CONSTRUCTION MATERIALS CONSULTANTS, INC.

# Cracking Of A Swimming Pool Plaster – A Laboratory Investigation

Motamed Pool
3347 Green Acres Drive
Bethlehem, PA 18015

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CMC 0121100

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## EXECUTIVE SUMMARY

The present study involves detailed petrographic examinations of a pool plaster and adhering shotcrete composite core reportedly collected from the spa area of an outdoor swimming pool located in Bethlehem, PA. Extensive cracking in the dark gray pool plaster has initiated this investigation. The pool was excavated in June of 2017 and plastered in May of 2018. The cracking of plaster was first brought into attention in May of 2020.

As a result, a 2$^{3}/_{4}$ in. (70) diameter and 7 in. (175 mm) long core from over a visible crack in plaster was provided, which showed a $^{5}/_{8}$ in. (15 mm) thick dark gray dense plaster well-bonded to a shotcrete base. The crack has extended through the entire thickness of plaster down to the shotcrete for a total depth of 2 in. (50 mm). The crack is wider at the exposed surface of plaster and tapered down, and mostly circumscribed the aggregate particles along its path. The fresh fractured opposite end of the core shows many fractured surfaces of dark crushed shale coarse aggregate particles in shotcrete that have white secondary deposits confined mostly within the fractured aggregate surfaces, which indicates a potentially deleterious reaction of those crushed stone particles in shotcrete resulting in white secondary deposits.

The core was examined in detail according to the procedures of ASTM C 856 to evaluate the conditions and compositions of plaster and shotcrete, and evidence of any deleterious chemical and/or physical reactions within plaster and/or shotcrete which may have contributed to the cracking. The method involved detailed microscopical examinations of lapped cross sections and thin section of plaster and underlying shotcrete components.

Field photos showed extensive cracking of dark gray plaster inside the spa areas, as well as some visible cracks on the masonry wall around the spa from the limestone tiles above the masonry wall to the outer surface of the masonry wall where cracks have extended along the interfaces between the masonry units and jointing mortars, often associated with white efflorescence deposits along the cracks. It is possible that the mechanism that has contributed to the cracking of pool plaster may also have caused cracking in the surrounding masonry wall and tiles.

Based on detailed petrographic examinations, the pool plaster is found to be very dense, well-consolidated, well-bonded to underlying shotcrete, and made using crushed stone aggregate, which is a mixture of major amount of crushed limestone and subordinate amount of crushed amphibole-pyroxene schist, all having nominal maximum sizes of 3 mm; particles are dense, angular, well-graded, well-distributed, and present in sound conditions in plaster without any evidence of any potentially deleterious reactions let alone to cause the observed cracking. Paste is Portland cement based as seen by abundant residual Portland cement particles, very dense, and of very low water-cement ratio, which is estimated to be less than 0.40. Plaster lacks any intentionally introduced entrained air. A pigment is perhaps added to impart the overall dark gray color tone of plaster. There is no evidence of any potentially deleterious reactions found in the plaster.

The shotcrete beneath the plaster showed a thin (about 5 mm in thickness) carbonated paste zone indicating a period of air exposure (i.e., between June 2017 and May 2018) and interaction with atmospheric carbon dioxide prior to the installation of plaster. The shotcrete contains: (a) crushed shale coarse aggregate having a nominal maximum size of $^{1}/_{2}$ in. (12.5 mm); (b) natural siliceous sand fine aggregate having a nominal maximum size of $^{3}/_{8}$ in. (9.5 mm) consisting of major amount of quartz and subordinate amounts of quartzite, quartzite siltstone, feldspar, etc., (c) a Portland cement paste having a cement content estimated to be 7 to 7$^{1}/_{2}$ bags per cubic yard and a water-cement ratio estimated to be 0.45 to 0.50; and (d) air entrainment where total air content is estimated to be 5 to 6 percent.

The crushed shale coarse aggregate particles in shotcrete are physically and chemically unsound due to potential expansions associated with: (a) moisture absorption of clay minerals in shale, and, (b) potential alkali-silica reaction of the reactive silica component in the shale during exposures to high alkalis and moisture. Besides Portland cement, potential sources of high alkalis are pool water and chemical admixtures (e.g., set accelerator) used in shotcrete mix. Evidence of alkali-silica reaction of shale is found from: (a) microcracking within many shale particles, (b) alkali-silica reaction gels filling the microcracks and air voids, and (c) white secondary deposits of dissolved reaction gels found within the fresh fractured shale surfaces on the fractured end of core when received.

Based on detailed petrographic examinations cracking in the pool plaster is found to be due to expansion of the underlying shotcrete component due to potentially deleterious reactions of the crushed shale aggregate used in shotcrete in the presence of moisture. Expansion of shotcrete has put the well-bonded plaster skin in tension to cause development of tensile cracks that are thus wider at the exposed surface end of plaster and tapered downward into shotcrete. The plaster is found be present in sound condition without any chemical or physical deterioration and simply responded to the expansion of shotcrete by development of tensile cracks. Cracks once formed have provided the pathways for deeper migration of pool water to sustain deleterious reactions in shotcrete and, thus, continued expansion and cracking.

## INTRODUCTION

Reported herein are the results of laboratory studies of a composite core consisting of a swimming pool plaster and underlying shotcrete collected from the spa area of an in-ground outdoor pool located in Bethlehem, PA. The spa area has reportedly shown extensive cracking of the dark gray pool plaster.

### BACKGROUND INFORMATION

The subject pool was reportedly excavated in June of 2017 and plastered in May of 2018. The client who has installed the pool plaster was first informed about cracking of plaster in May of 2020.

### FIELD PHOTOGRAPHS

Figures 1 through 5 show field photos of the spa area that shows extensive cracking of pool plaster as well as cracks in the outer wall and limestone tiles in the spa area.

a. Figure 1 shows the overall condition of the spa area of the pool consisting of dark gray pool plaster inside the masonry wall of the spa. Limestone tiles are seen on top of the masonry wall.
b. Figure 2 shows a close view of the masonry wall where cracking and white efflorescence deposits along the cracks are seen. Cracks mostly followed the paths between the masonry units and jointing mortars.
c. Figure 3 shows visible cracks on the limestone tiles at the top of the masonry wall in the spa. These cracks are either random isolated or intersecting.
d. Figure 4 shows close-up of cracking in the pool plaster, which is the purpose of this investigation. Cracks are mostly oriented vertical, parallel to each other, although some are diagonal or horizontal at the bench and more concentrated at the corners.
e. Figure 5 shows a close-up of extensive cracking at the corners of the spa where not only visible cracking but spalling of pool plaster has occurred.

### PURPOSE OF PRESENT INVESTIGATION

Based on the background information, the purposes of the present investigation are to determine:

a. Compositions, qualities, and overall conditions of the concrete substrate portion of the core received where the concrete is present in relatively intact condition; and,
b. Chemical, mineralogical, and microstructural features of concrete to investigate future durability and serviceability of the concrete.


Figure 1: Field photo of the spa area of swimming pool showing limestone tiles on pool deck and masonry wall around the spa. The present investigation addresses extensive cracking in the dark gray pool plaster within the spa area.

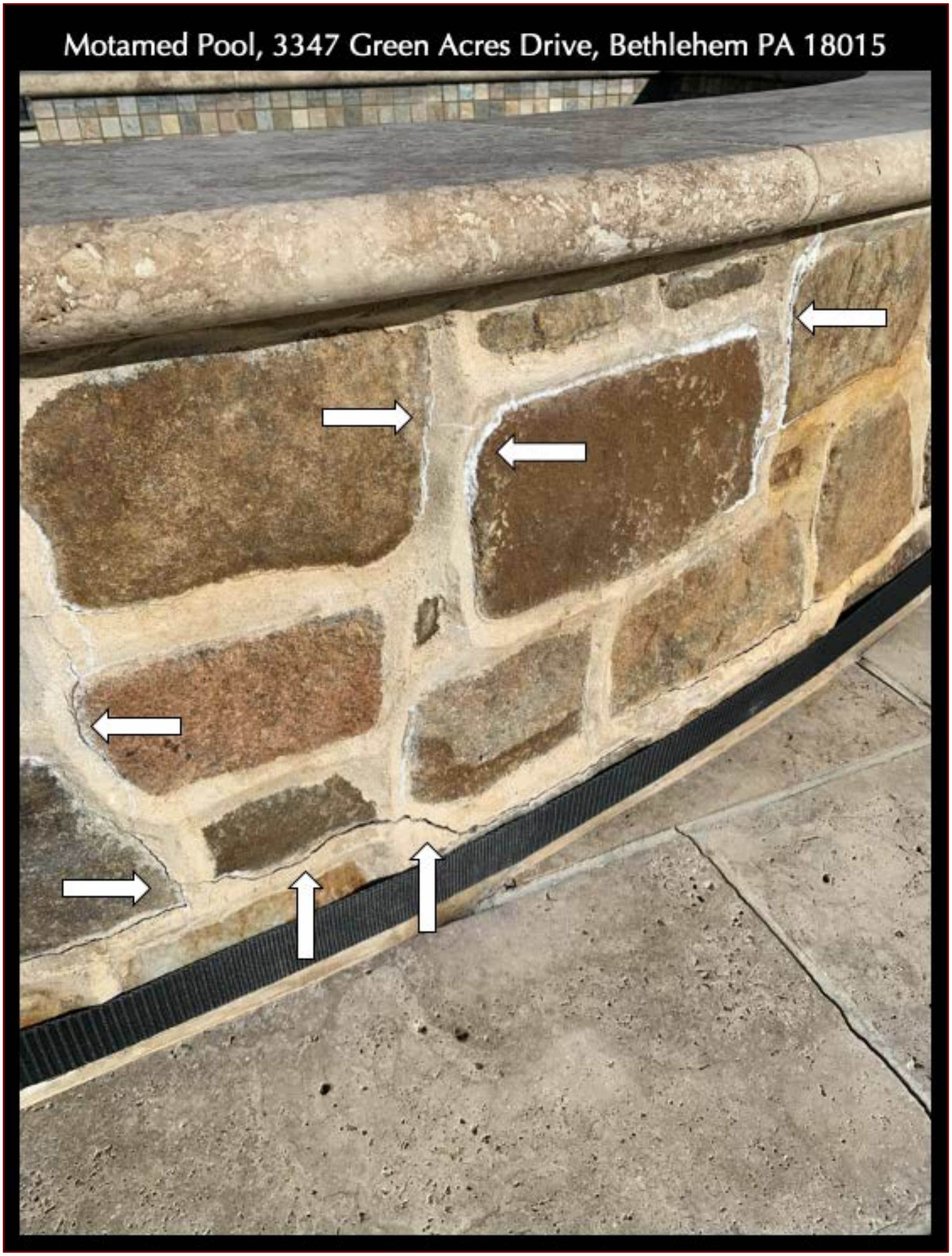



Figure 2: A close view of some cracking and white efflorescence deposits on the outer masonry wall of the spa that are marked with arrows. These cracks may represent an extension of the cracks seen in the inside dark gray plaster in the spa and may as well have formed due to the same mechanism that has caused cracking in the plaster.

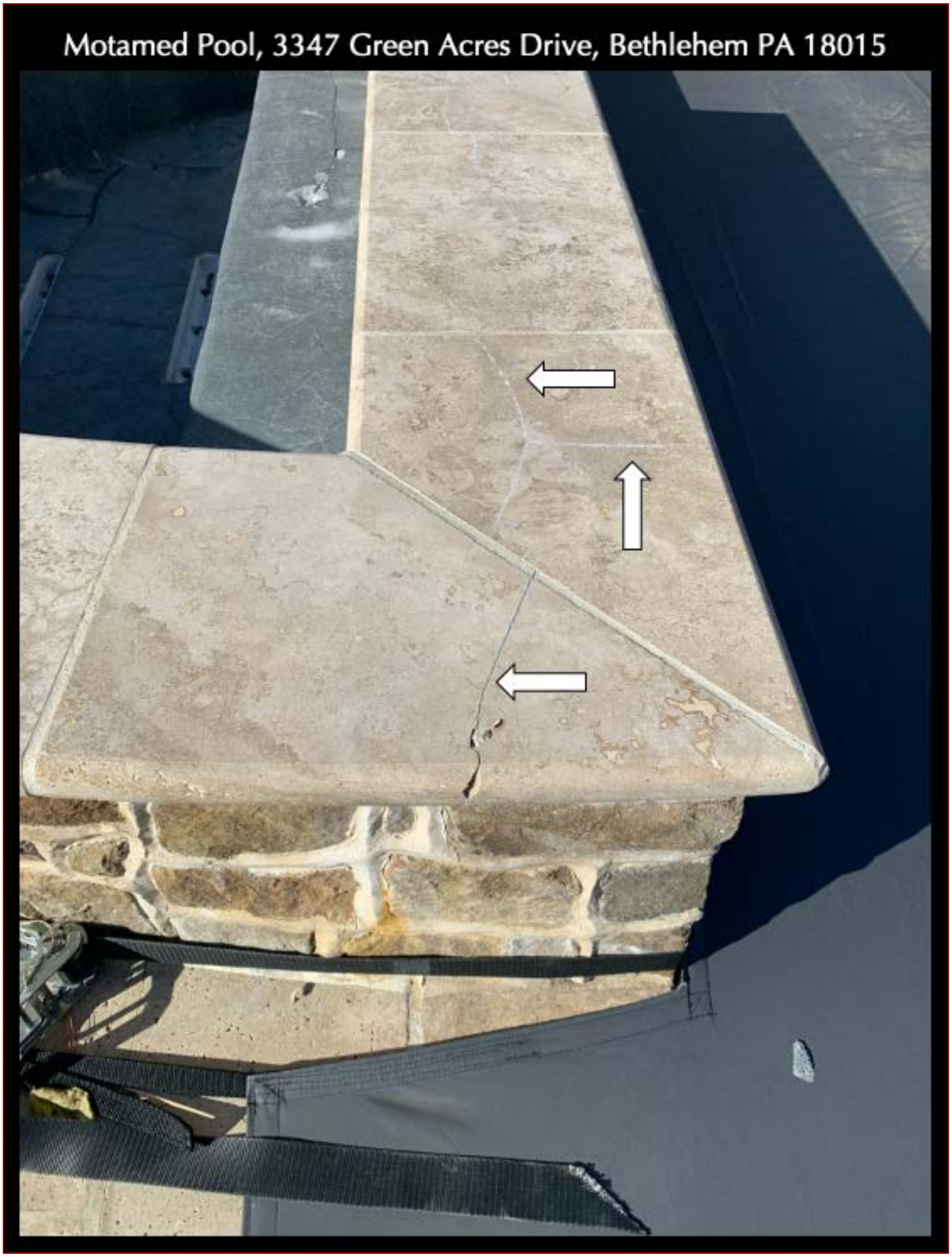



Figure 3: Enlarged view of some fine, visible cracks on the limestone tiles around the spa.

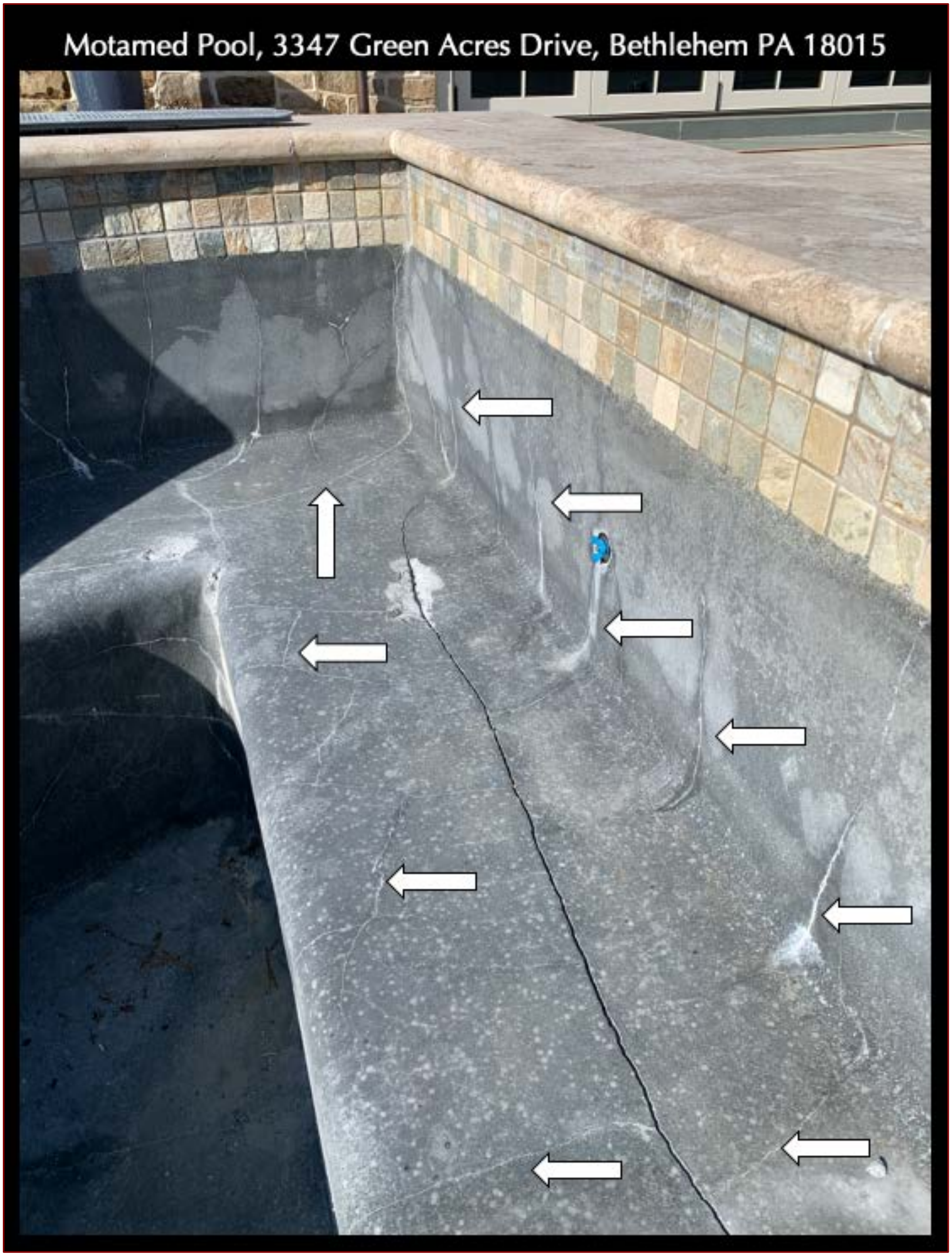



Figure 4: Extensive cracking in the dark gray pool plaster within the spa area, where many cracks show a more or less parallel pattern along with some diagonal cracks. These cracks are the reason for the present investigation.

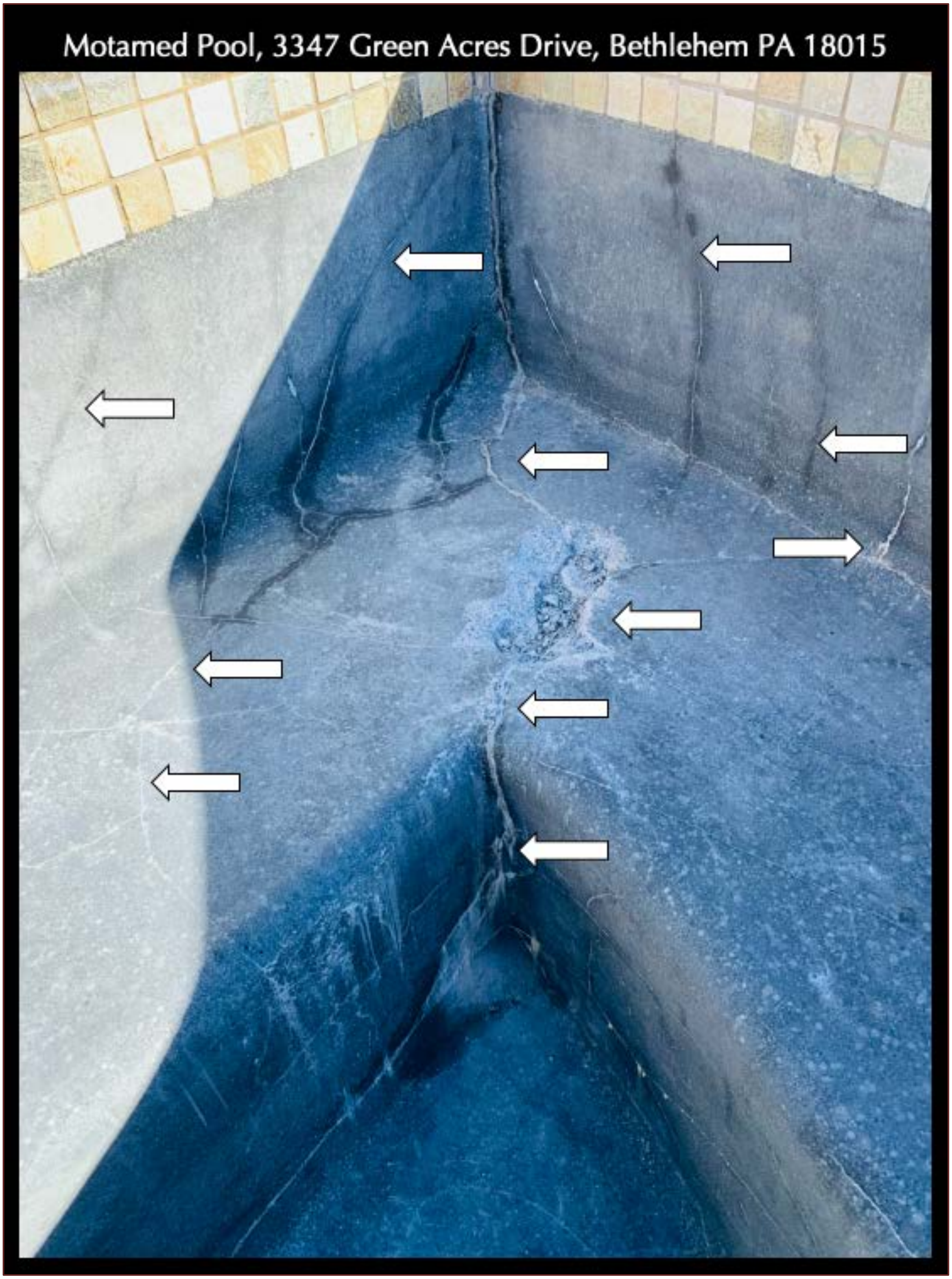



Figure 5: Enlarged view of extensive cracking in pool plaster. These cracks are the reason for the present investigation.

## METHODOLOGIES

### PETROGRAPHIC EXAMINATIONS (ASTM C 856)

The core sample was examined by petrographic examinations by following the methods of ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete." Details of petrographic examinations and sample preparation are described in Jana (2006). The steps of petrographic examinations include (Jana 2006):

i. Visual examinations of sample, as received;
ii. Low-power stereo microscopical examinations of as-received, saw-cut and freshly fractured sections, and lapped cross sections of sample for evaluation of textures, and composition;
iii. Low-power stereo microscopical examinations of air contents and air-void systems of concrete in the sample;
iv. Examinations of oil immersion mounts in a petrographic microscope for mineralogical compositions of specific areas of interest;
v. Examinations of fluorescent dye-mixed (to highlight open spaces, cracks, etc.) epoxy-impregnated lapped cross sections and large area (50 mm × 75 mm) thin section in a petrographic microscope for detailed compositional and microstructural analyses;
vi. Photographing samples, as received and at various stages of preparation with a digital camera and a flatbed scanner; and,
vii. Photomicrographs of lapped sections and thin section of sample taken with stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information of concrete.

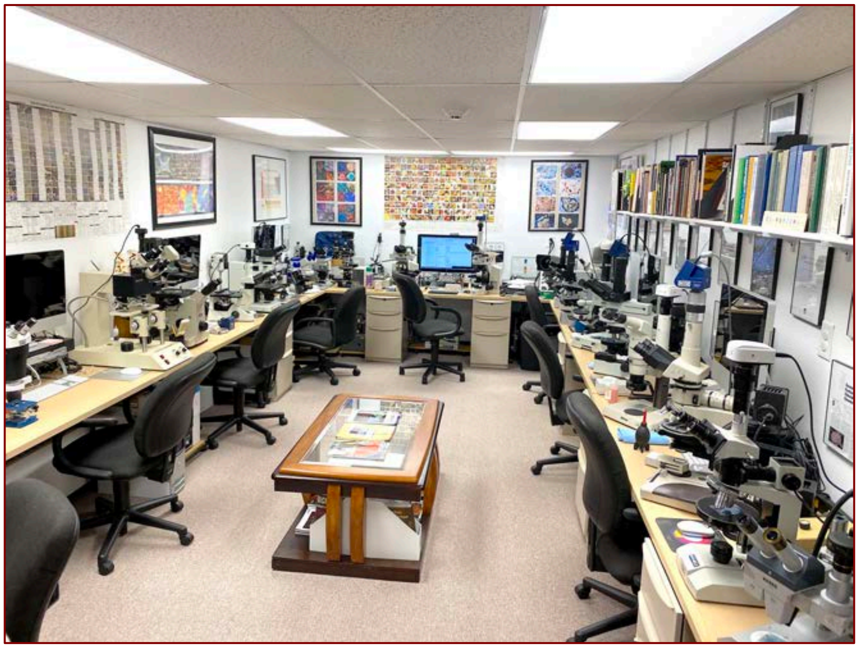


Figure 6: Optical microscopy laboratory in CMC that houses various stereo-microscopes, and petrographic microscopes used in this study.

The main purposes of optical microscopy are characterization of: (a) aggregates in plaster and shotcrete, e.g., type(s), chemical and mineralogical compositions, size, shape, angularity, grain-size distribution, soundness, alkali-aggregate reactivity, etc. (b) paste, e.g., compositions and microstructures to diagnose various type(s) of binder(s) used, (c) air, e.g., presence or absence of air entrainment, air content, etc., (d) alterations, e.g., lime leaching, carbonation, staining, etc. due to interactions with the environmental agents during service, and effects of such alterations on properties and performance; and (e) various chemical and/or physical deteriorations during service, including explanation of any visible cracking from various mechanisms. Portions selected from preliminary examinations for microscopy are sectioned, polished, and thin-sectioned (down to 25-30 micron thickness) preferably after encapsulating and impregnating with a fluorescent dye-mixed epoxy to improve the overall integrity of the sample during precision sectioning and grinding, and to highlight porous areas, voids, and cracks. Prepared sections are then examined in a high-power (up to 100X) Stereozoom microscope having reflected, transmitted, fluorescent light, and plane and crossed polarized-light facilities, and eventually in a high-power (up to 600X) petrographic microscope equipped with transmitted, reflected, polarized, and fluorescent-light facilities. Capturing high-resolution photomicrographs with these microscopes via digital microscope cameras with image analyses software are an integral part of documentations during petrographic examinations.

## SAMPLE

### PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figure 7 and the following Table 1 provide the overall dimensions and conditions of the core received. Figures 8 through 12 show lapped cross sections of core where the dark gray plaster intimately bonded to the shotcrete as well as a major vertical crack transecting the plaster and entering into shotcrete to a depth of 2 inches (50 mm) is seen.

| Core ID | Diameter | Topping Length | Plaster thicknesses | End Surfaces | Distress/Condition |
|---|---|---|---|---|---|
| #2 | $2^{3}/4$in. (70 mm) | 7 in. (175 mm) | Plaster $^{5}/8$ in. (15 mm) | Smooth flat dark gray plaster surface with a major visible crack that has extended to a depth of 2 inches (50 mm) through the entire thickness of plaster to the shotcrete; the crack is wider at the exposed plaster surface and tapered down into shotcrete<br><br>The bottom end is fresh fractured that shows white secondary deposits mostly concentrated within the fractured surfaces of crushed dark shale aggregate particles in shotcrete indicating potentially deleterious reactions in shale aggregate to form those white deposits | As mentioned, two types of distress are seen:<br>(a) Major visible cracking through plaster and shotcrete to a depth of 2 in.;<br>(b) White secondary deposits in fractured surfaces of crushed dark shale aggregate particles in shotcrete |

Table 1: Overall dimensions and conditions of the core received for laboratory examinations.

### END SURFACES

End surfaces of cracked exposed plaster side and fresh fractured interior shotcrete side are described in Table 1.

### CRACKING & OTHER VISIBLE DISTRESS, IF ANY

A major visible crack is extended to a depth of 2 inches (50 mm) through the entire thickness of plaster to the shotcrete; the crack is wider at the exposed plaster surface and tapered down into shotcrete. Additionally, the fresh fractured surfaces of crushed shale coarse aggregate particles in shotcrete show internal cracking and white secondary deposits that are indicative of a potentially deleterious reaction (e.g., alkali-aggregate reaction) in shotcrete, which may have caused both internal cracking in many crushed shale particles from expansions as well as overall expansion of shotcrete to cause tensile cracking in shotcrete and plaster.

### EMBEDDED ITEMS

No wire mesh, fiber, or other embedded items are found in the core.

### RESONANCE

The core has a ringing resonance, when hammered.

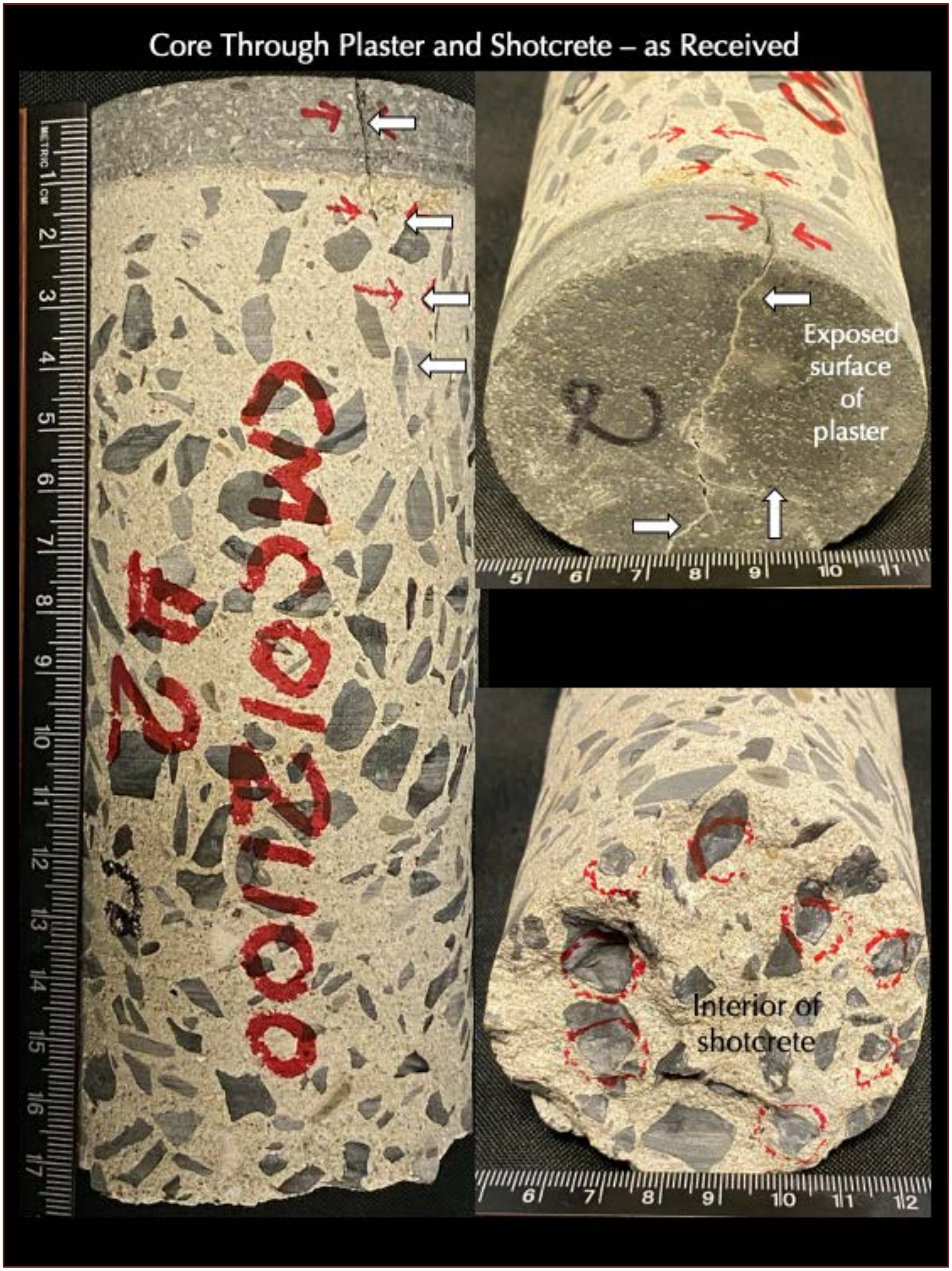



Figure 7: Core 2 as received showing:

(a) A 5/8-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) A vertical crack through plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(c) Internal cracking in many crushed stone particles in shotcrete;

(d) White secondary deposits within fresh fractured surfaces of crushed stone in shotcrete some of which are circled in red in the bottom right photo; and,

(e) Overall dense and well-consolidated natures of plaster and shotcrete despite the visible cracking.

## PETROGRAPHIC EXAMINATIONS

### LAPPED CROSS SECTIONS


Figure 8: Lapped cross sections of Core No. 2 sectioned parallel to each other showing:

(a) A 5/8-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) A vertical crack (thick white arrows) through the plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(c) Internal cracking in many crushed stone particles in shotcrete; and,

(d) Overall dense and well-consolidated natures of plaster and shotcrete despite the visible cracking.

The yellow dotted lines show a crack formed during the sample preparation (lapping) step and does not indicate any pre-existing crack.

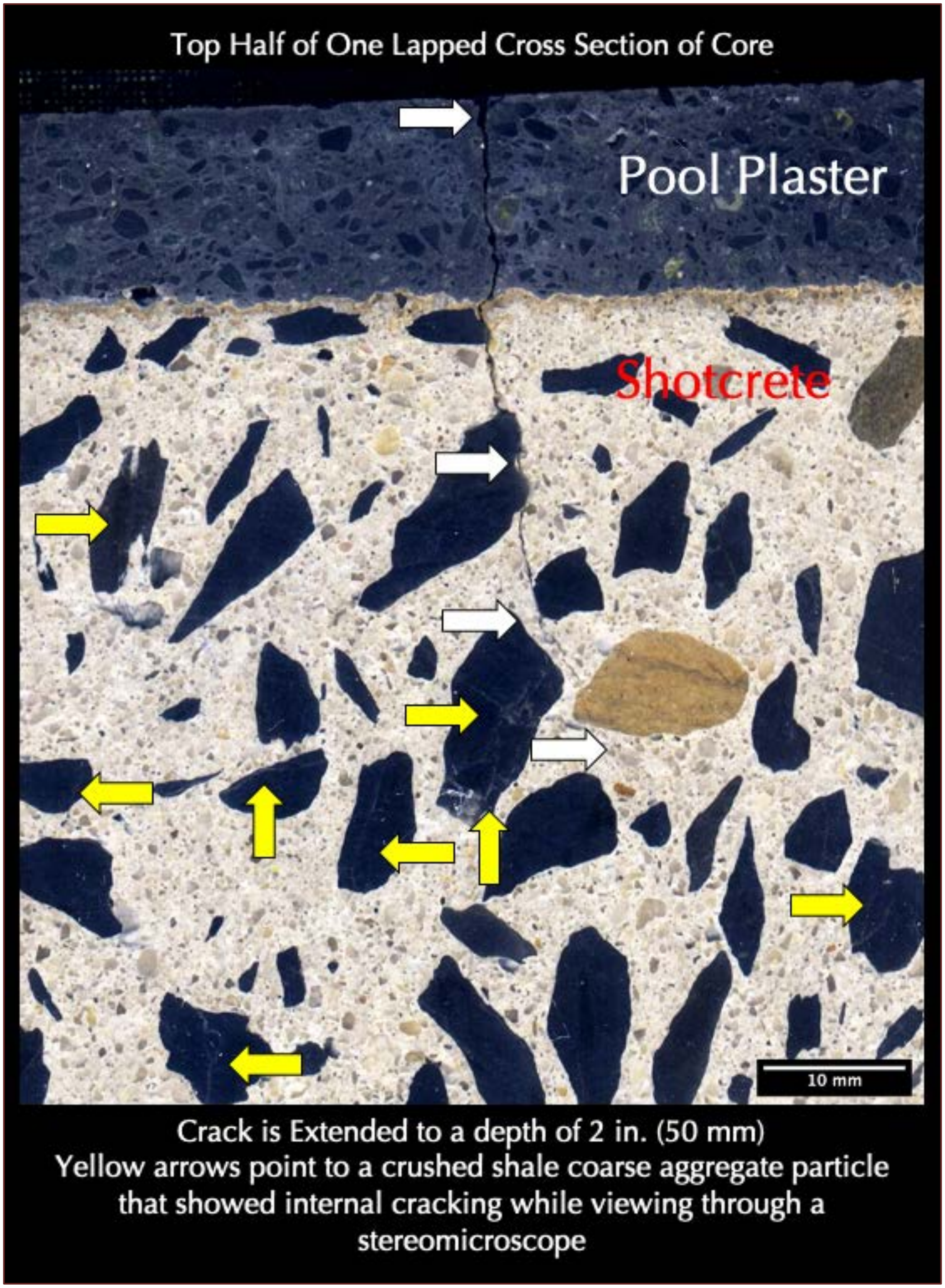



Figure 9: Lapped cross section of Core No. 2 showing:

(a) A 5/8-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) A vertical crack (thick white arrows) through the plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(c) Internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete; and,

(d) Overall dense and well-consolidated natures of plaster and shotcrete despite the visible cracking.

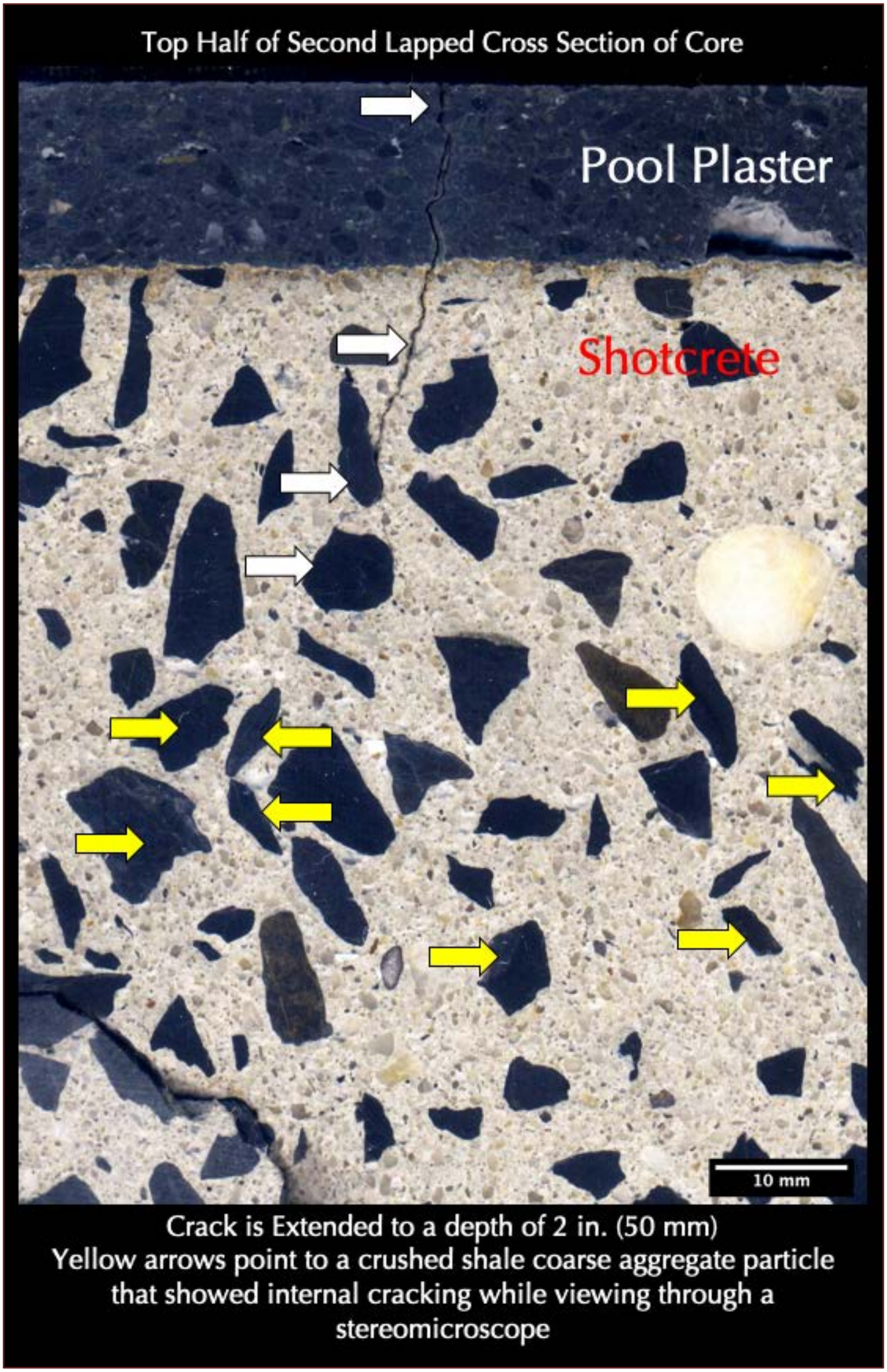



Figure 10: Lapped cross section of Core No. 2 showing:

(a) A 5/8-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) A vertical crack (thick white arrows) through the plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(c) Internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete; and,

(d) Overall dense and well-consolidated natures of plaster and shotcrete despite the visible cracking.

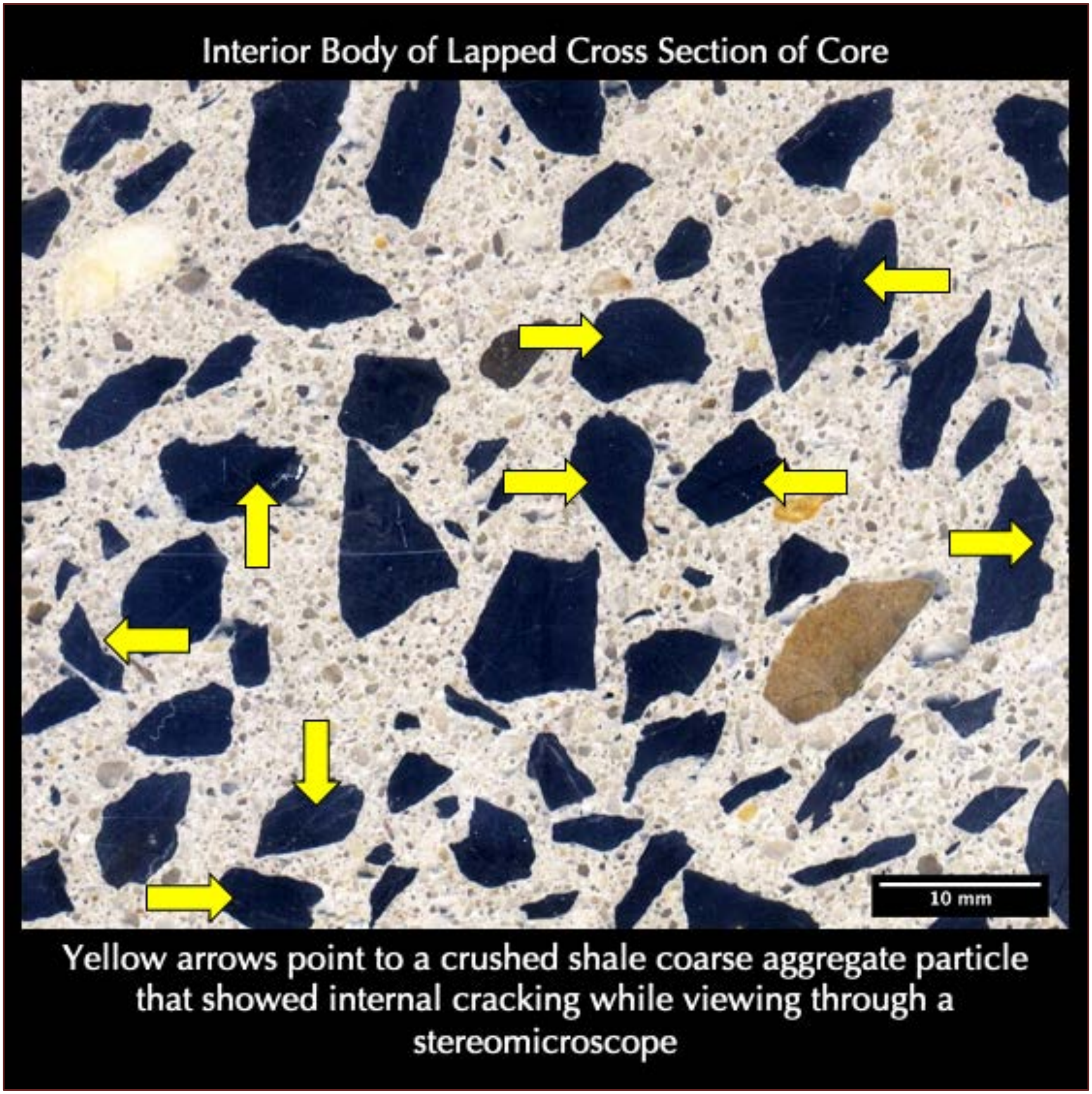



Figure 11: Lapped cross section of Core No. 2 showing the shotcrete portion particularly the well-graded and well-distributed nature of crushed stone aggregate, and internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete.

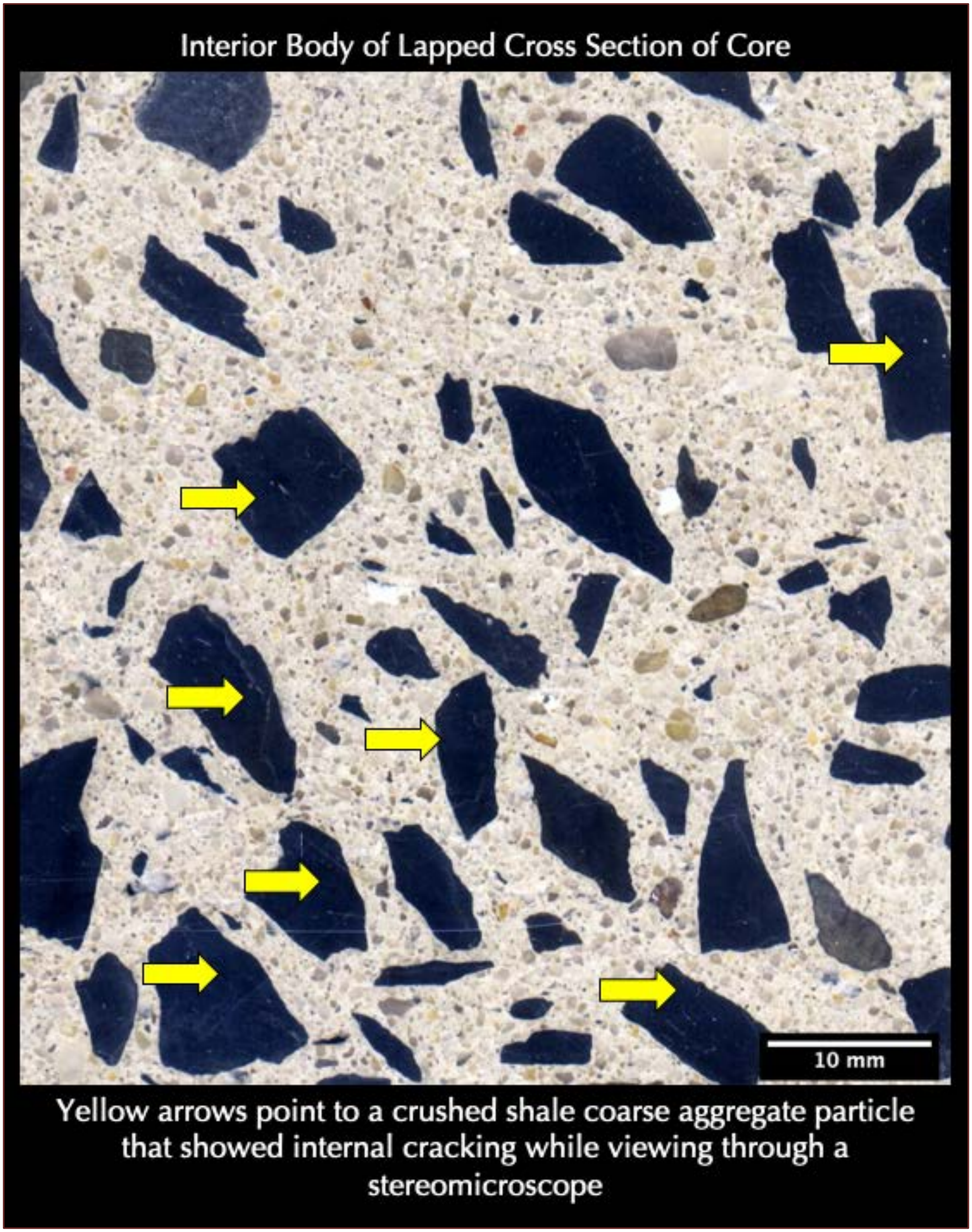



Figure 12: Lapped cross section of Core No. 2 showing the shotcrete portion particularly the well-graded and well-distributed nature of crushed stone aggregate, and internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete.

## MICROGRAPHS OF LAPPED CROSS SECTIONS

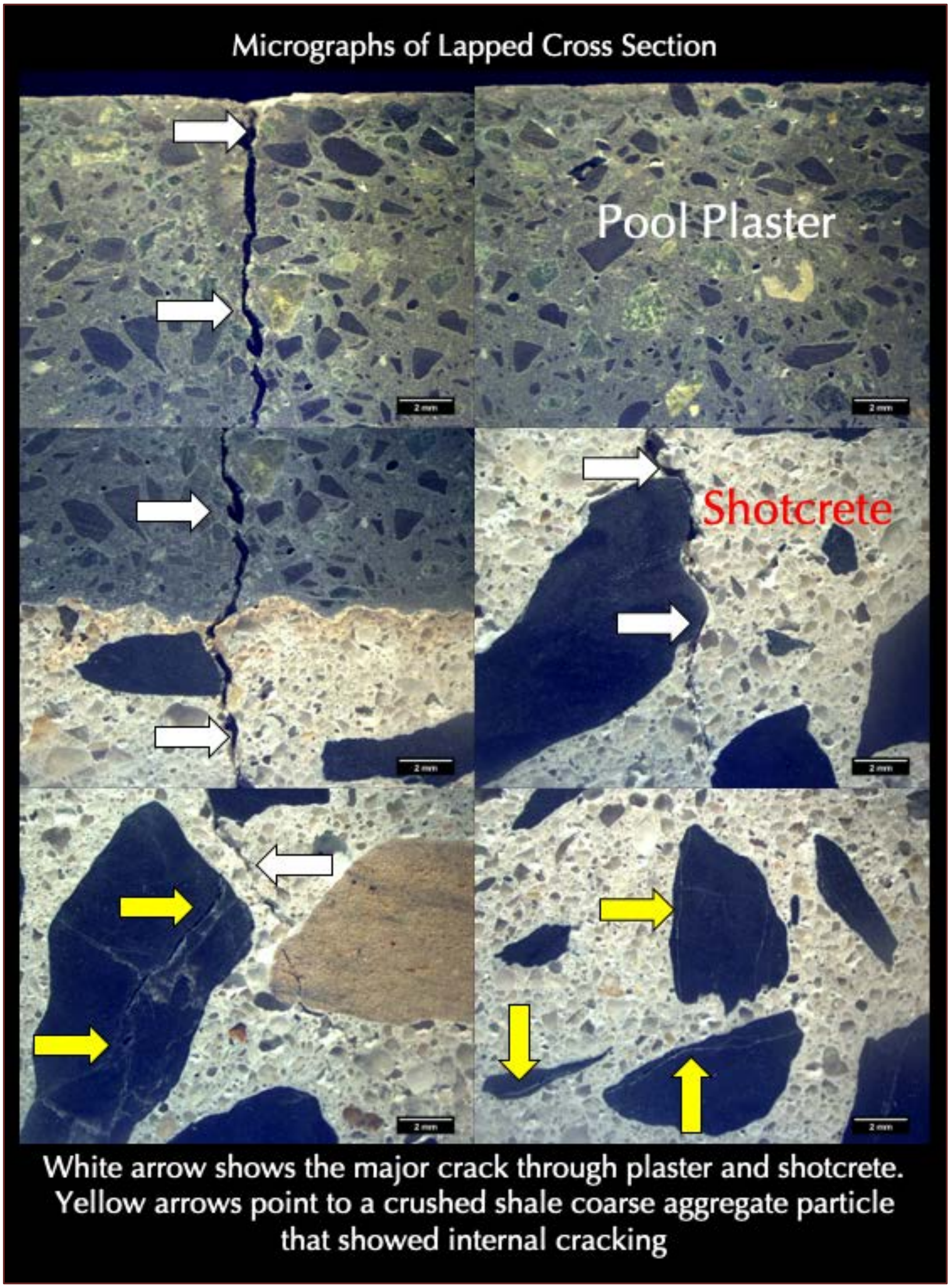



Figure 13: Micrographs of lapped cross section of core showing:

(a) 5/8-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) Beige discoloration of shotcrete at the interface to plaster due to a period of atmospheric carbonation of shotcrete prior to the installation of plaster;

(c) A vertical crack (thick white arrows) through the plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(d) Internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete; and,

(e) Lack of air entrainment in the plaster, whereas air-entrained nature of shotcrete.

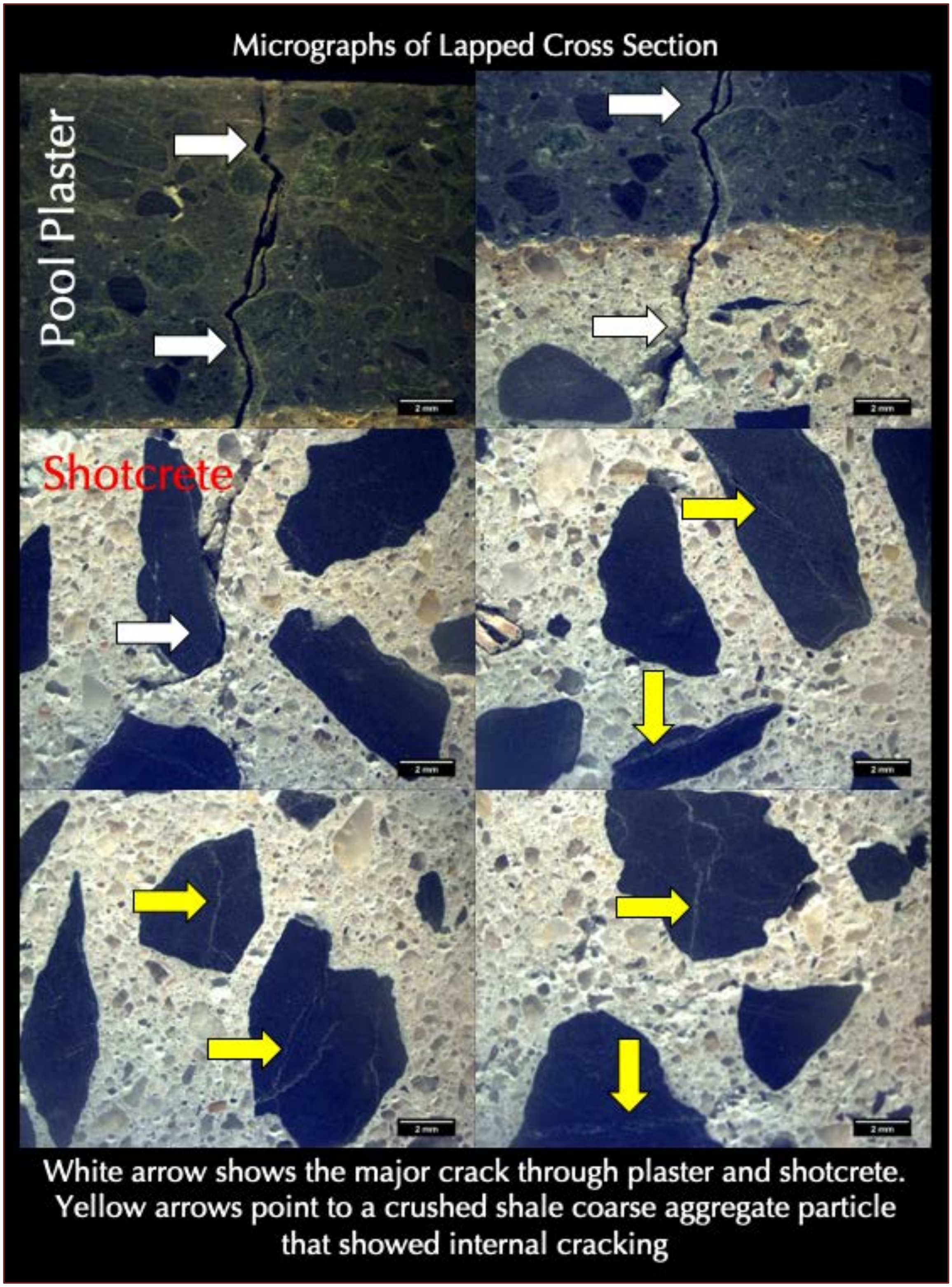



Figure 14: Micrographs of lapped cross section of core showing:

(a) $^{5}/_{8}$-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) Beige discoloration of shotcrete at the interface to plaster due to a period of atmospheric carbonation of shotcrete prior to the installation of plaster;

(c) A vertical crack (thick white arrows) through the plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(d) Internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete; and,

(e) Lack of air entrainment in the plaster, whereas air-entrained nature of shotcrete.

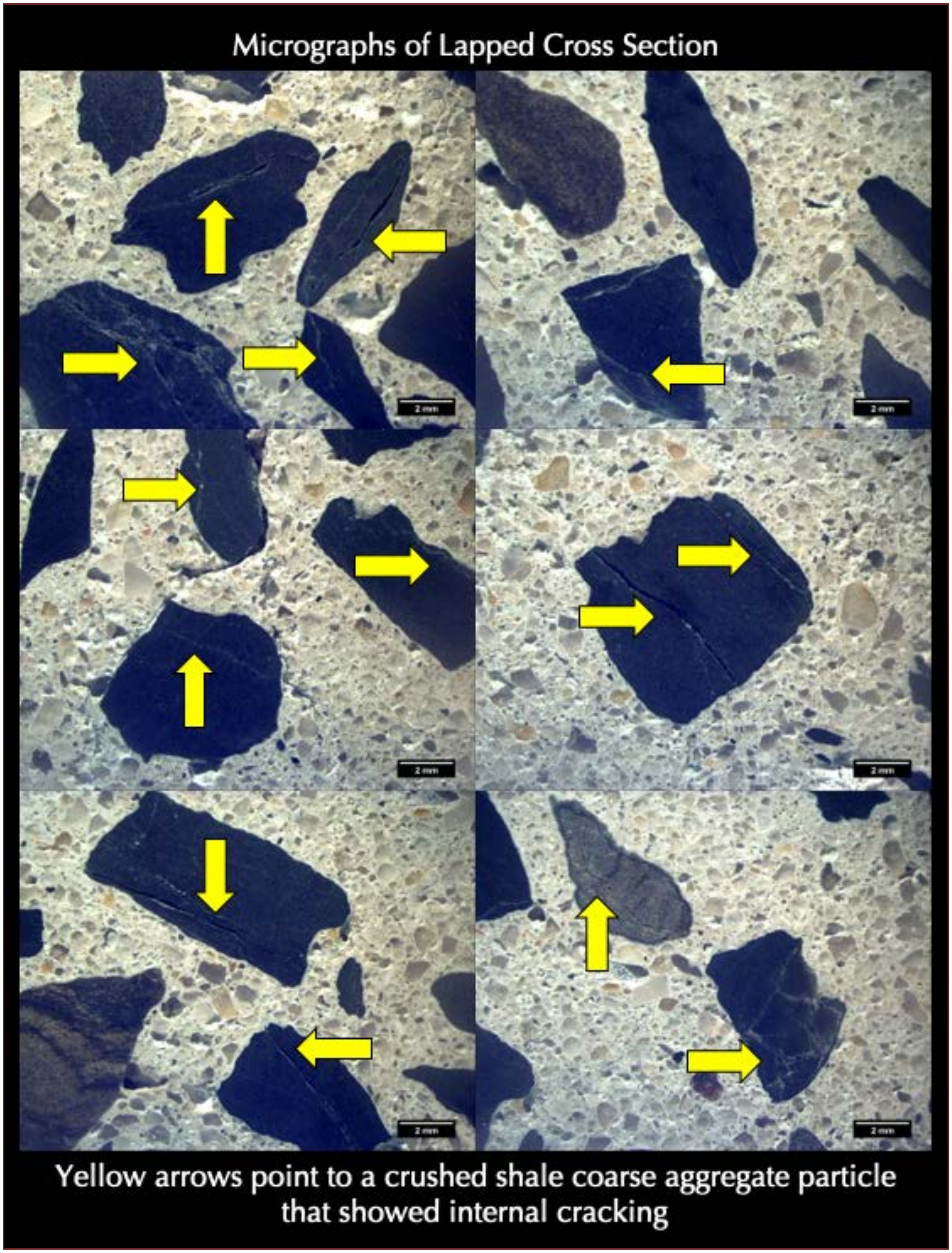



Figure 15: Micrographs of lapped cross section of core showing the shotcrete portion particularly:

(a) The well-graded and well-distributed nature of crushed stone aggregate;

(b) internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete.

(c) The air-entrained nature of the shotcrete is revealed through numerous very fine, discrete spherical and near-spherical voids of sizes 1 mm or less.

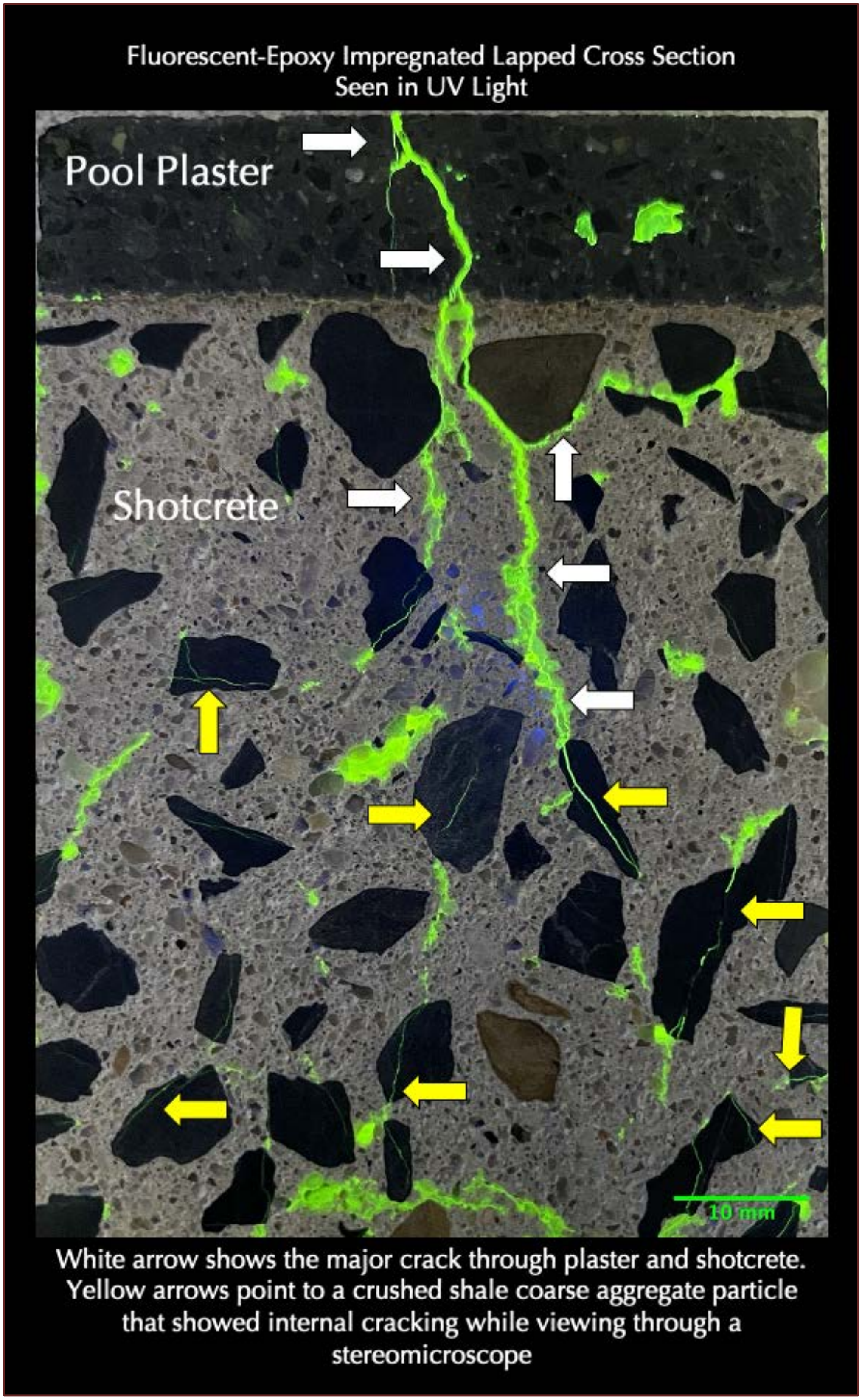



Figure 16: Fluorescent dye-mixed epoxy-impregnated lapped cross section highlighting the cracks while viewing in an UV light. Along with the major vertical cracks many fine hairline microcracks in crushed shale aggregate particles in shotcrete are highlighted.

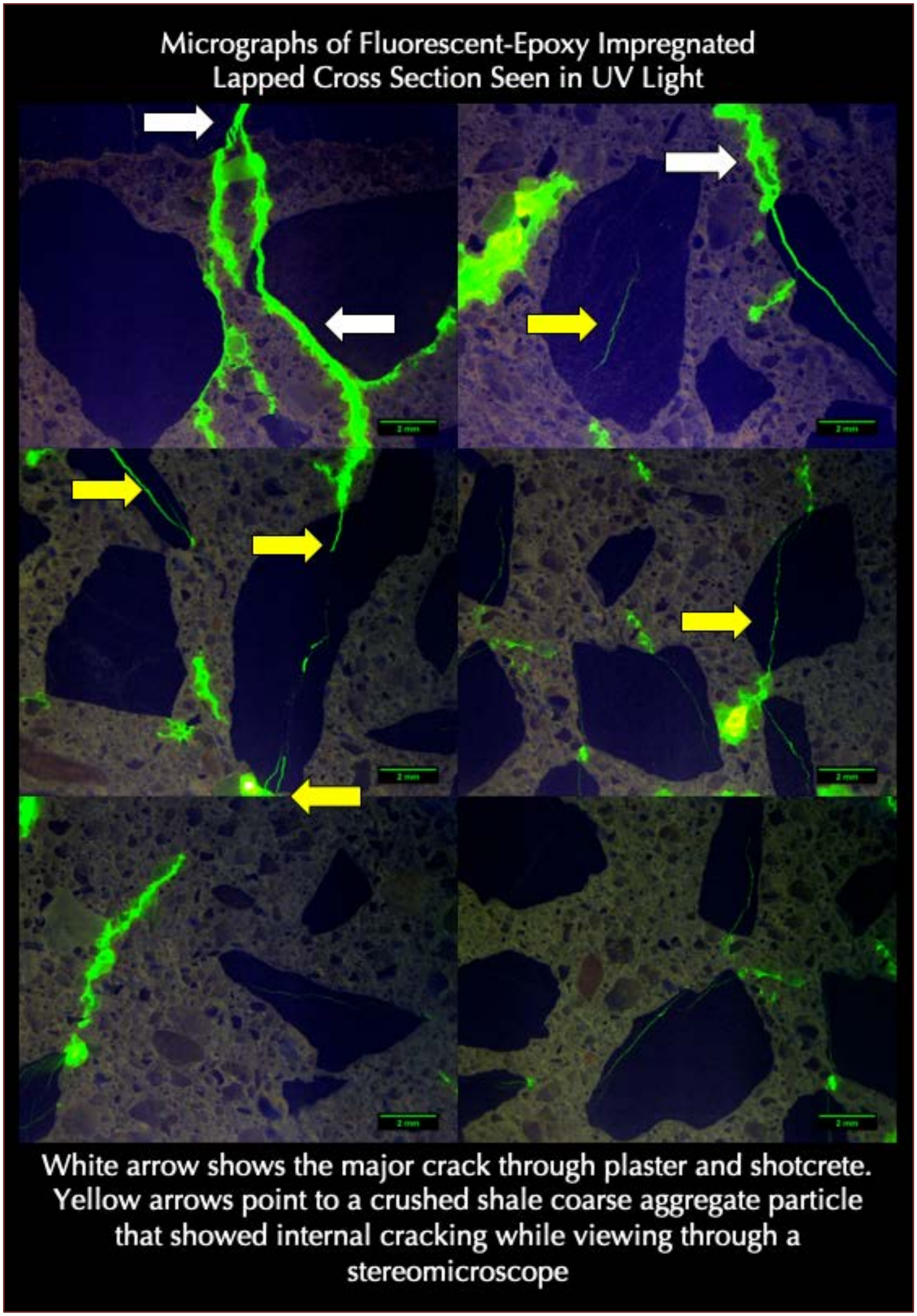
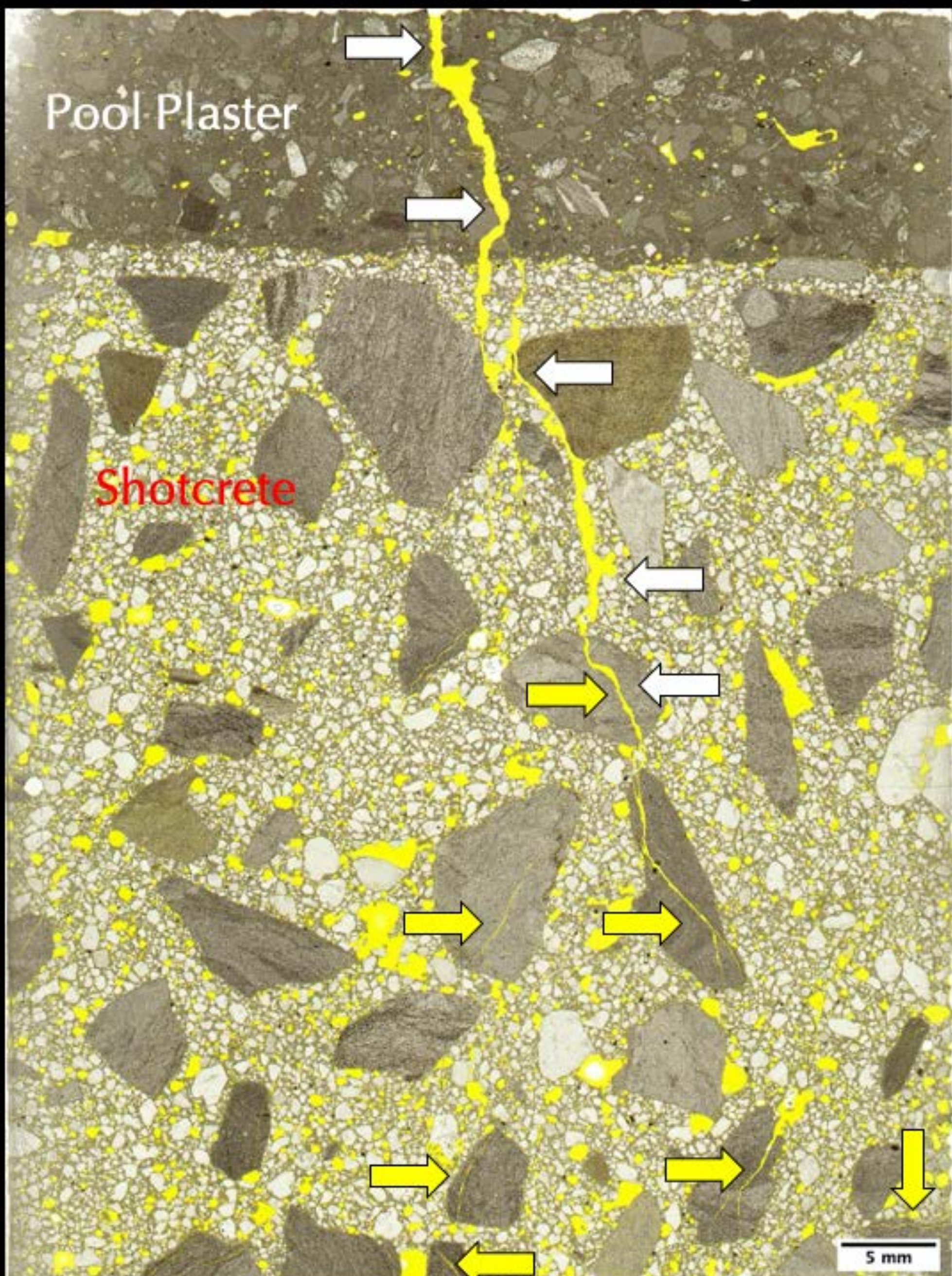



Figure 17: Micrographs of fluorescent dye-mixed epoxy-impregnated lapped cross section highlighting cracks while viewing in an UV light where along with the major vertical cracks many fine hairline microcracks in crushed shale aggregate particles in shotcrete are highlighted.

## THIN SECTION

**Fluorescent Dye-Mixed Epoxy-Impregnated Thin Section Scanned On A Film Scanner in Plane Polarized Light**




Crack is Extended to a depth of 2 in. (50 mm)
White arrow shows the major crack through plaster and shotcrete.
Yellow arrows point to a crushed shale coarse aggregate particle that showed internal cracking while viewing through a stereomicroscope

Figure 18: Fluorescent dye-mixed epoxy-impregnated thin section of core where the major and micro cracks, air voids, and porous areas of paste are highlighted by fluorescent epoxy. The image was taken in plane-polarized light mode (PPL) in a film scanner to highlight air voids in the shotcrete as opposed to lack of voids in plaster, crushed shale coarse aggregate particles, and air-entrained mortar fraction of fine silica sand and paste in shotcrete.

Thin section shows:

(a) $^5/_8$-in. (15-mm) thick dark gray pool plaster well-bonded to underlying shotcrete;

(b) A vertical crack (thick white arrows) through the plaster extended to a depth of 2 in. (50 mm) into shotcrete which is wider at the exposed end and tapered down;

(d) Internal cracking (thick yellow arrows) in many crushed stone particles in shotcrete;

(e) Lack of air entrainment in the plaster, whereas air-entrained nature of shotcrete; and,

(f) Compared to the porous nature of shotcrete a noticeably denser nature of the plaster.

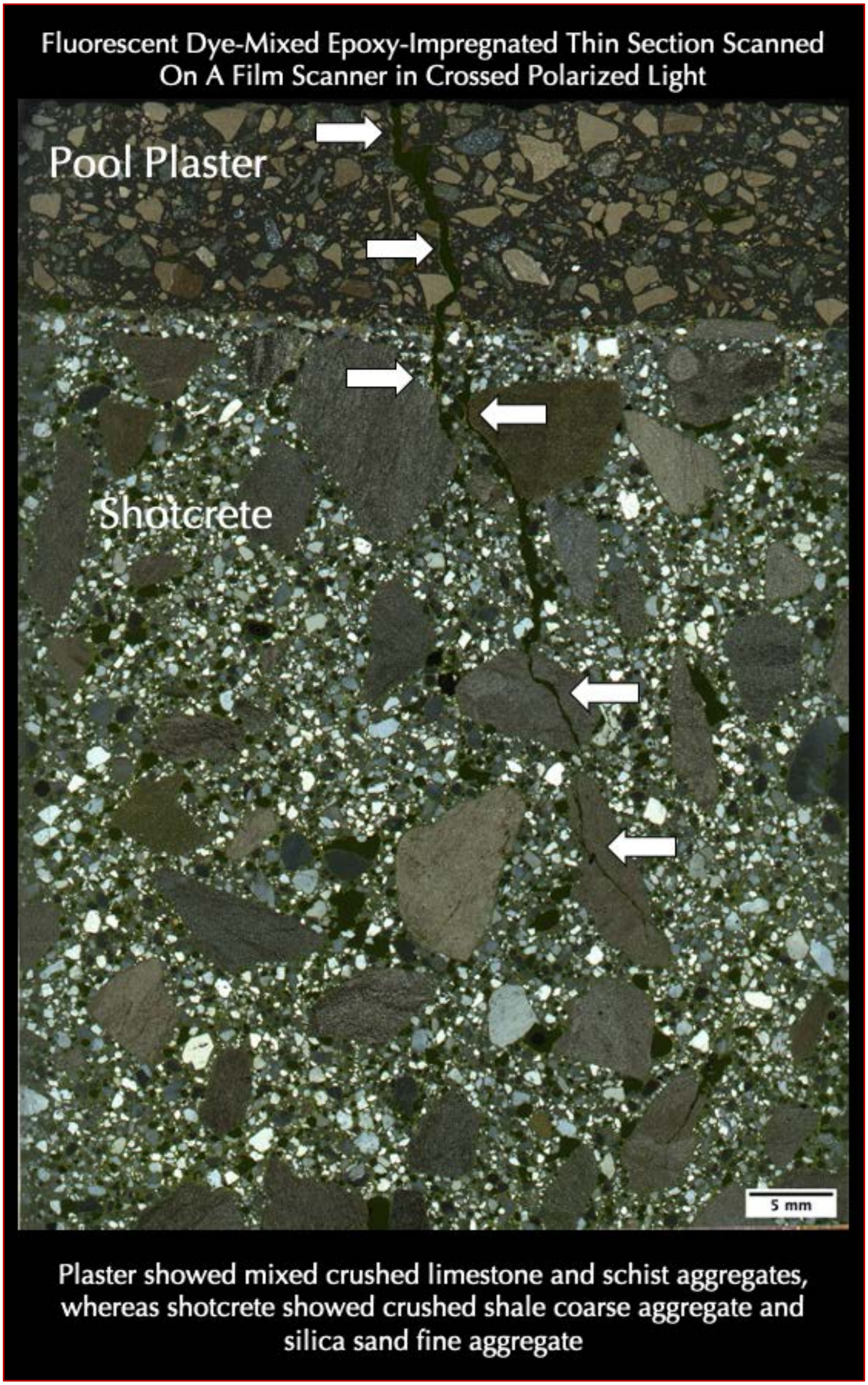



Figure 19: Fluorescent dye-mixed epoxy-impregnated thin section of core shown in crossed polarized light (XPL) mode to highlight:

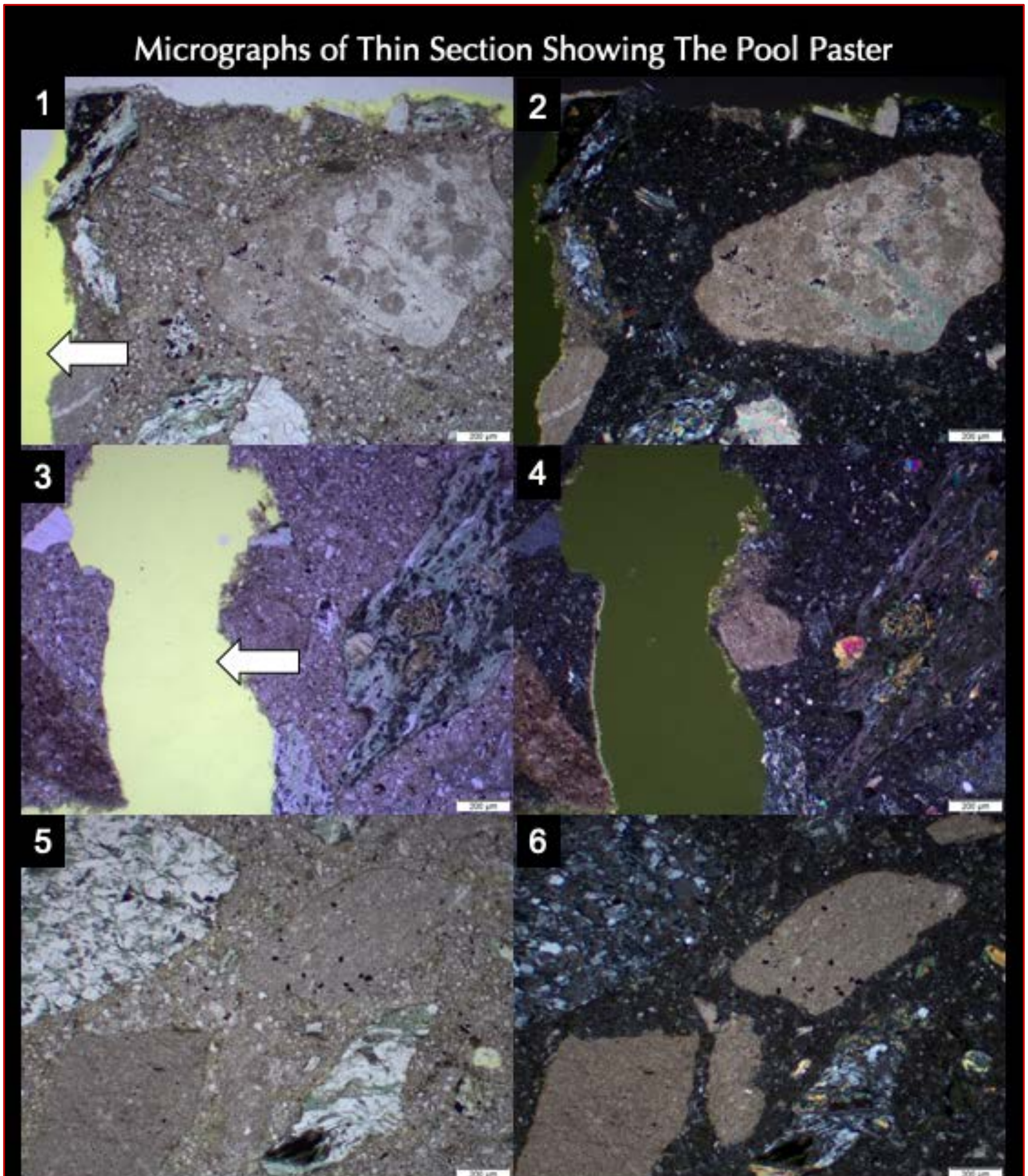
(a) Mixed crushed limestone and schist particles in plaster;

(b) Crushed shale coarse aggregate particles in shotcrete which are mostly dark in XPL image;

(c) Fine siliceous sand particles consisting of major amounts of quartz and subordinate amounts of quartzite, feldspar, and other siliceous rocks and minerals.

Thin section is approximately 30 microns (0.03 mm) in thickness and transparent to polarized-light.

## MICROGRAPHS OF THIN SECTION

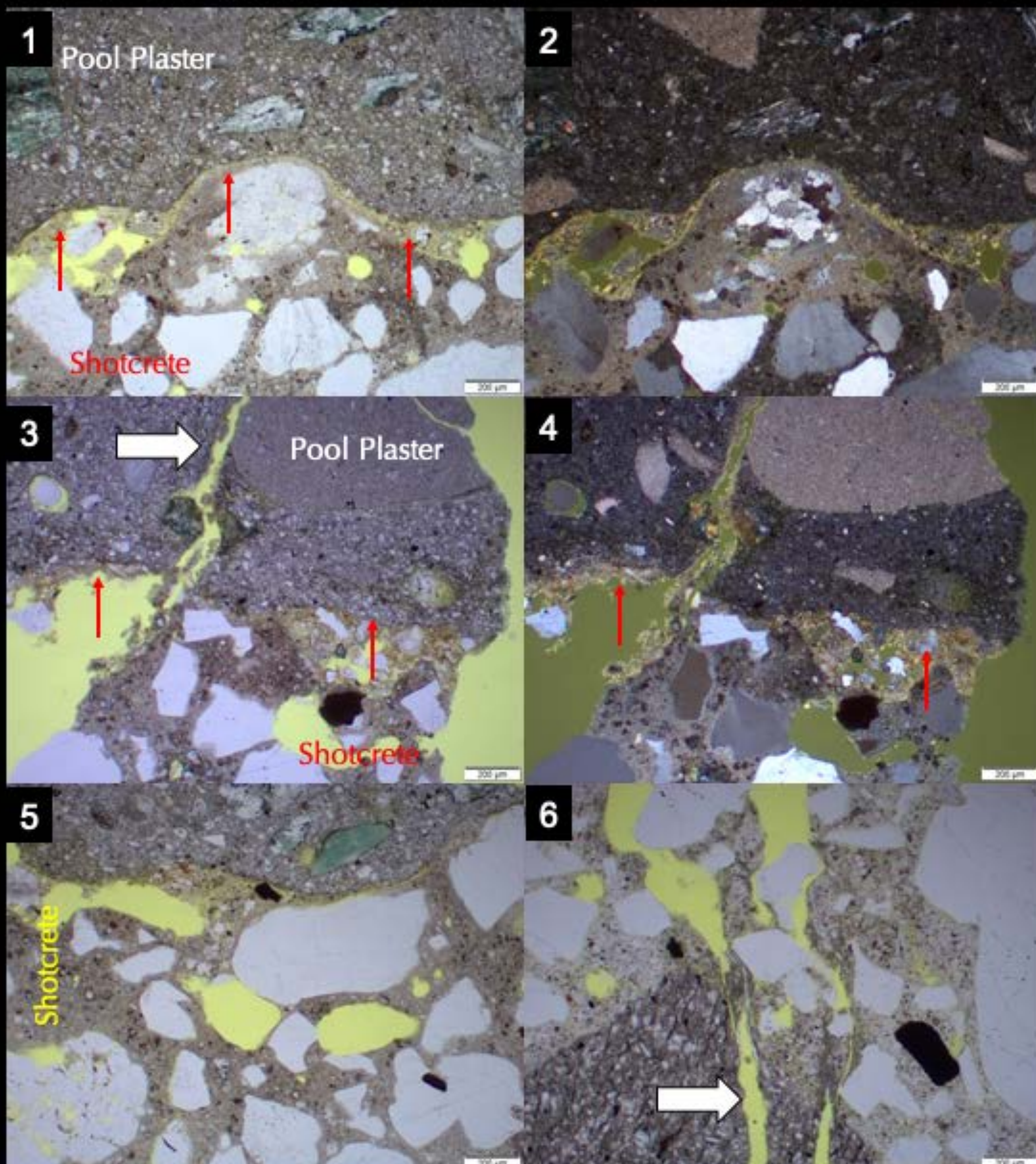



| # | Microstructure |
|---|---|
| 1 | Dense low *w/c* Portland cement Paste, mixed crushed limestone and schist aggregate, and non-air-entrained pool plaster, PPL |
| 2 | Mixed crushed limestone and schist aggregate in pool plaster, XPL |
| 3 | The visible macrocrack through plaster that has extended to the shotcrete for a total depth of 2 in., PPL |
| 4 | The visible macrocrack through plaster that has extended to the shotcrete for a total depth of 2 in., XPL |
| 5 | Dense low *w/c* Portland cement Paste, mixed crushed limestone and schist aggregate, and non-air-entrained pool plaster, PPL |
| 6 | Mixed crushed limestone and schist aggregate in pool plaster, XPL |

Figure 20: Micrographs of thin section showing compositions and microstructures of plaster portion.

Plaster showed mixed crushed limestone and amphibole-pyroxene mafic schist rocks in the aggregate; a dense Portland cement paste; and lack of air entrainment. The major vertical crack is shown with white arrows.

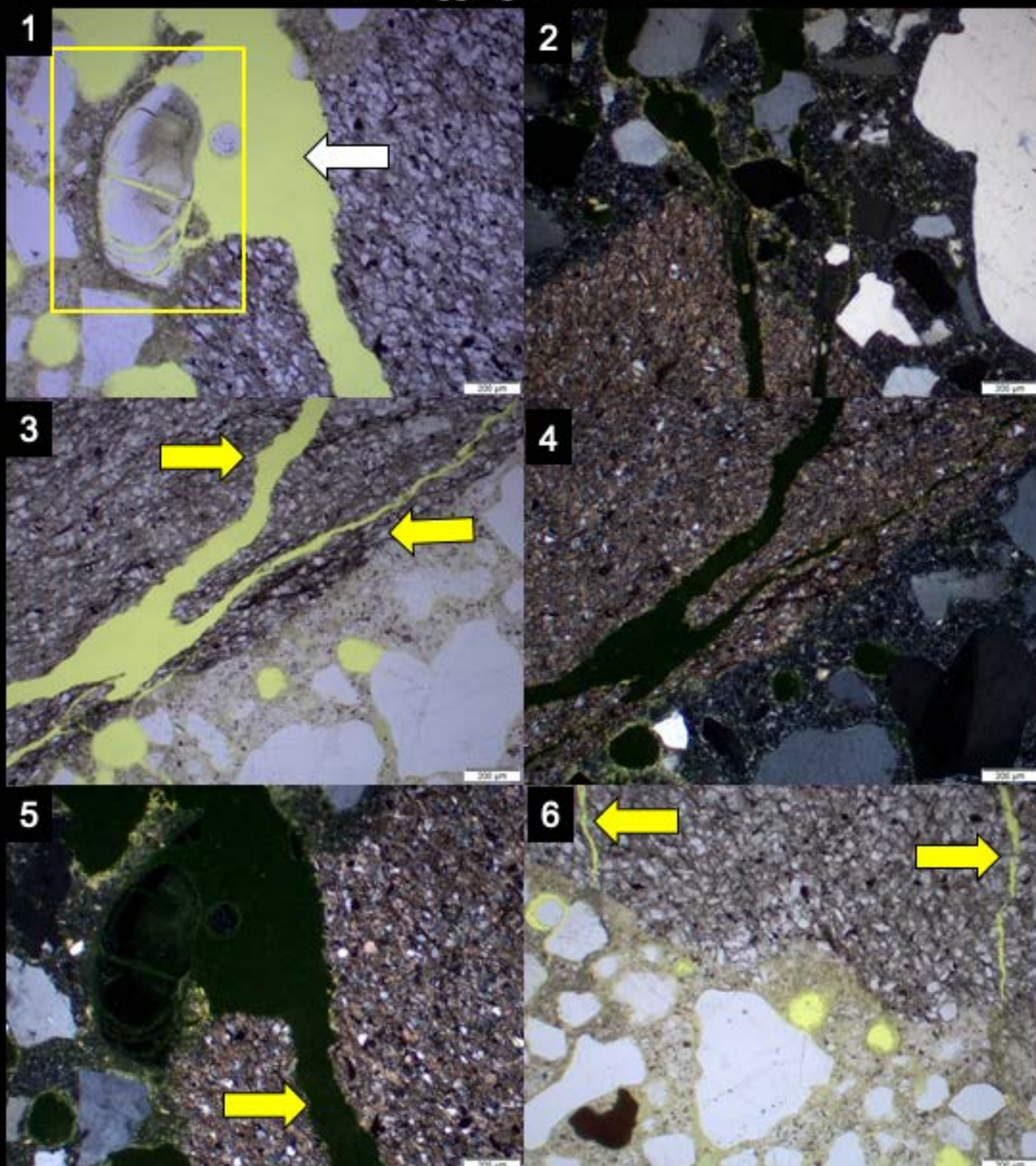
**Micrographs of Thin Section Showing The Shotcrete Beneath The Pool Paster**




| # | Microstructure |
|---|---|
| 1 | Dense low *w/c* Portland cement Paste, mixed crushed limestone and schist aggregate, and non-air-entrained pool plaster whereas less dense, higher *w/c*, carbonated shotcrete paste beneath, PPL |
| 2 | Same as Photo#1 but taken in XPL |
| 3 | The visible macrocrack through plaster that has extended to the shotcrete for a total depth of 2 in., PPL |
| 4 | The visible macrocrack through plaster that has extended to the shotcrete for a total depth of 2 in., XPL |
| 5 | Non-air-entrained shotcrete having crushed hale coarse aggregate and silica sand fine aggregate, PPL |
| 6 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, PPL |

Figure 21: Micrographs of thin section showing the interface between the plaster and shotcrete, the carbonated nature of shotcrete at the interface (marked by thin red arrows) due to a prior exposure to atmospheric carbon dioxide before installation of plaster, the noticeably denser nature of low water-cement ratio paste in the plaster as opposed to relatively porous, higher water-cement ratio paste in the shotcrete, and the major vertical crack highlighted by fluorescent epoxy that has transected the plaster and entered (actually originated from) shotcrete.

## Micrographs of Thin Section Showing Alkali-Silica gel in A Void, and Macro and Microcracks in Shale Coarse Aggregate in Shotcrete

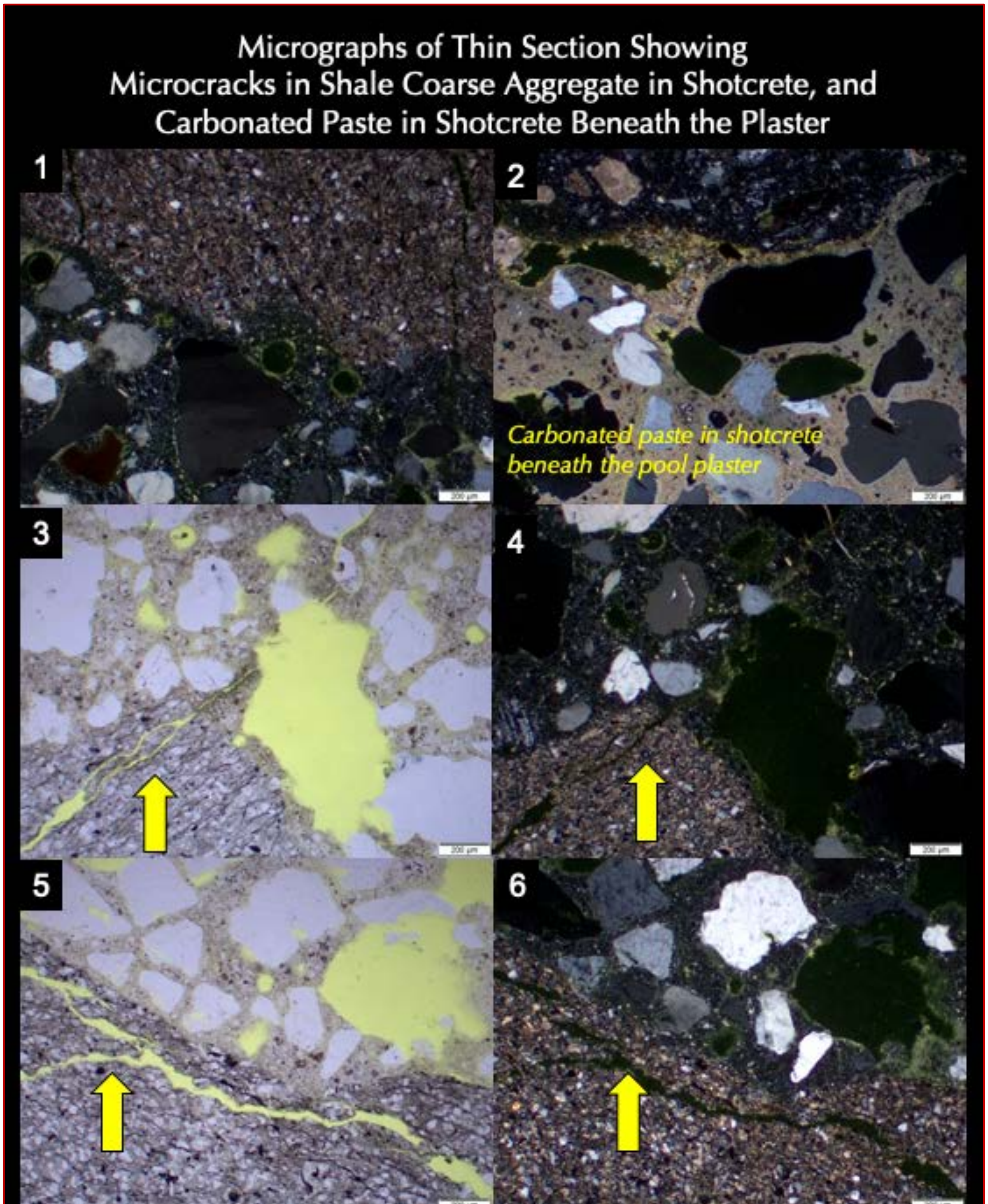



| # | Microstructure |
|---|---|
| 1 | Alkali-silica gel (boxed) in a void from a reactive shale crushed stone coarse Aggregate, PPL |
| 2 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, XPL |
| 3 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, PPL |
| 4 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, XPL |
| 5 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, XPL |
| 6 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, PPL |

Figure 22: Micrographs of thin section of the shotcrete portion showing potentially deleterious alkali-silica gel in an air void adjacent to a potentially reactive crushed shale coarse aggregate particle in shotcrete where the reactive silica component has participated in alkali-silica reaction and formed the gel in the presence of moisture.

The macro and microcracks are shown in white and yellow arrows, respectively.

A few entrained air voids in shotcrete are shown in photos 3 and 6 that are highlighted by fluorescent epoxy.




| # | Microstructure |
|---|---|
| 1 | Crushed shale coarse aggregate particles in shotcrete extending into paste, XPL |
| 2 | Carbonated paste in shotcrete immediately beneath the plaster, XPL |
| 3 | Fine microcracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, PPL |
| 4 | Fine microcracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, XPL |
| 5 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, PPL |
| 6 | Cracks in many crushed shale coarse aggregate particles in shotcrete extending into paste, XPL |

Figure 23: Micrographs of thin section showing the shotcrete portion to depict shale coarse aggregate and siliceous sand fine aggregate of shotcrete in Photo 1, carbonated paste at the exposed surface region in Photo 2, and fine hairline microcracks in unsound crushed shale coarse aggregate particles marked by yellow arrows.

## POOL PLASTER - AGGREGATE

Aggregate in pool plaster is crushed stone, which is a mixture of major amount of crushed limestone and subordinate amount of crushed amphibole-pyroxene schist, all having nominal maximum sizes of 3 mm. Particles are dense, angular, well-graded, well-distributed, and present in sound conditions without any evidence of potentially deleterious reactions let alone to cause the observed cracking.

Figures 13, 14, 18, 19, 20, and 21 show compositions and textures of crushed aggregate particles in plaster.

## POOL PLASTER - PASTE

Paste is Portland cement based, dense, of very low water-cement ratio, which is estimated to be less than 0.40. Plaster lacks any intentionally introduced entrained air. A pigment is added to impart the dark gray color tone of plaster. There is no evidence of any potentially deleterious reactions found in the plaster.

Figure 20 shows textural and compositional features of dense paste in plaster in the thin section micrographs.

## POOL PLASTER - AIR

Plaster is non-air-entrained having an air content estimated to be less than 1 percent by volume. Figures 13 and 14 show the lack of air entrainment in the plaster and its overall dense and well consolidated nature.

## SHOTCRETE - COARSE AGGREGATE

Coarse aggregate in the shotcrete is crushed shale (Figures 8 through 19) having a nominal maximum size of $^1/_2$ inch (12.5 mm). Particles are variably dense, variably porous, medium to dark gray, mostly cracked where cracks are confined mostly within the particles indicating potential unsoundness of the particles leading to cracking. Particles are equidimensional to elongated, sub-rounded to well-rounded, well-graded, well-distributed, unaltered, and many show evidence of unsoundness as described below.

The crushed shale coarse aggregate particles in shotcrete are physically and chemically unsound due to potential expansions associated with: (a) moisture absorption of clay minerals in shale, and, (b) potential alkali-silica reaction of the reactive silica component in the shale during exposures to high alkalis and moisture. Besides Portland cement, potential sources of high alkalis are pool water and chemical admixtures (e.g., set accelerator) used in shotcrete mix. Evidence of alkali-silica reaction of shale is found from: (a) microcracking within many shale particles, (b) alkali-silica reaction gels filling the microcracks and air voids, and (c) white secondary deposits of dissolved reaction gels found within the fresh fractured shale surfaces on the fractured end of core when received.

Figures 24 and 25 show X-ray diffraction studies of some crushed shale aggregate particles in shotcrete that were selected on the lapped cross section by drilling with a benchtop drill to collect fine powders of shale for analysis in Bruker's D2 Phaser X-ray diffractometer with copper k-alpha radiation. Results show about 60% quartz, 30% calcite, and rest clay minerals (e.g., illite, kaolinite) and mica (biotite).

## SHOTCRETE - FINE AGGREGATE

Fine aggregate is natural siliceous sand having a nominal maximum size of 3/8 in. (9.5 mm) consisting of major amount of quartz and subordinate amounts of quartzite, quartzite siltstone, feldspar, etc. Particles are variably colored, rounded to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and mostly uncracked except the ones along the paths of cracks. Fine aggregate particles are well-graded and well-distributed. There is no evidence of alkali-aggregate reaction of fine aggregate particles found in shotcrete.

Fine aggregate particles have been sound during their service in the concrete and did not contribute to the cracking of plaster.

## SHOTCRETE - PASTE

Paste is moderately dense, medium gray, uniform in color throughout the depth of shotcrete. Freshly fractured surfaces have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 8 to 10 percent of the paste volumes. Besides Portland cement, no other pozzolanic or cementitious materials are found. Hydration of Portland cement is normal.

The textural and compositional features of paste are indicative of a cement content estimated to be 7 to 7 1/2 bags per cubic yard and a water-cement ratio estimated to be 0.45 to 0.50. The shotcrete beneath the plaster shows a thin (about 5 mm in thickness) carbonated paste zone indicating a period of air exposure and interaction with atmospheric carbon dioxide prior to the installation of plaster.

## SHOTCRETE - AIR

Shotcrete is air-entrained having an air content estimated to be 5 to 6 percent.

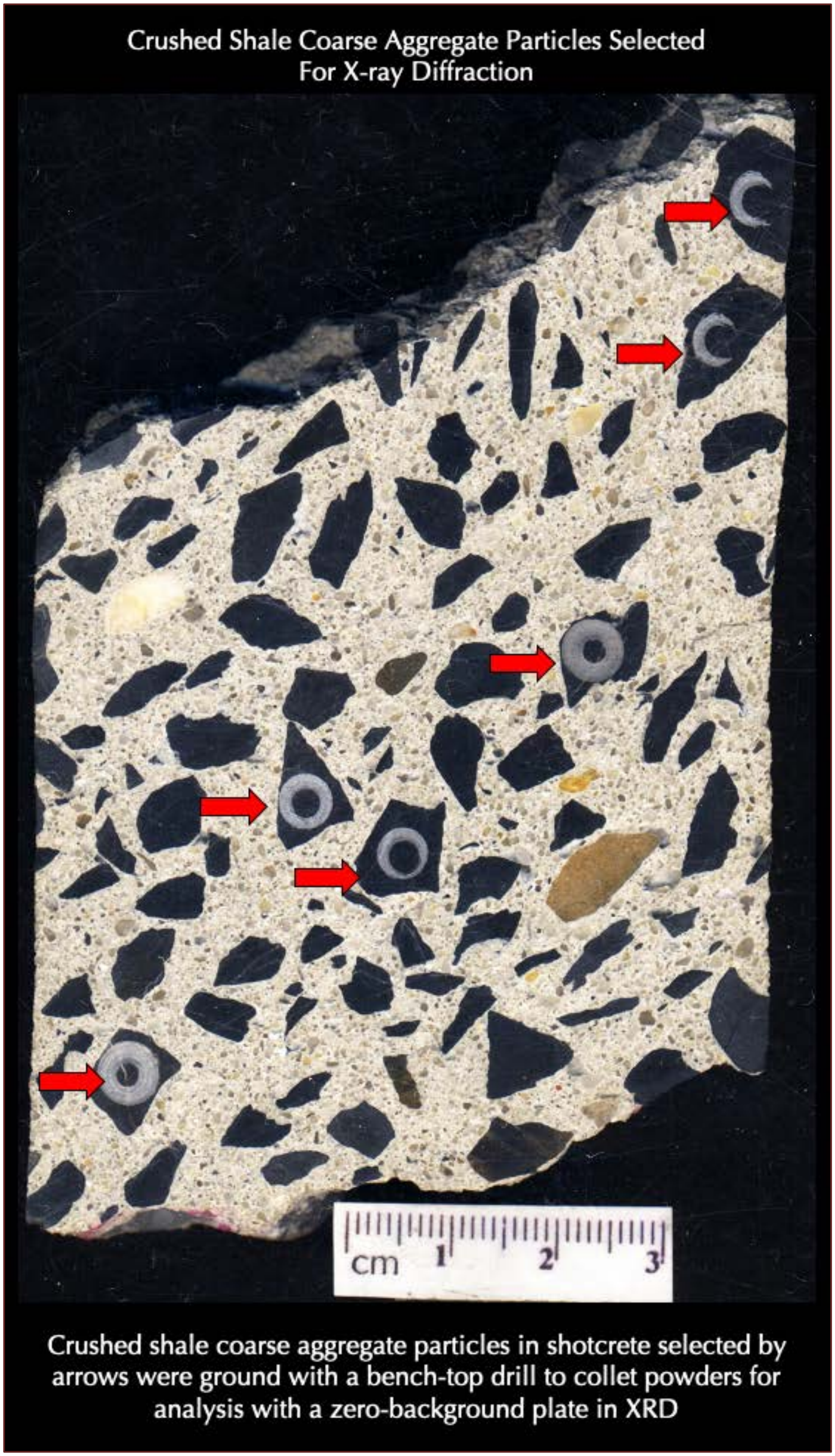
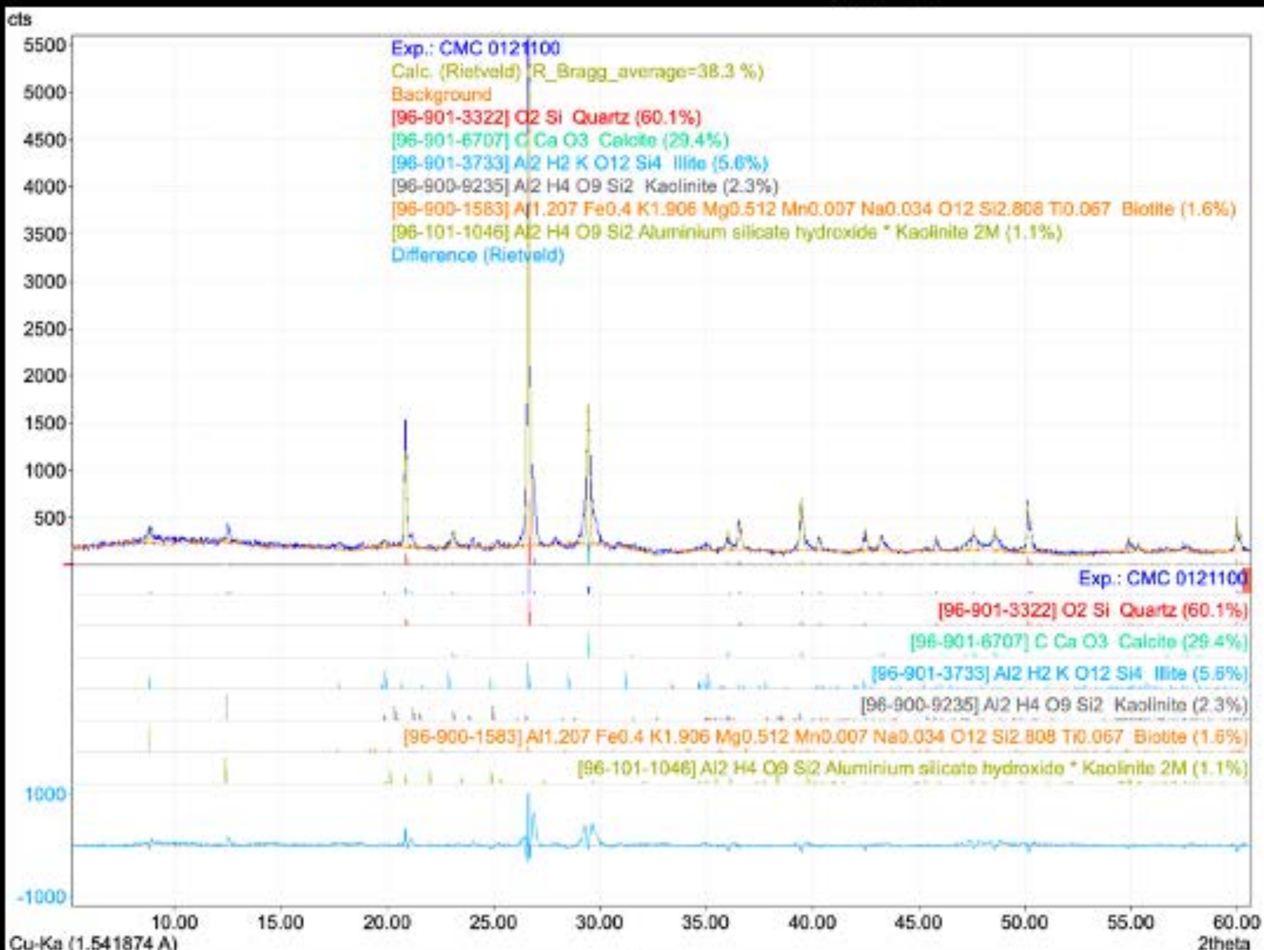



Figure 24: Lapped cross section of a portion of shotcrete where multiple potentially unsound crushed shale coarse aggregate particles were drilled with a benchtop drill to collect dusts of those particles to be used for X-ray diffraction analysis. The purpose is to determine the mineralogial composition of shale particles.

## XRD Pattern of Crushed Shale Coarse Aggregate Particles




| Phases Detected | Proportion |
|---|---|
| Quartz | 60.1% |
| Calcite | 29.4% |
| Clay - Illite | 5.6% |
| Clay - Kaolinite | 2.3% |
| Clay – Kaolinite 2M | 1.1% |
| Mica - Biotite | 1.6% |

Figure 25: X-ray diffraction pattern of dusts collected from six randomly selected crushed shale coarse aggregate particles in shotcrete which are marked with arrows in the previous Figure.

## DISCUSSIONS

### SOUND POOL PLASTER

Based on detailed petrographic examinations, the pool plaster is found to be present in sound condition and well-bonded to shotcrete. There is no evidence of any potentially deleterious physical or chemical reactions found in the plaster let alone to cause the observed cracking. The crushed limestone and schist aggregate particles are present in sound conditions. Interstitial Portland cement paste is very dense and sound.

### UNSOUND CRUSHED SHALE AGGREGATE IN SHOTCRETE

The crushed shale coarse aggregate particles in shotcrete are physically and chemically unsound due to potential expansions associated with:

a. Moisture absorption of clay minerals in shale, and,
b. Potential alkali-silica reaction of the reactive silica component in the shale during exposures to high alkalis and moisture.

Besides Portland cement, potential sources of high alkalis are pool water and chemical admixtures (e.g., set accelerator) used in shotcrete mix.

Evidence of alkali-silica reaction of shale aggregate in shotcrete is found from:

a. Microcracking within many shale particles,
b. Alkali-silica reaction gels filling the microcracks and air voids, and
c. White secondary deposits of dissolved reaction gels found within the fresh fractured shale surfaces on the fractured end of core when received.

### CRACKING OF POOL PLASTER

Based on detailed petrographic examinations cracking in the pool plaster is found to be due to expansion of the underlying shotcrete component due to potentially deleterious reactions of the crushed shale aggregate used in shotcrete in the presence of moisture. Expansion of shotcrete has put the well-bonded plaster skin in tension to cause development of tensile cracks that are wider at the exposed surface end of plaster and tapered downward into shotcrete. The plaster is found to be present in sound condition without any chemical or physical deterioration and simply responded to the expansion of shotcrete by development of tensile cracks. Cracks once formed provided the pathways for deeper migration of pool water to sustain deleterious reactions in shotcrete and continued expansion and cracking.

## REFERENCES

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# END OF REPORT[1]

[1] The CMC logo is made using a lapped polished section of a 1930's concrete from an underground tunnel in the U.S. Capitol.