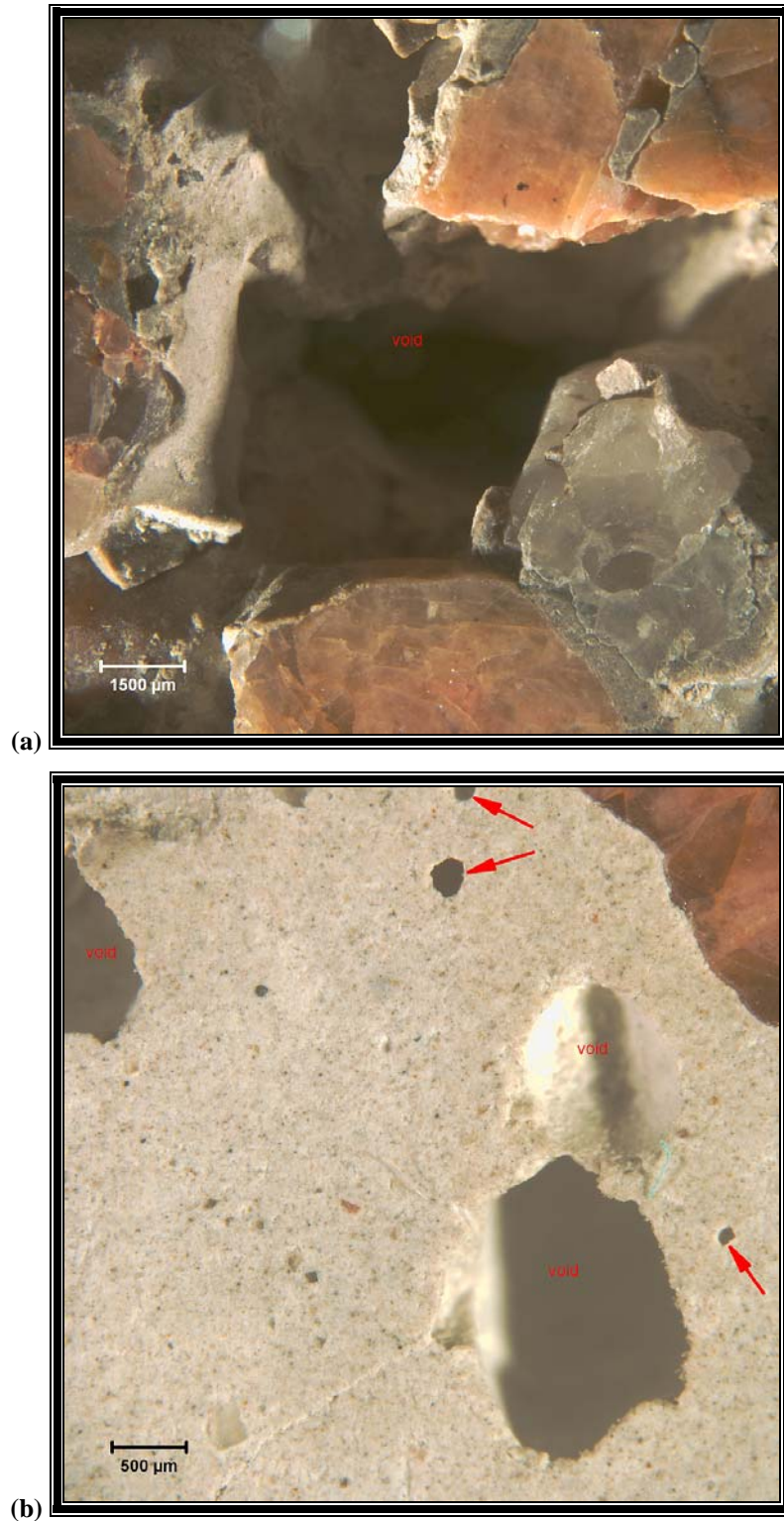


Figure A5. Reflected light photomicrographs of (a) a large void near the top of the slab and (b) smaller voids (red arrows and labeled) in the lower portion of the slab.



Figure A6. Photograph of polished surface showing overview of aggregate; scale in millimeters.



Figure A7. Photograph of polished surface showing overview of paste color variations; scale in millimeters.

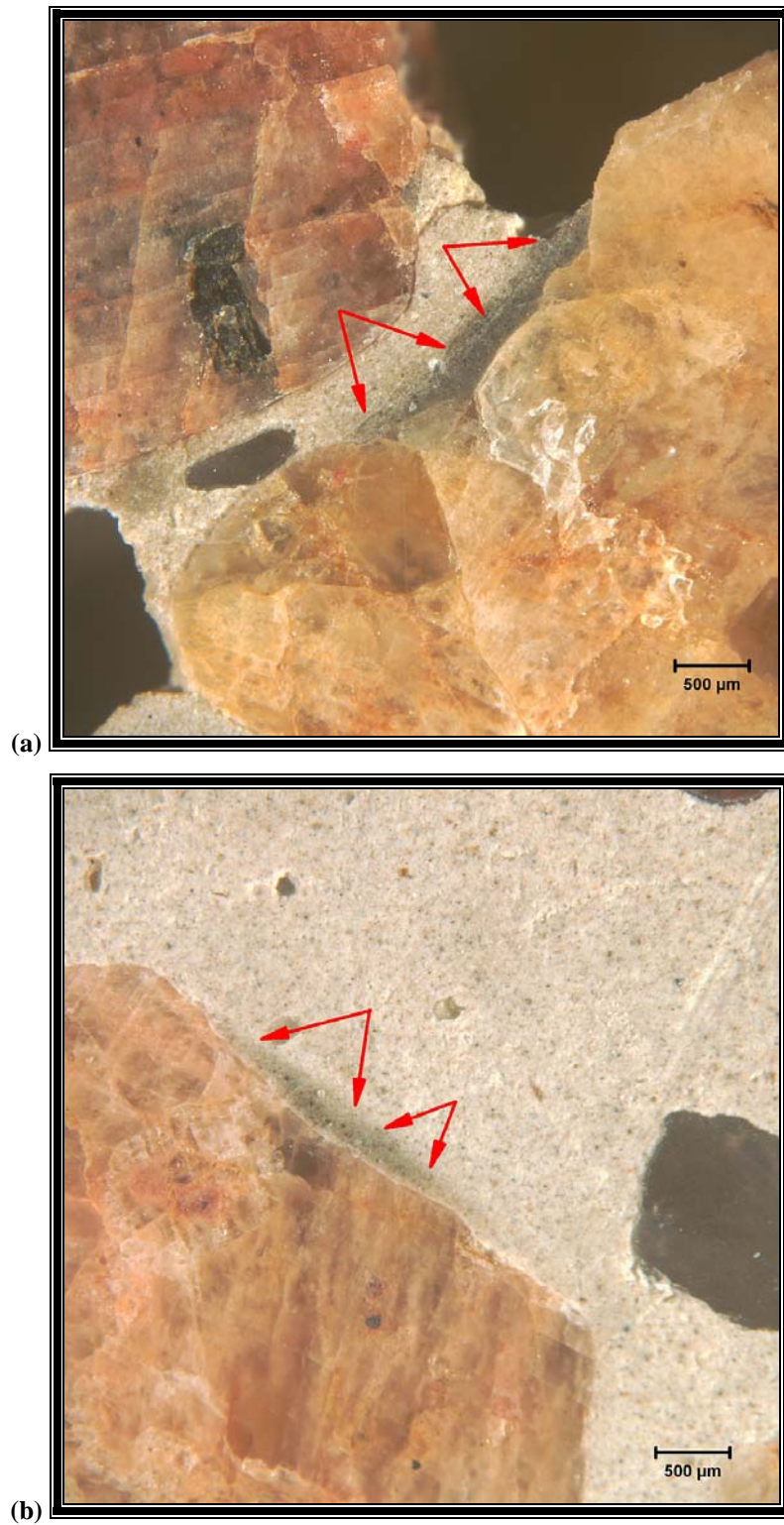


Figure A8. Reflected light photomicrographs of polished surface showing low w/cm mortar coatings (red arrows) on aggregates (a) near the top of the slab and (b) within the middle of the slab.

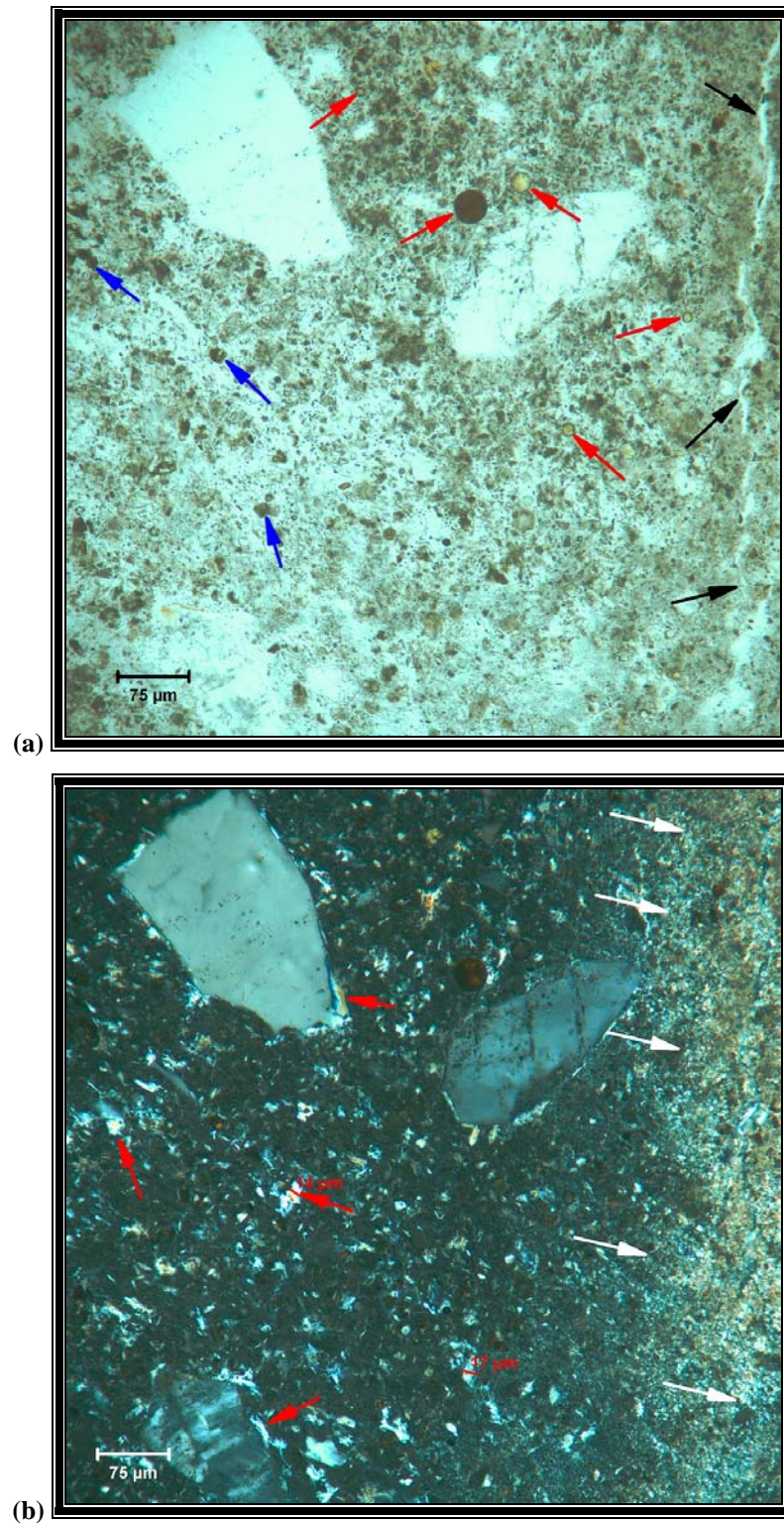


Figure A9. Transmitted light photomicrographs of thin section showing detail of paste in (a) plane-polarized and (b) cross-polarized light. In (a) red and blue arrows indicate fly ash and RRCG; respectively. The black arrows highlight a microcrack. In (b) red arrows and bars indicate CH; white arrows show carbonated paste adjacent to microcrack.

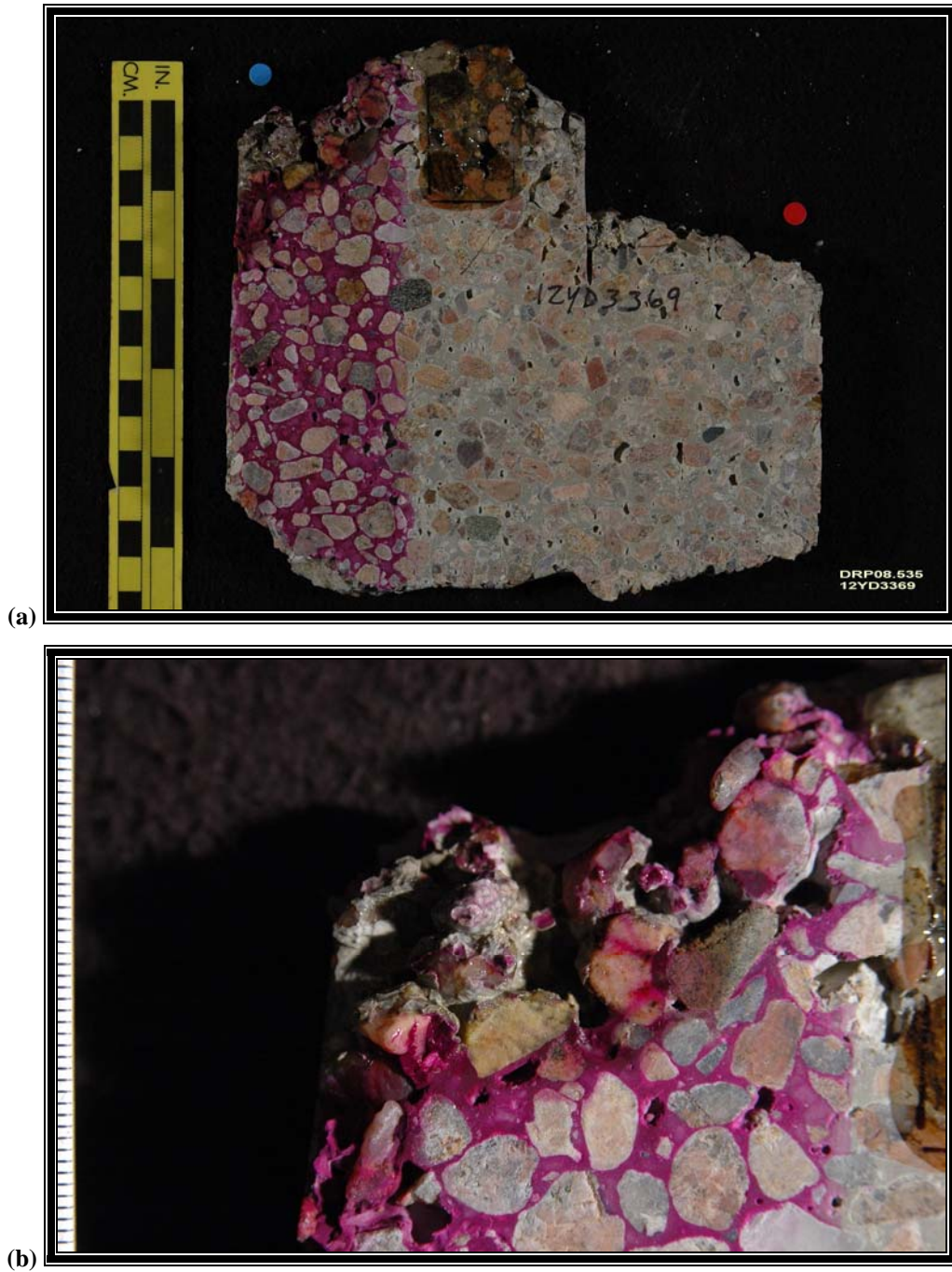


Figure A10. Photographs of phenolphthalein stained surface showing (a) overview of stained slab and (b) detail of slab near the top surface. The scale in (b) is in millimeters.

1. RECEIVED CONDITION	
ORIENTATION	Vertical block cut from concrete slab measures 170 mm (~ 6 ¾ in.) long, 50 mm (~ 2 in.) wide, and 163 mm (~ 6 ½ in.) deep (Figure B1, B2).
SURFACES	Top surface has float finish; bottom surface is a fracture. The block does not represent the full thickness of the pavement.
GENERAL CONDITION	Concrete is relatively compact and hard. No aggregate tears or unusual crumbling was reported.

2. EMBEDDED OBJECTS	
GENERAL	None observed

3. CRACKING	
MACROSCOPIC	Occasional sub-horizontal cracks and adhesion cracks are present in the top 38-50 mm (1 ½-2 in.). These cracks are up to 100 µm (4 mil) wide and 9.5 mm (¾ in.) long and cut exclusively around aggregate particles (Figure B3).
MICROSCOPIC	Frequent microcracking is observed in the top 38-50 mm (1 ½-2 in.) where the microcracks show no preferred orientation. Most of the microcracks are less than 50 µm (2 mil) wide and up to 9.5 mm (¾ in.) long. The deposits are mostly free of secondary deposits but occasional cracks are filled with calcium carbonate or lined with ettringite along segments of the microcrack. Randomly oriented microcracks measuring 25-50 µm (1-2 mil) wide are common in the lower portion of the core (Figure B4). Some microcracking is present near the bottom of the slab but these appear related to sample extraction.

4. VOIDS	
VOID SYSTEM	The concrete is not air-entrained. Large voids are present in the top 38-50 mm (1 ½-2 in.); many of these voids are more than 15 mm (5/8 in.) long and are part of the pervious concrete system (Figure B5a). In the lower portion of the core the grading and distribution of air voids is very irregular. Voids most commonly measure less than 1 mm (40 mil) across and are spherical; rare sub-circular voids measure up to 3 mm (1/8 in.) across as well in the lower portion of the slab (Figure B5b).
VOID FILLINGS	The luster of interior walls is dull and voids are mostly free of secondary deposits. Traces of ettringite are present in rare voids.

5. COARSE AGGREGATE	
PHYSICAL PROPERTIES	Natural gravel with nominal top size of 9.5 mm (¾ in.; Figure B7). The gradation of the aggregate appears limited to a few sieve sizes with no appreciable amount of sand present. The aggregate particles are typically sub-equant to oblong in shape with well-rounded to sub-angular edges. No preferred orientations were observed.
ROCK TYPES	The aggregate consists predominantly of granitic rocks (> 75%) that range in color from light ink to deep red to light gray. Other rock types that make up minor components (< 10%) of the aggregate include siliceous volcanic rocks, coarse particles of quartz and feldspar that appear derived from pegmatite, metagraywackes, and amphibolites
OTHER FEATURES	No deleterious coatings or incrustations were observed. There is no significant internal microcracking of the aggregates and no evidence of reaction rims or other evidence of ASR. Low w/cm mortar coatings are present on many aggregate particles throughout the thickness of the slab.

6. PASTE OBSERVATIONS	
POLISHED SURFACE	Color: Paste color varies significantly between the top 38-50 mm (1 ½-2 in.) and the lower section of the core (Figure B7). In the top section the color is gray (Munsell N5-N6) whereas the lower section is light gray to white (2.5Y/6/1 to 2.5Y/7/1). Dark gray low w/cm mortar coatings are present on aggregate particles throughout the depth of the slab (Figure B8) Texture: Granular Luster: Dull Hardness (Mohs): Medium (2-3); bends when scratched.
THIN SECTION*	Hydration: Moderately advanced hydration with 4-7% RRCG that consists primarily of belite and interstitial ferrite that is fairly fine grained (Figure B9a) SCM: Fly Ash is present; no other SCM observed. CH: 15-25% total paste, fine-grained and evenly distributed (Figure B9b).
FRACTURE SURFACE	Color: light gray Texture: Granular Luster: Dull Paste/Aggregate Bonding: cuts exclusively around aggregate

7. SECONDARY DEPOSITS	
PHENOLPHTHALEIN	Stains full depth of slab (Figure B10).
DEPOSITS	Minor carbonation observed around some cracks and microcracks and around some voids near the top of the slab. Traces of ettringite observed in rare voids.

* Abbreviations are as follows: RRCG, relict and residual cement grains (calcium silicates); SCM, supplemental cementitious materials; CH, portlandite or calcium hydroxide; ITZ, interfacial transition zone (thin zone of paste adjacent to aggregate particles). Modal percentages are based on visual estimations, not quantitative measurements.

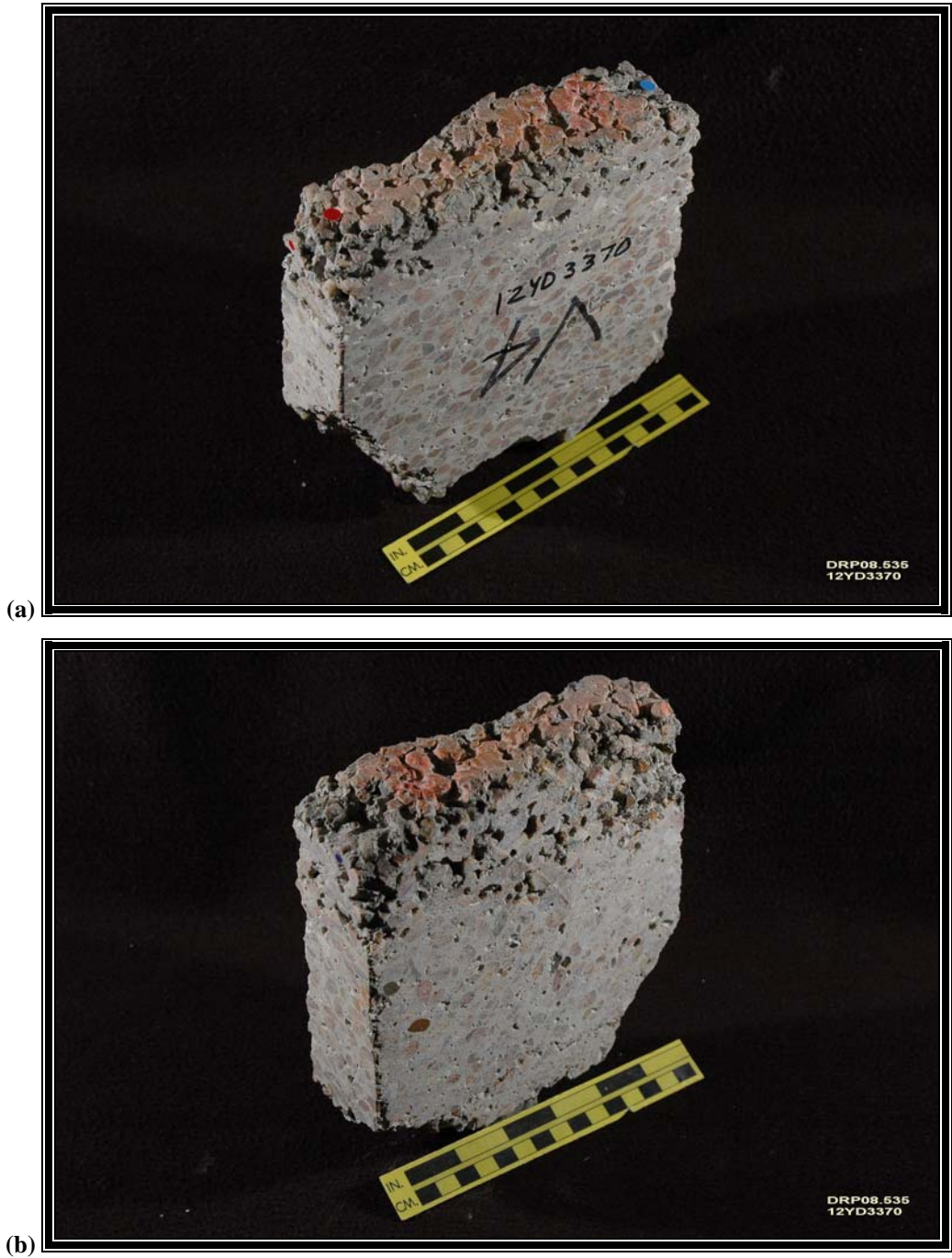


Figure B1. Photographs of sample in as-received condition showing. Red and blue dots in (a) show orientation of saw cut.



(c)



(d)

Figure B1 (cont'd). Photograph of sample in as-received condition.

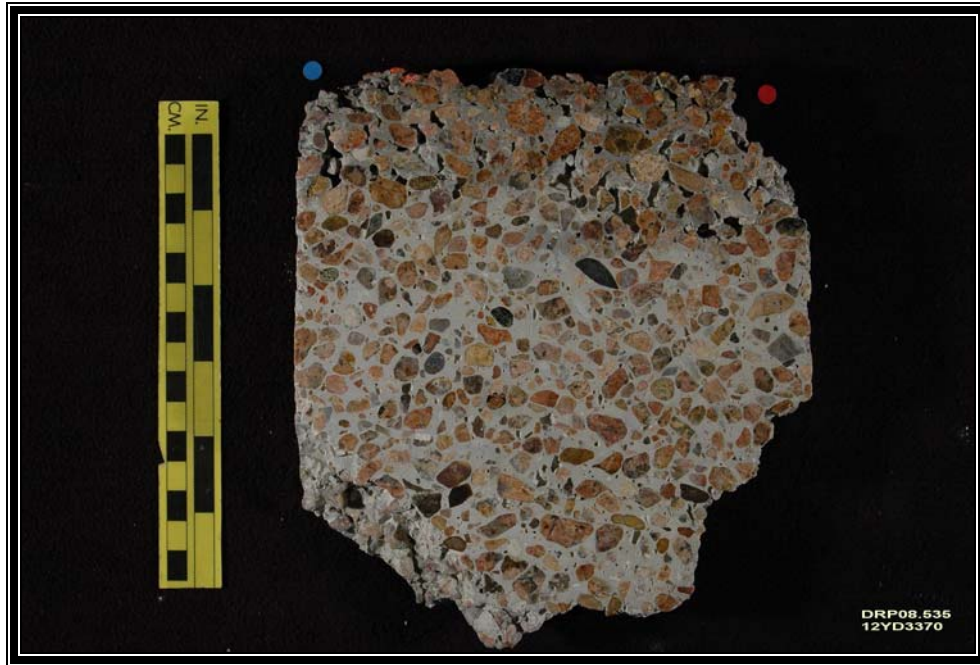


Figure B2. Photograph of polished surface of sample.



Figure B3. (a) Photograph of polished surface showing overview of cracking near the top of the slab; scale in millimeters.



(b)

Figure B3 (cont'd). (b) Photograph of polished surface showing overview of cracking near the top of the slab; scale in millimeters.

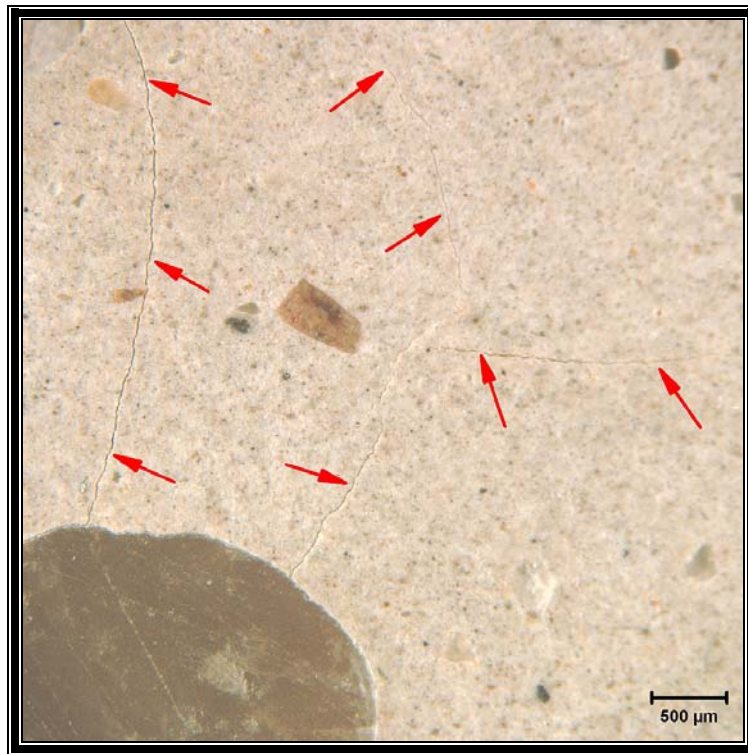


Figure B4. Reflected light photomicrographs showing microcracks (red arrows) in the central portion of the slab.

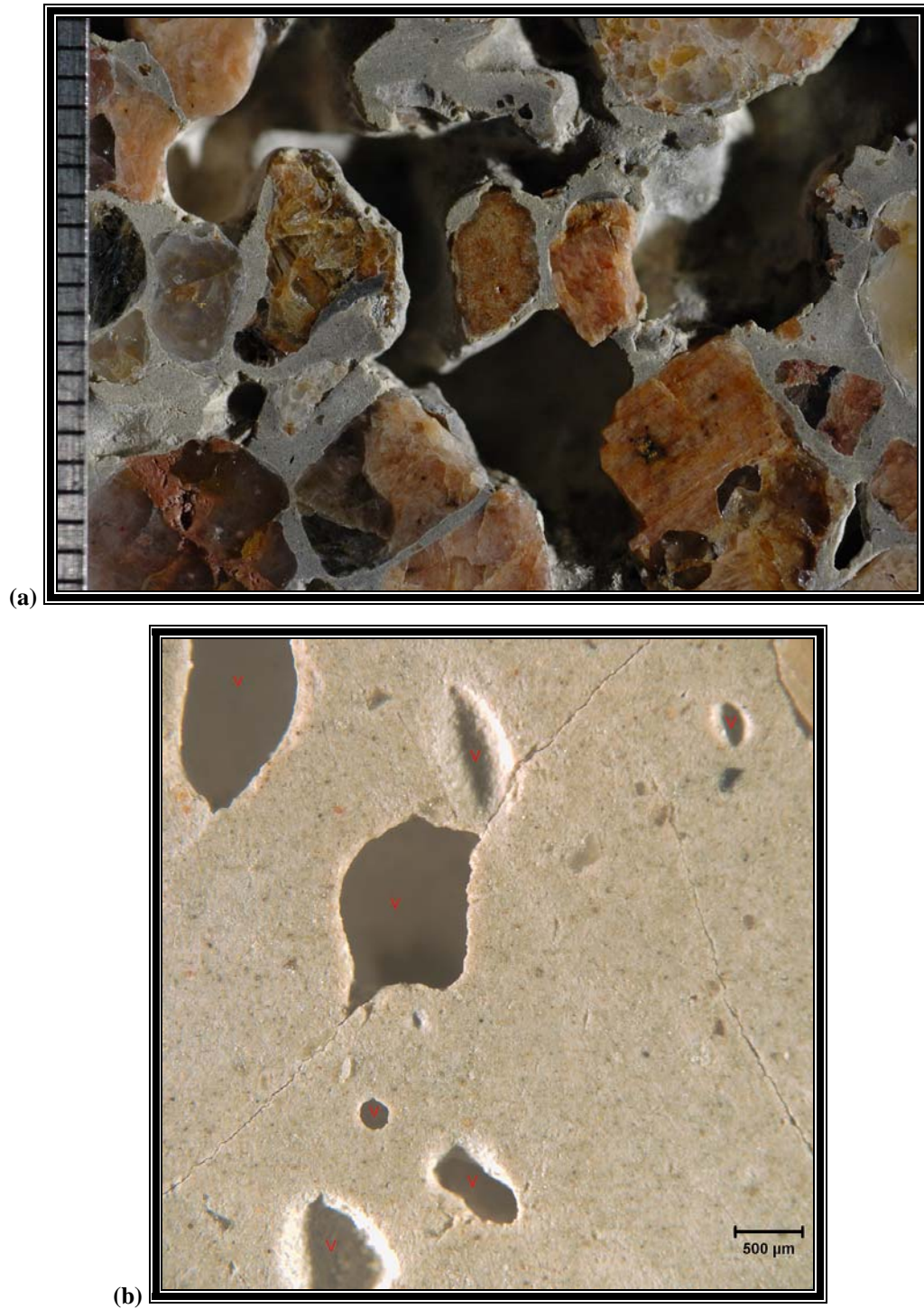


Figure B5. (a) Photograph of polished surface showing large voids near the top of the slab. (b) Reflected light photomicrograph of polished surface showing smaller voids (red “v”) in the middle of the slab.

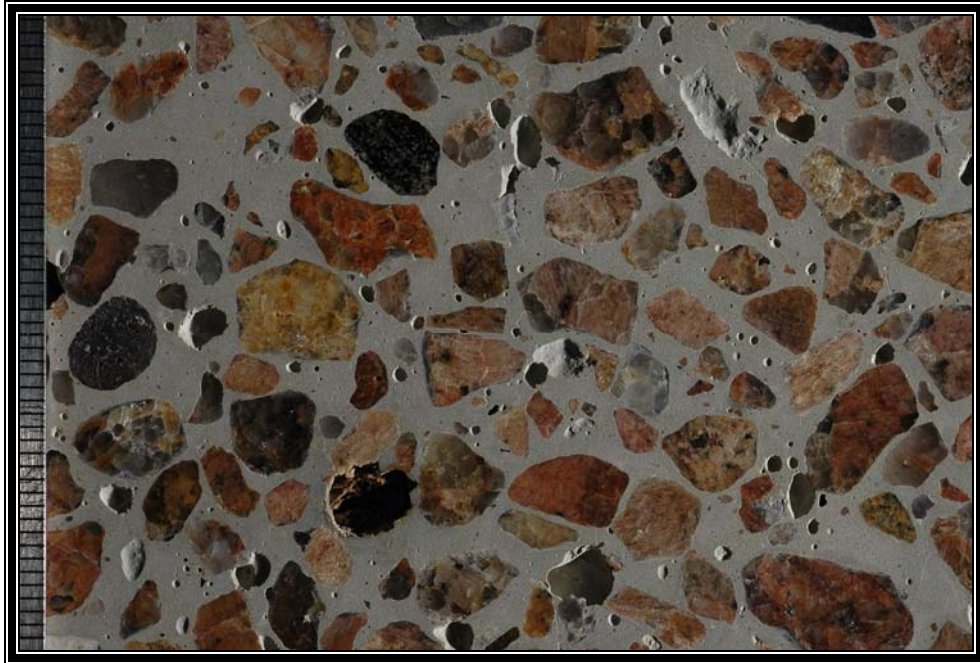


Figure B6. Photograph of polished surface showing overview of aggregate; scale in millimeters.



Figure B7. Photograph of polished surface showing paste color variations; scale in millimeters.

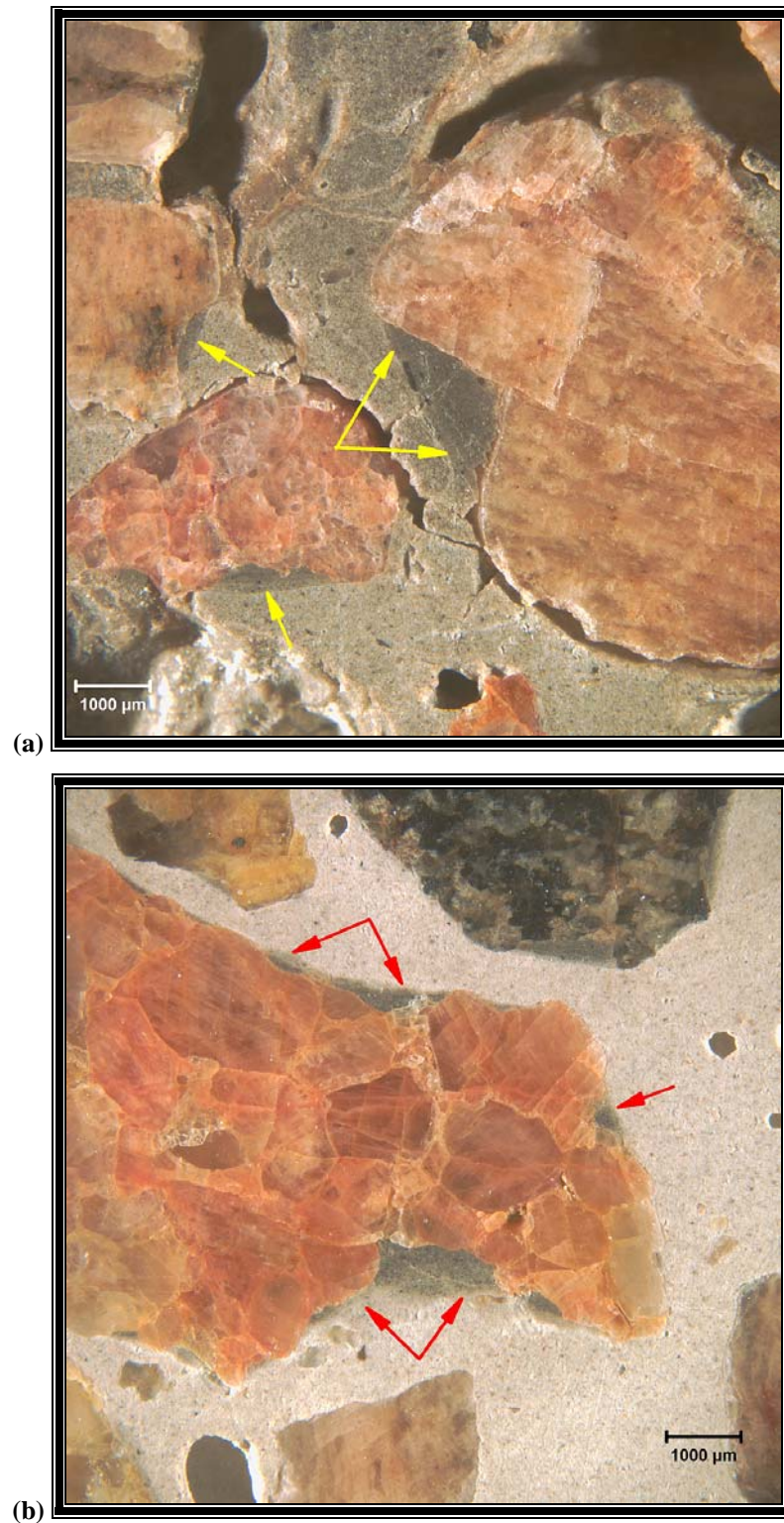


Figure B8. Reflected light photomicrograph of polished surface showing low w/cm mortar coatings (red arrows) on aggregates (a) near the top of the slab and (b) in the middle of the slab.

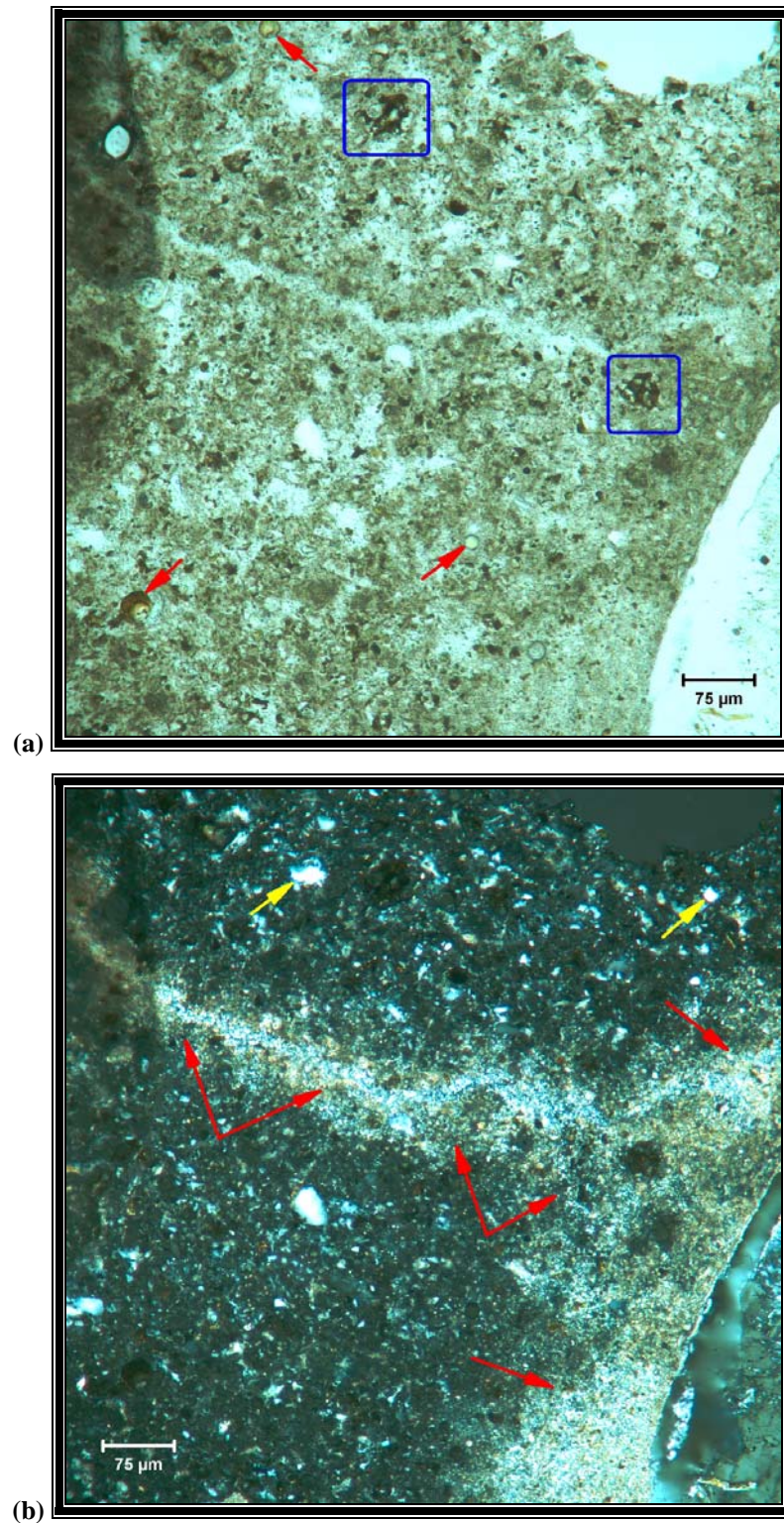


Figure B9. Transmitted light photomicrographs of thin section showing detail of paste in (a) plane-polarized and (b) cross-polarized light. In (a) red arrows indicate fly ash and blue boxes indicate RRCG. In (b) red arrows indicate carbonated paste along walls of a microcrack and yellow arrows indicate CH.

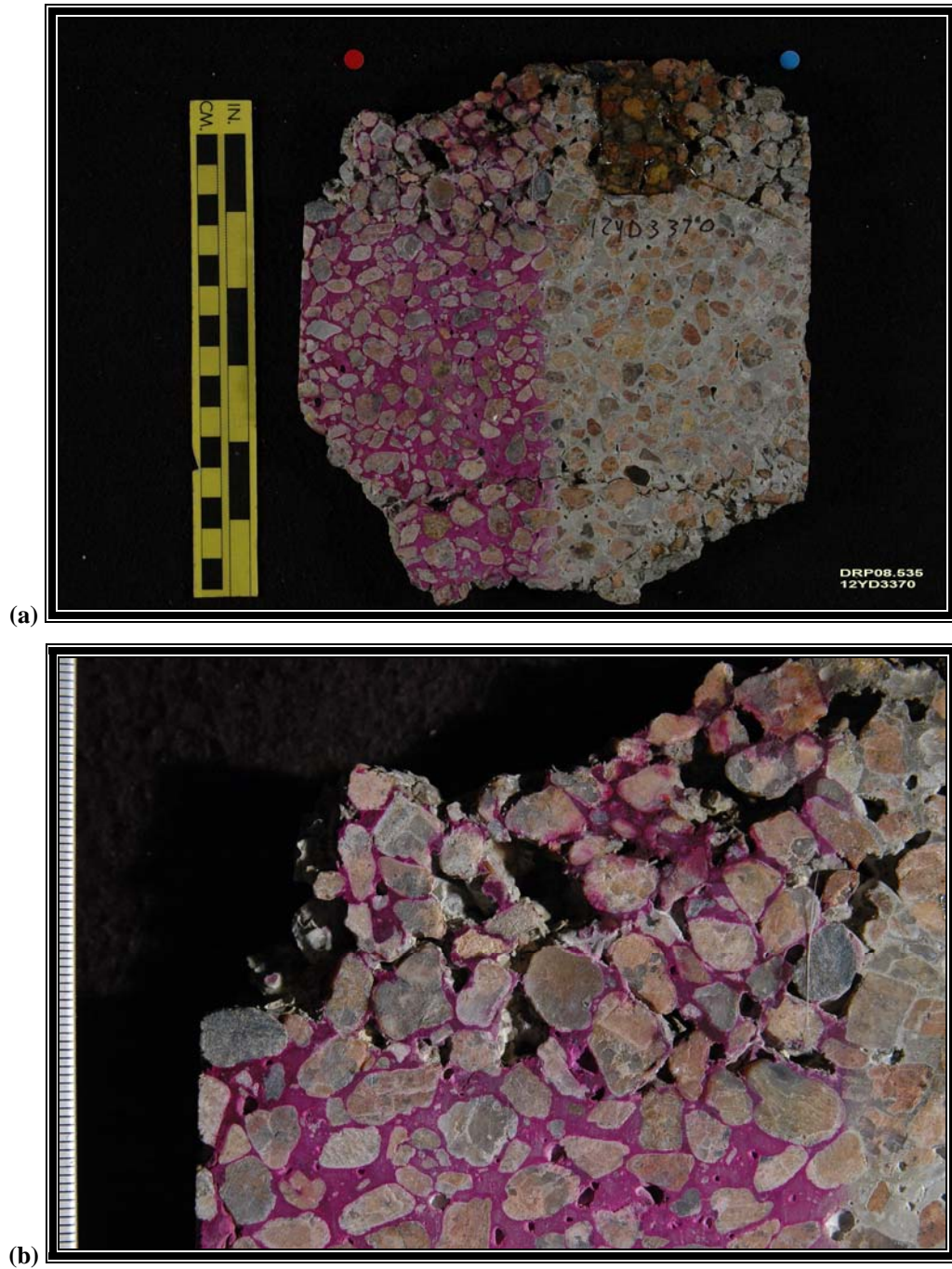


Figure B10. Photographs of phenolphthalein stained surface showing (a) overview of surface and (b) detail of surface near the top of the slab. The scale in (b) is in millimeters.