CONSTRUCTION MATERIALS CONSULTANTS, INC.

Investigation of Concrete Sidewalk Scaling by Petrographic Examinations Of A Concrete Core

Traditions of America
1076 Constitution Drive
Lititz, Pennsylvania 17543

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CMC 0421122

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Suggested Reading:
Jana, D., Concrete, Construction or Salt – Which Causes Scaling? Part I: Importance of air-void system in concrete, Concrete International, American Concrete Institute, November 2004, pp. 31-38.
Jana, D., Concrete, Construction or Salt – Which Causes Scaling? Part II: Importance of finishing practices, Concrete International, American Concrete Institute, December 2004, pp. 51-56.

EXECUTIVE SUMMARY

Surface scaling, as the loss of the original finished surface of concrete sidewalks exposing the underlying aggregates and paste across a housing development *Traditions of America* in Lititz, Pennsylvania has prompted this investigation. As a result, a concrete core identified as C-3 was provided for detailed petrographic examinations to investigate all possible causes for surface distress from evaluation of concrete qualities to investigation of any workmanship-related issues to the potentially deleterious effects of deicing chemicals on the short and long-term durability of the sidewalk surfaces. The core was tested by detailed petrographic examinations *a la* ASTM C 856 to determine the compositions and conditions of concretes in the cores.

Based on detailed petrographic examinations, concrete placed at the core location is found to contain (a) crushed limestone coarse aggregate having a nominal maximum size of $^3/_4$ in. (19 mm), (b) natural siliceous sand fine aggregate having nominal maximum sizes of $^3/_8$ in. (9.5 mm), (c) binary cementitious blends of major amount of Portland cement and subordinate amount of fly ash, having a total cementitious materials content estimated to be equivalent to $6^1/_2$ to 7 bags of Portland cement, of which 15 to 20 percent is estimated to be fly ash, and a water-cementitious materials ratio (*w/cm*) estimated to be 0.40 to 0.45 in the interior and slightly higher (0.45 to 0.50) at the top 5 mm of surface region.

Concrete placed at the location of the examined core lacks air entrainment, which is contrary to common industry recommendations for an outdoor concrete exposed to cyclic freezing and thawing and deicing chemicals. Absence of entrained air is judged to have caused the surface scaling, which was potentially aggravated by exposure to chloride-containing deicing chemicals during service.

The crushed limestone coarse aggregate and siliceous sand fine aggregate particles are present in sound conditions and did not contribute to the observed surface distress. There is no evidence of any potentially deleterious alkali-aggregate reaction of coarse or fine aggregate found in the cores. A few crushed shale particles in coarse aggregate, however, has shown potential unsoundness as cracking from moisture absorption and potential freezing at critically saturated conditions, which are the conditions to cause popups of such aggregate particles situated immediately beneath the finished surface.

The lighter-toned higher *w/cm* paste at the top 5 mm of scaled surface is due to finishing in the presence of bleed water at the surface and/or addition of water during finishing where either practice or both can increase the *w/cm* of paste at the surface and decrease the resistance of finished surface to abrasion and salt scaling.

The interior concrete is dense and well-consolidated without any coarse voids or honeycombing, indicating adequate consolidation of concrete during placement. There is also no evidence of any segregation of coarse aggregate particles during placement. There is, therefore, no evidence of any improper consolidation practice of slabs at the location of the examined core.

Curing is essential for adequate cement hydration at the surface, and, thereby, development of the necessary strength of concrete at the surface by providing enough moisture and optimum temperature for cement hydration. Exposed scaled surface of the core shows no evidence of inadequate curing of concrete, e.g., no evidence of restricted cement hydration at the scaled surface at least to cause the reported surface scaling.

For adequate resistance to freezing-related stresses, the common industry (e.g., ACI Committee 201)-recommended compressive strength of concrete exposed to an outdoor environment of moisture and freezing is at least 4000 psi. A concrete having a compressive strength of at least 4500 psi is usually recommended for an outdoor concrete slab exposed to moisture, salts, and snow, where the good strength of concrete provides the necessary resistance against freezing-related tensile stresses in concrete. Reported compressive strength of a companion core from the field is 4070 psi, which is less than the common industry specification of 4500 psi for an outdoor concrete exposed to freezing, moisture, salt, and snow.

The maturity of concrete is defined as: (i) a period of air drying and (ii) a compressive strength of at least 4000 psi – both prior to the first exposure of salts and snow so that the concrete does not contain any ‘freezable’ water in its capillary pores to freeze, expand, and thus cause distress (hence the importance of at least a period of air drying), and is strong enough to resist freezing-related stresses (hence the importance of adequate strength of at least 4500 psi) both prior to the first exposure of snow and salt (Jana 2004, Jana 2007). A concrete, therefore, needs to be ‘matured’ prior to the first exposure of freezing, especially during the winter weather constructions.

Potential placement of the slab at early Spring or late Fall may prevent attainment of maturity of concrete at the surface region, especially if concrete at the surface region does not attain a strength of at least 4000 psi at the time of freezing in which case distress may occur from freezing prior to the attainment of at least 4000 psi strength for surface concrete.

Additionally, fly ash in the cementitious components is known to slow down the strength gain, which for a concrete placed in later Fall or early Spring and not protected from freezing can develop scaling issues.

Deicing salts usually do not cause surface scaling in a properly air-entrained concrete having a good air-void system that is made using sound aggregates, and has been placed, finished, cured, and was matured properly *unless*: (i) salt is applied prior to the attainment of maturity of concrete, and/or (ii) a chemically aggressive (e.g., magnesium or ammonium sulphate or urea-based) salt is applied that can chemically decompose the paste (calcium silicate hydrate, the heart of concrete). A well-designed concrete placed, finished, and cured properly should resist the deleterious action of salt unless salt was brought in too early and/or a chemically corrosive salt (magnesium sulfate or ammonium-based) was present that has caused chemical erosion of paste.

Lack of air entrainment, however, intensifies salt-related scaling due to the lack of necessary air voids to prevent stresses that develop during freezing in the presence of salts. The hygroscopic nature of salts increases the degree of saturation of salt-soaked surface where having adequate air entrainment is essential to prevent salt scaling.

Exposed scaled surface of core showed no evidence of application of a surface sealer. It is, however, the concrete itself, i.e., an adequately air-entrained concrete made using optimum air content and good air-void system, sound aggregates, good paste, placed, finished, and cured properly, and has been matured prior to the first exposure to freezing, salts, and snow, which should provide the necessary durability in an outdoor environment of freezing, salt, and snow. When all these basic factors are fulfilled from concrete materials to construction practices, having an additional surface sealer is not needed for protection. A surface sealer, however, does provide an additional protection, particularly when the inherent concrete quality and/or construction practices is/are questionable such as in this present case, where concrete is found to be non-air-entrained and hence vulnerable to distress from moisture, freezing, and salts.

Loss of the repair patch from most of the exposed surface of core except only two isolated remains of such patch indicate inadequate bond of the patch to the underlying concrete, which could be due to ineffective surface preparation of concrete before installation of the patch, or thin application of patch or other reasons not evident in the present study.

Based on detailed laboratory investigations, surface distress of concrete sidewalk are found to be due to:

a. Lack of air entrainment in the concrete exposed to outdoor environment of cyclic freezing and thawing and potentially deleterious deicing chemicals;
b. Potentially deleterious effects of some crushed shale particles in coarse aggregate, which can cause pop outs from moisture absorption and subsequent freezing;
c. Finishing in the presence of bleed water at the surface and/or addition of water during finishing where either practice or both can increase the *w/cm* of paste at the surface and decrease the resistance of finished surface to abrasion and salt scaling;
d. Potential exposure to freezing and salt prior to the attainment of concrete maturity, especially in early Spring or late Fall placement when the surface region may not have developed at least 4000 psi compressive strength and has gone through a period of air drying; and,
e. Potentially deleterious effects of various deicing chemicals, which may have been applied which can aggravate the surface distress especially due to the lack of air entrainment.

Due to the lack of air entrainment, surface scaling is expected to continue in future from exposures to freezing, moisture, and potentially deleterious deicing salts. A good, durable, repair coating well-bonded to the existing slab can prolong the long-term serviceability of the slab.

INTRODUCTION

Surface scaling, as the loss of the original finished surface of concrete sidewalks exposing the underlying aggregates and paste across a housing development *Traditions of America* in Lititz, Pennsylvania has prompted this investigation. As a result, a concrete core identified as C-3 was provided for detailed petrographic examinations to investigation all possible causes for surface distress from evaluation of concrete qualities to investigation of any workmanship-related issues to the potentially deleterious effects of deicing chemicals on the short and long-term durability of the sidewalk surfaces.

BACKGROUND INFORMATION

Apart from the reported sidewalk scaling and aggregate exposures across various locations of the housing complex, no other additional information regarding the surface conditions of the sidewalks were provided. No field photos of conditions of sidewalks were provided. Result of compressive strength of a companion core is reported to be 4070 psi.

SAMPLE

PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figures 1 and 2 show the core, as received. The core has a nominal diameter of 4 in. (100 mm) and a nominal length of $4^1/_2$ in. (115 mm).

END SURFACES

The top exposed/wearing surface shows severe scaling as loss of the original finished surface and exposures of underlying coarse aggregate particles and mortar fraction of concrete and remains of dark gray thin (thickness 5 mm) repair patch at two locations. The bottom end is freshly fractured indicating partial-depth recovery of core.

CRACKING & OTHER VISIBLE DISTRESS, IF ANY

Except surface scaling, there are no visible cracks, or any other signs of distress found in the core.

EMBEDDED ITEMS

No reinforcing steel, wire mesh, fibers, or other embedded items are present in the core.

RESONANCE

The core has a ringing resonance, when hammered.

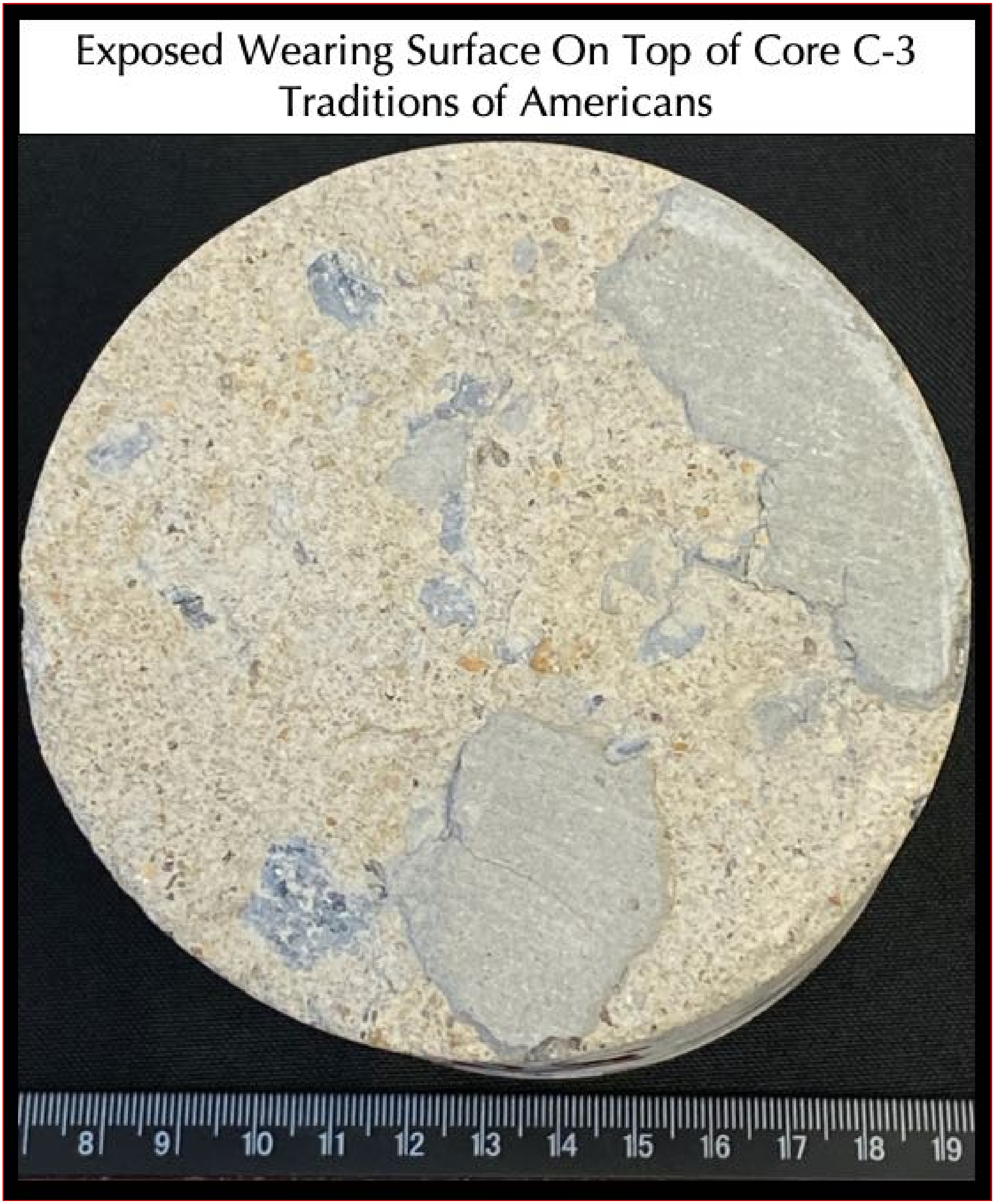

Figure 1: The top exposed surface of core showing severe scaling as loss of the original finished surface and exposure of underlying coarse aggregate and mortar fraction of concrete, and two remains of dark gray thin repair patches.

Figure 2: The side cylindrical surface (top) and bottom fresh fractured end (bottom) of the core, as received indicating partial-depth recovery of core from the slab.

METHODOLOGIES

PETROGRAPHIC EXAMINATIONS

The core was examined by petrographic examinations 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 (1997a, b, 2001, 2004a, b, 2005a, b, 2006, 2007).

The steps of petrographic examinations include (Jana 2006):

i. Visual examinations of sample, as received;
ii. Low-power stereomicroscopical examinations of as-received, saw-cut and freshly fractured sections, and lapped cross sections of core for evaluation of textures, and composition;
iii. Low-power stereomicroscopical examinations of air contents and air-void systems of concrete in the core;
iv. Examinations of oil immersion mounts in a petrographic microscope for mineralogical compositions of specific areas of interest;
v. Examinations of blue dye-mixed (to highlight open spaces, cracks, etc.) epoxy-impregnated large area (50 mm × 75 mm) thin sections of concrete 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;
vii. Micrographs of lapped section and thin section of sample taken with stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information of concrete.

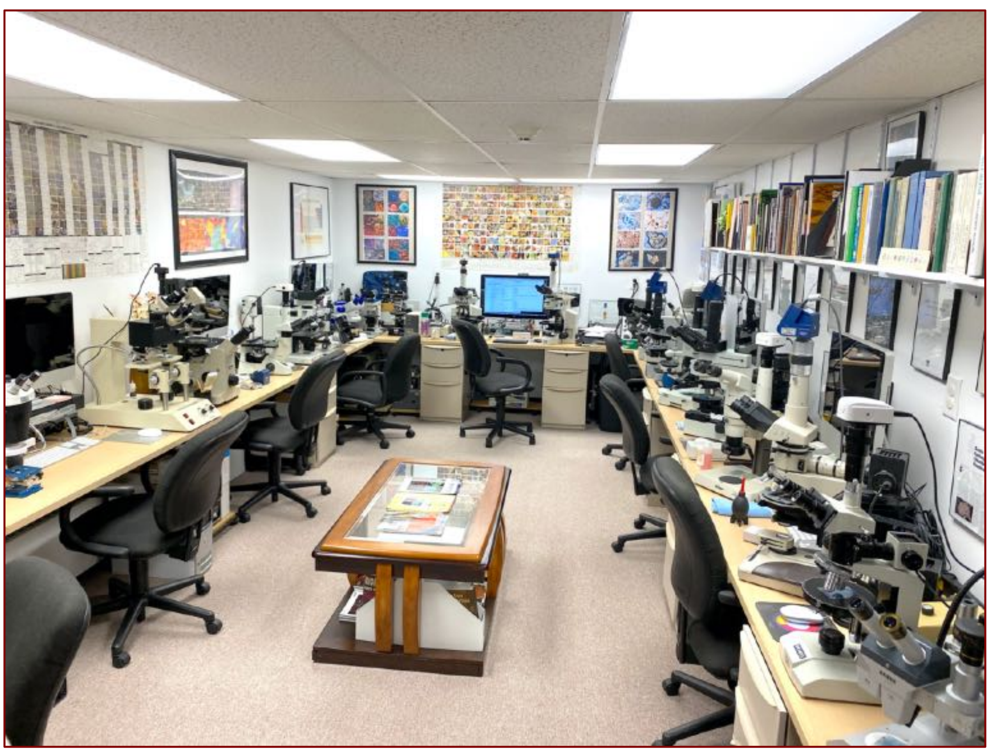

Figure 3: The optical microscopy laboratory at CMC that houses many microscopes used in this study.

PETROGRAPHIC EXAMINATIONS

LAPPED CROSS SECTIONS

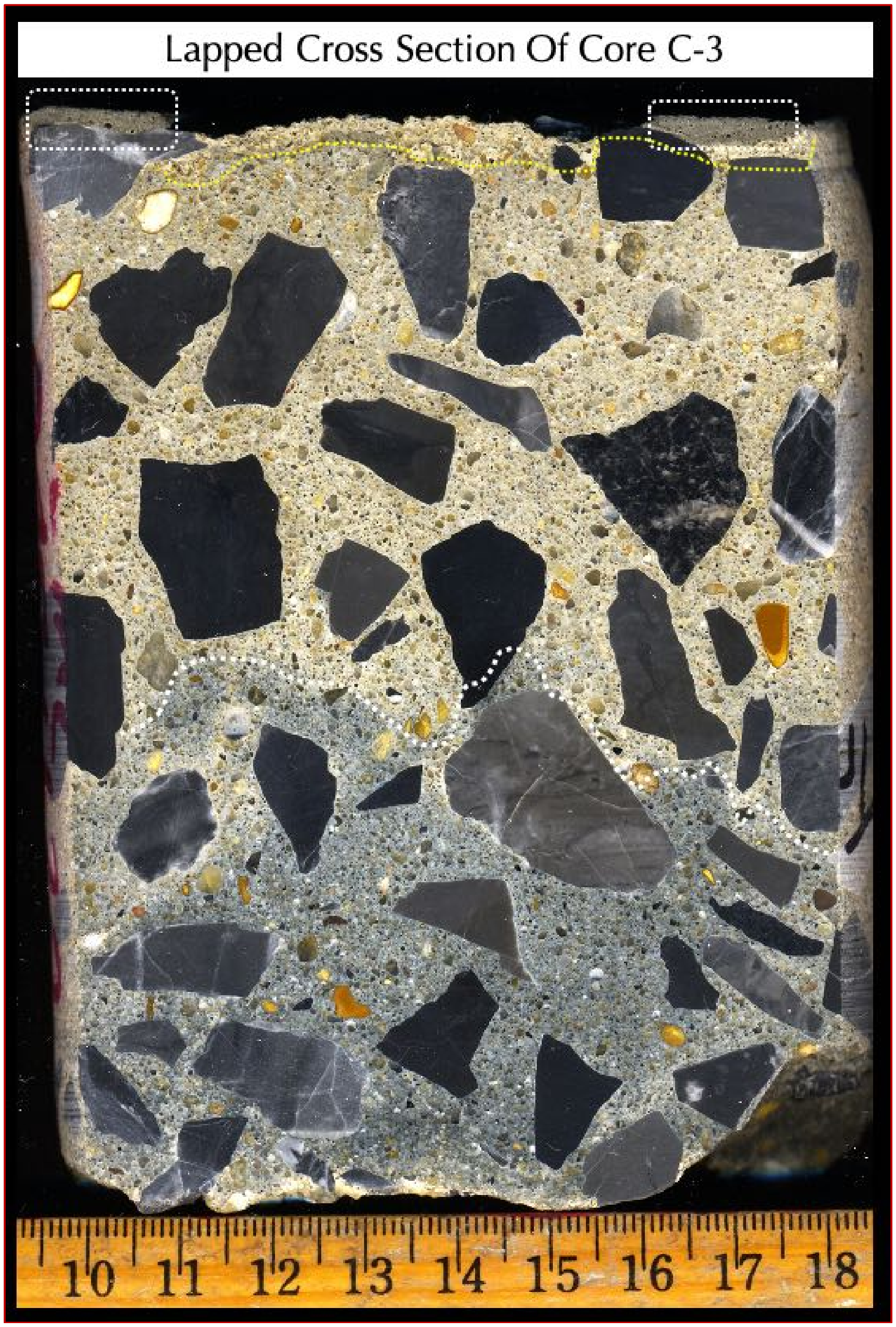

Figure 4: Lapped cross section of Core C-3 showing: (a) the scaled exposed surface end at the top; (a) a thin lighter gray colored paste at the top 3 to 5 mm compared to the relatively darker gray paste beneath and in the interior; (b) crushed stone coarse aggregate where particles are well-distributed but poorly graded due to the deficiency of some finer and intermediate-sized particles; (c) a darker gray tone of paste at the bottom half due to the presence of sulfide phases in the fly ash used as a supplementary cementitious material; and (d) two dark gray 4 to 5 mm thick remains of repair patch at two ends at the top (boxed) that are adhered to the concrete.

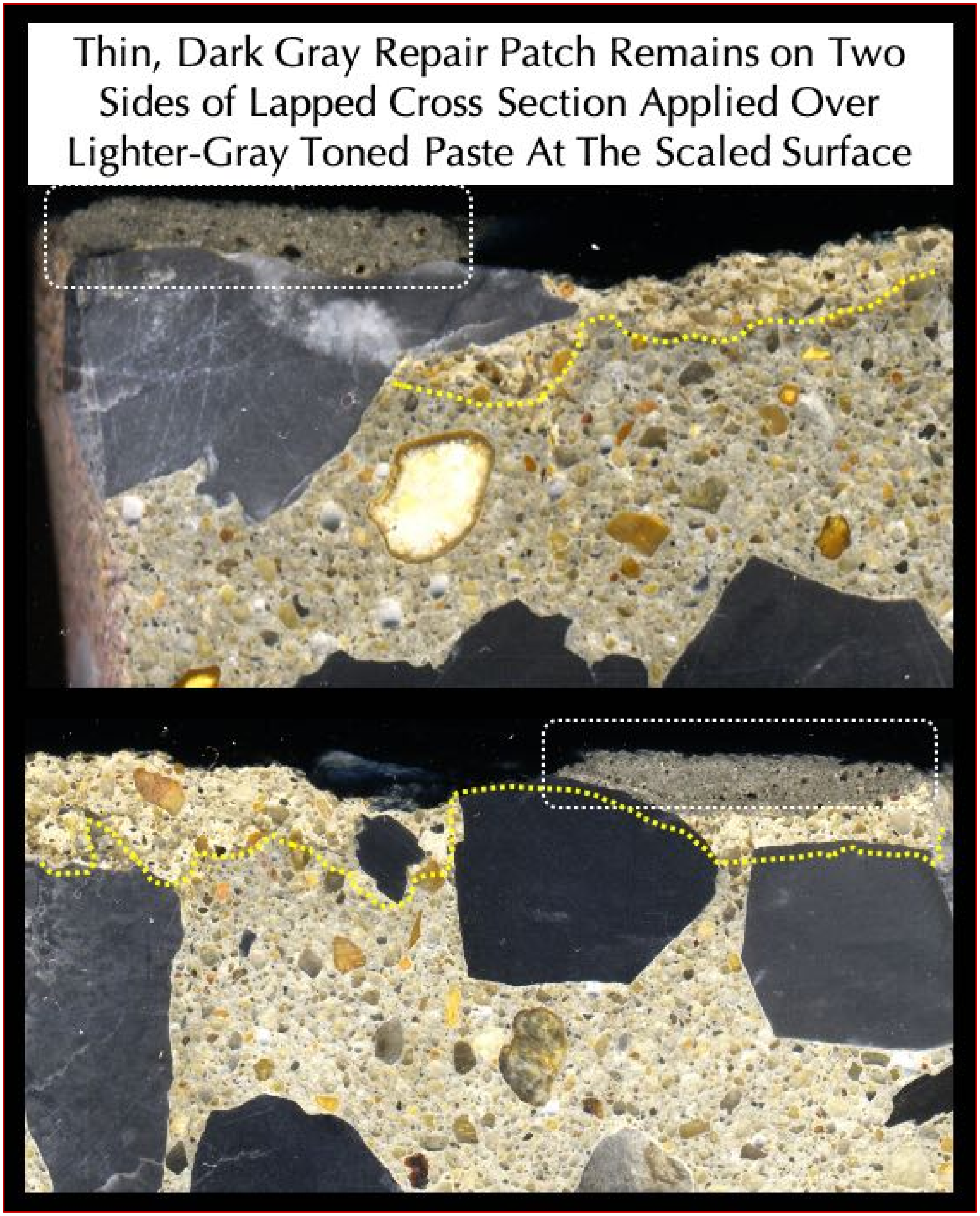

Figure 5: Lapped cross section of Core C-3 showing: (a) the scaled exposed surface end at the top; (a) a thin lighter gray colored paste at the top 3 to 5 mm compared to the relatively darker gray paste beneath and in the interior; (b) crushed stone coarse aggregate where particles are well-distributed but poorly graded due to the deficiency of some finer and intermediate-sized particles; (c) a darker gray tone of paste at the bottom half due to the presence of sulfide phases in the fly ash used as a supplementary cementitious material; and (d) two dark gray 4 to 5 mm thick remains of repair patch at two ends at the top surface (boxed) that are adhered to the concrete.

Figure 6: A second lapped cross section of Core C-3 sectioned parallel to the first one showing: (a) the scaled exposed surface end at the top; (a) a thin lighter gray colored paste at the top 3 to 5 mm compared to the relatively darker gray paste beneath and in the interior; (b) crushed stone coarse aggregate where particles are well-distributed but poorly graded due to the deficiency of some finer and intermediate-sized particles; (c) a darker gray tone of paste at the bottom half due to the presence of sulfide phases in the fly ash used as a supplementary cementitious material; and (d) a dark gray 4 to 5 mm thick remain of repair patch at the top left end (boxed) that is adhered to the concrete.

MICROGRAPHS OF LAPPED CROSS SECTIONS

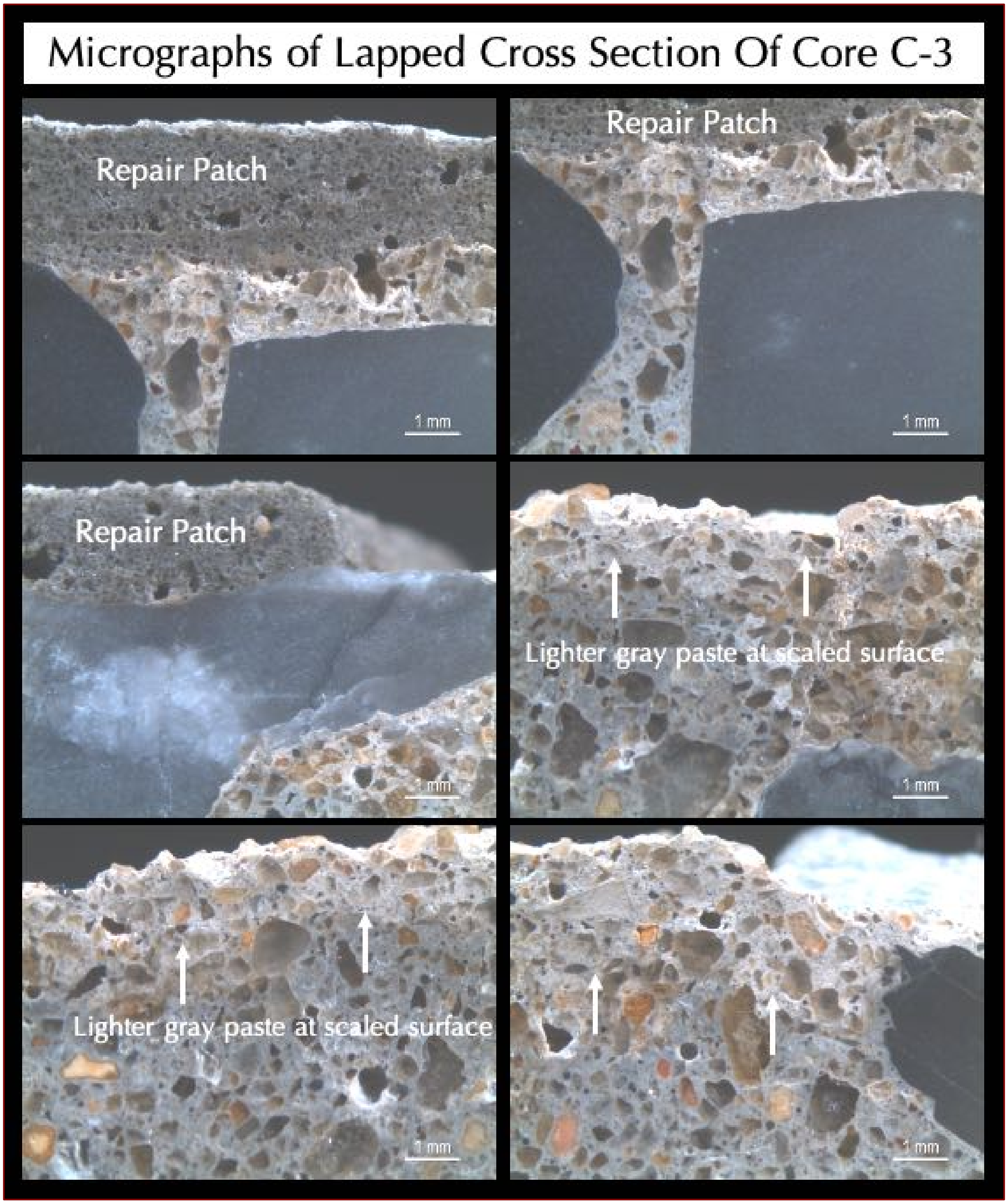

Figure 7: Micrographs of lapped cross section of the core showing: (a) the dark grey repair patch adhered to the scaled concrete surface; (b) lighter tone of paste at the top 3 mm of scaled surface due to higher water-cementitious materials ratio of paste at the scaled surface region (marked with vertical arrows) compared to the interior; and (c) lack of air entrainment in the concrete, or, in the repair patch except a few coarse spherical, near-spherical and irregularly-shaped entrapped air voids.

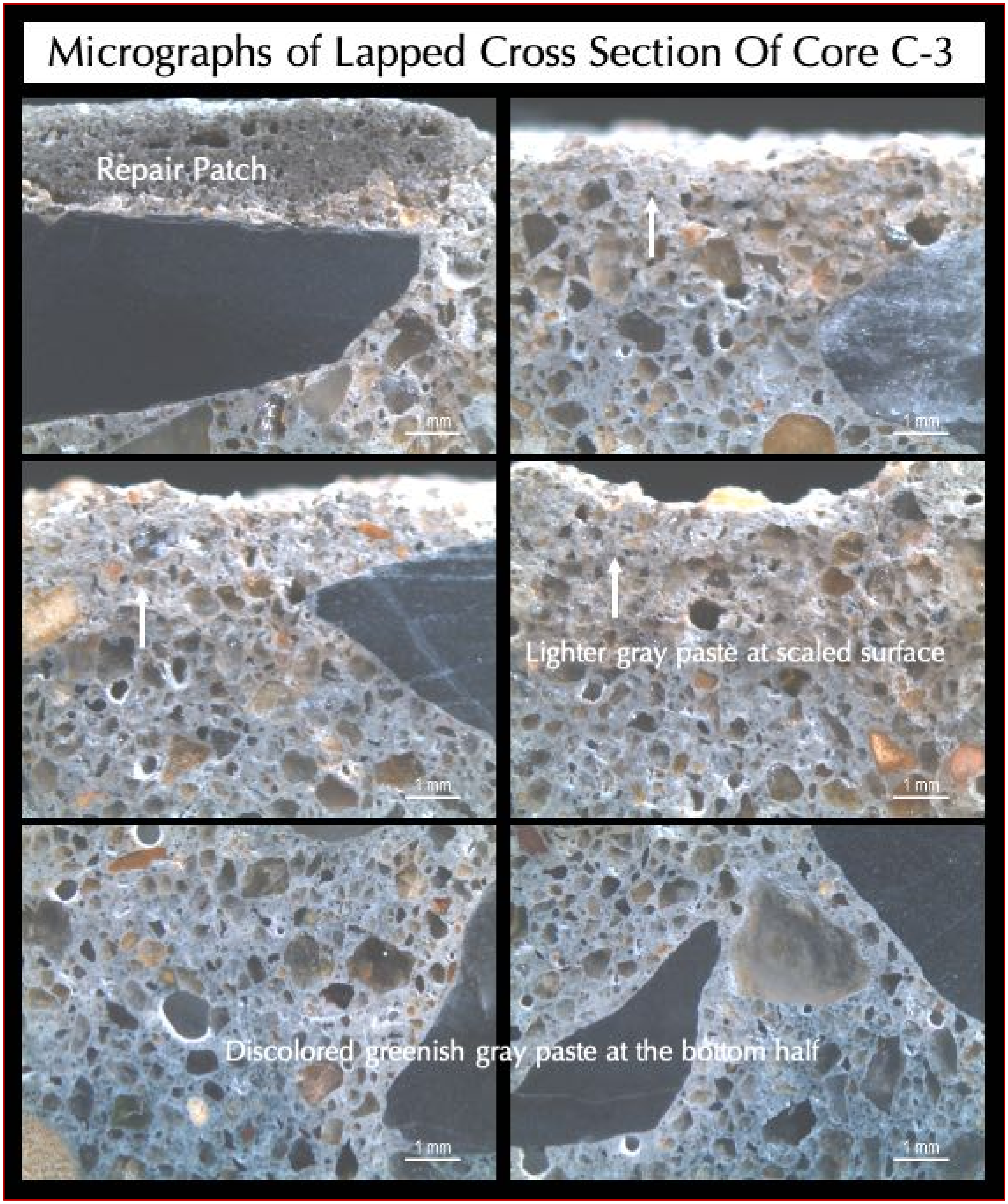

Figure 8: Micrographs of lapped cross section of the core showing: (a) the dark grey repair patch adhered to the scaled concrete surface; (b) lighter tone of paste at the top 3 mm of scaled surface due to higher water-cementitious materials ratio of paste at the scaled surface region (marked with vertical arrows) compared to the interior; and (c) lack of air entrainment in the concrete, or, in the repair patch except a few coarse spherical, near-spherical and irregularly-shaped entrapped air voids.

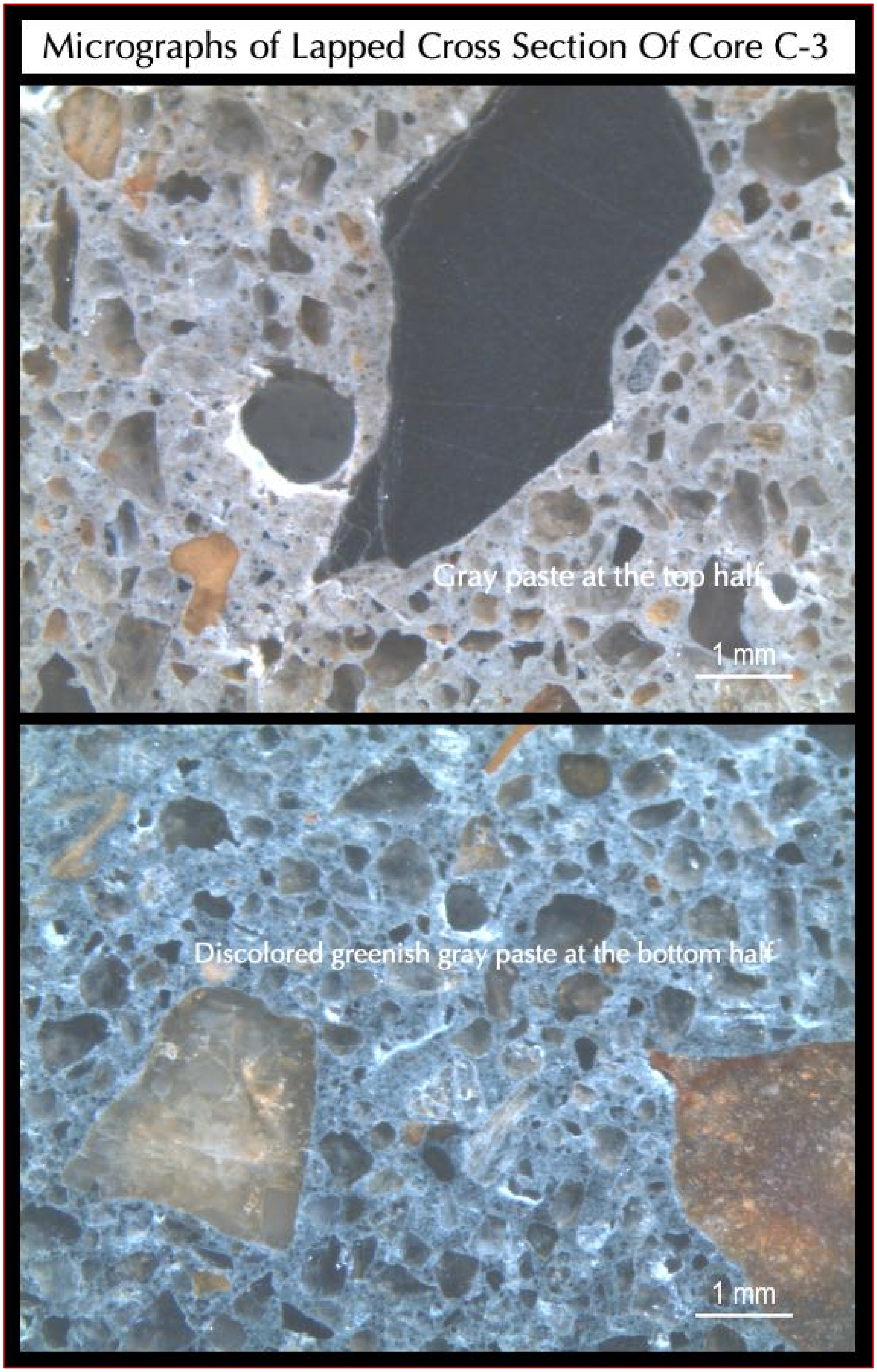

Figure 9: Micrographs of lapped cross section of the core showing the contrasting color tones of paste at the top half of core (top) versus the bottom half (bottom) due to the presence of sulfide phases in the fly ash used as a supplementary cementitious material which has imparted the greenish tone, whereas oxidation of binary Portland cement and fly ash paste has changed the original green discoloration to medium gray at the top half (except the very top 5 mm where paste is even lighter gray).

BLUE DYE-MIXED EPOXY-IMPREGNATED THIN SECTIONS

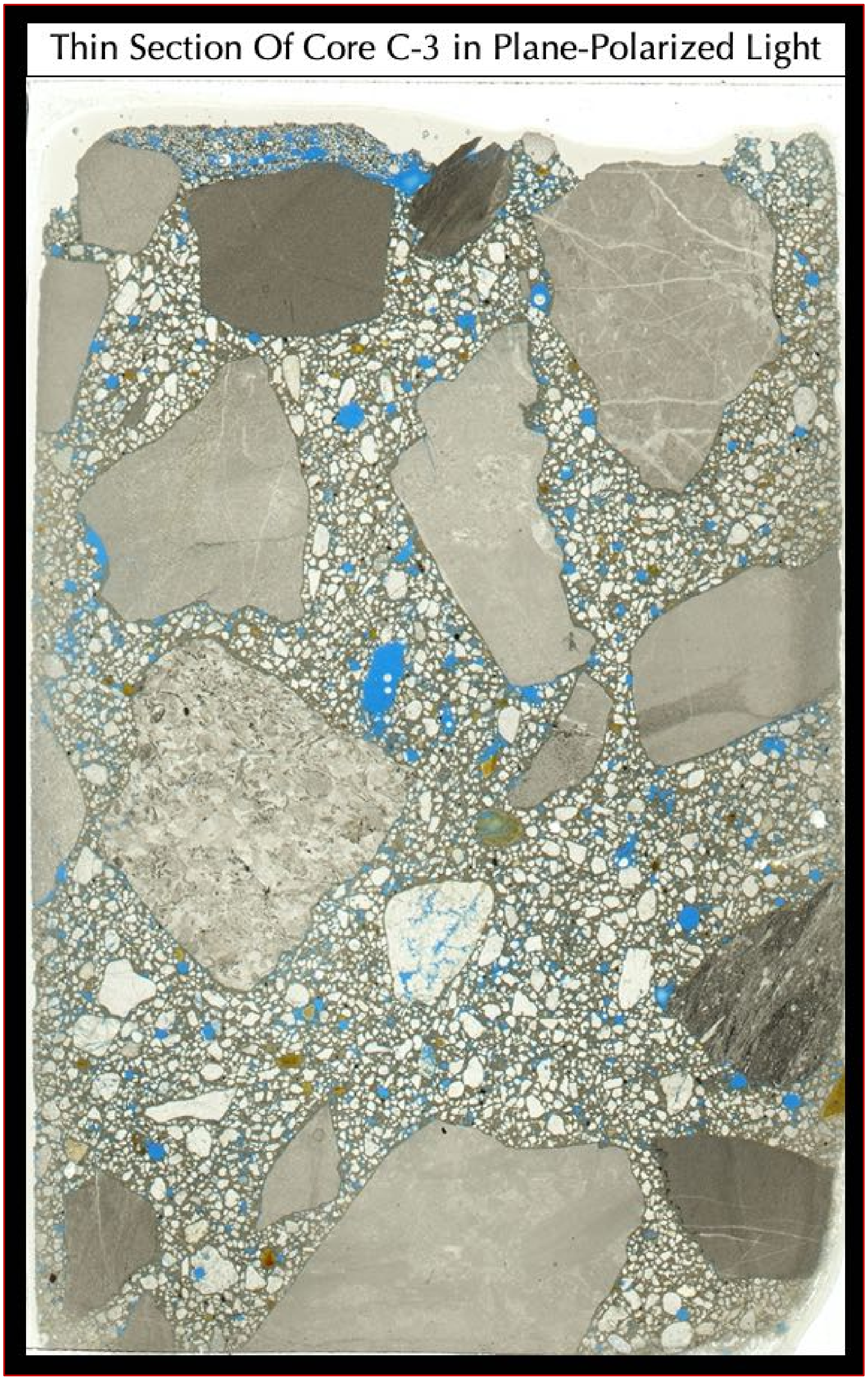

Figure 10: Blue dye-mixed epoxy-impregnated thin section of core showing crushed limestone coarse aggregate, natural siliceous sand fine aggregate, and interstitial paste marred with coarse spherical, near-spherical, and irregularly-shaped entrapped air voids. The image was taken on a flatbed film scanner with a polarizing filter.

Figure 11: Blue dye-mixed epoxy-impregnated thin section of core showing crushed limestone coarse aggregate, and natural siliceous sand fine aggregate. The image was taken on a flatbed film scanner with two perpendicular polarizing filters to generate crossed polarized light effect to highlight the compositions of crushed stone coarse aggregate and sand fine aggregate.

MICROGRAPHS OF THIN SECTION

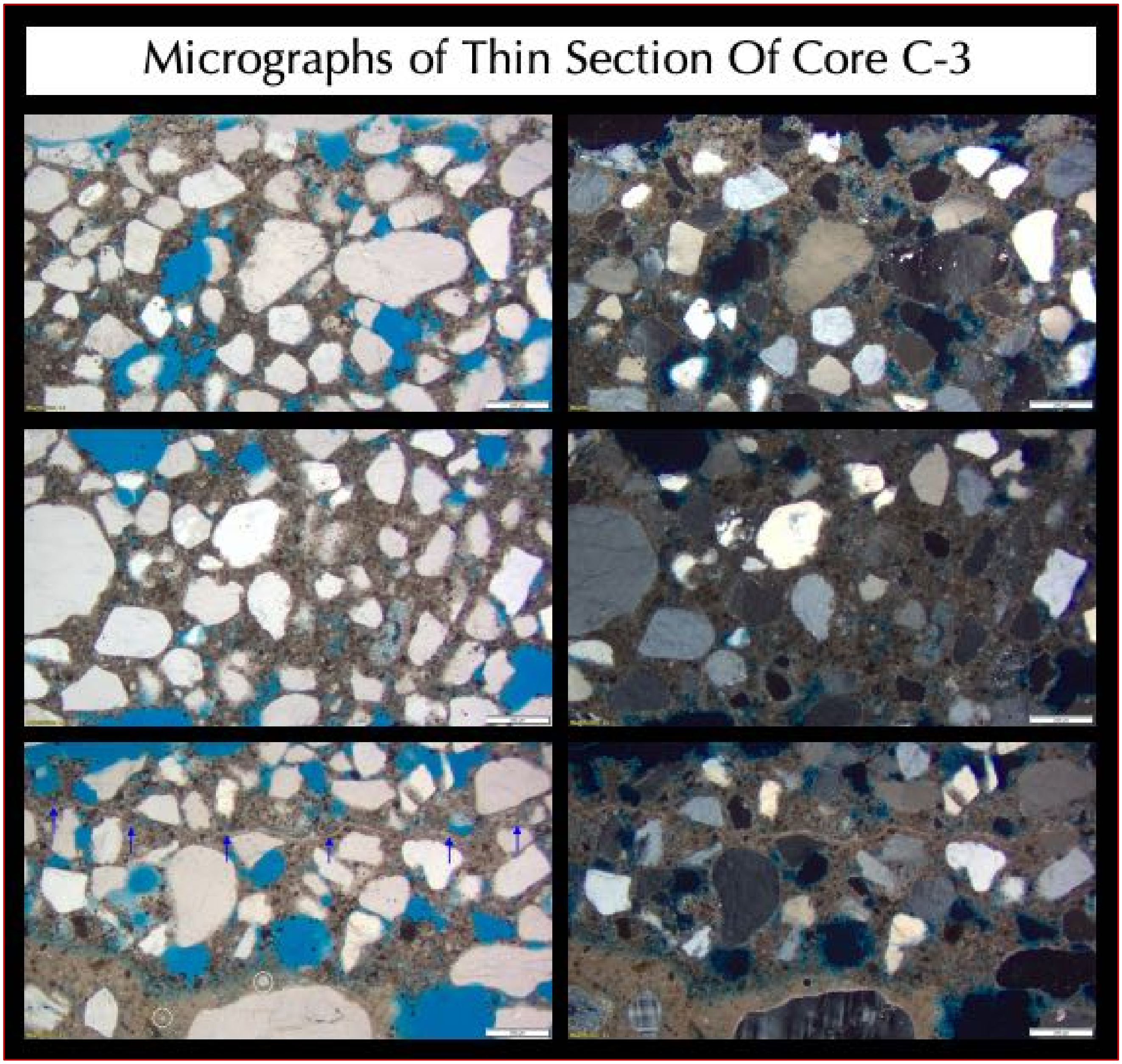

Figure 12: Micrographs of blue dye-mixed epoxy-impregnated thin section of core showing the dark gray repair patch consisting of fine quartz sand less than 1 mm in size, and dense, low water-cement ratio (estimated to be <0.40) Portland cement paste; and carbonation of pate in the repair grout from interaction with atmospheric carbon dioxide.

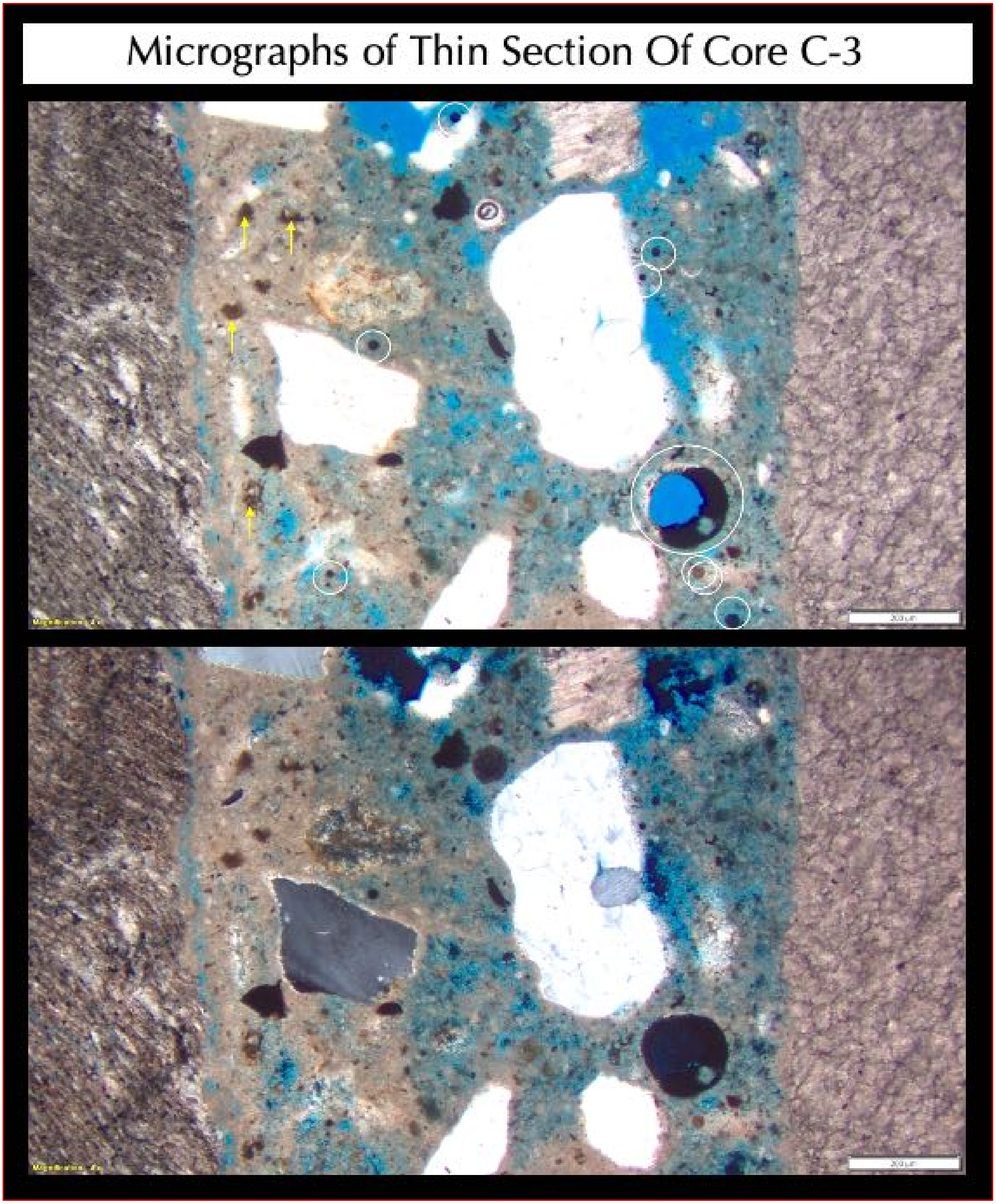

Figure 13: Micrographs of thin section of concrete at two ends showing crushed limestone coarse aggregate particles with interstitial mortar fraction containing silica sand and binary cement and fly ash paste where residual fly ash spheres are circled and a few residual Portland cement particles are marked with arrows. Paste is carbonated to form finely crystalline calcium carbonate deposits.

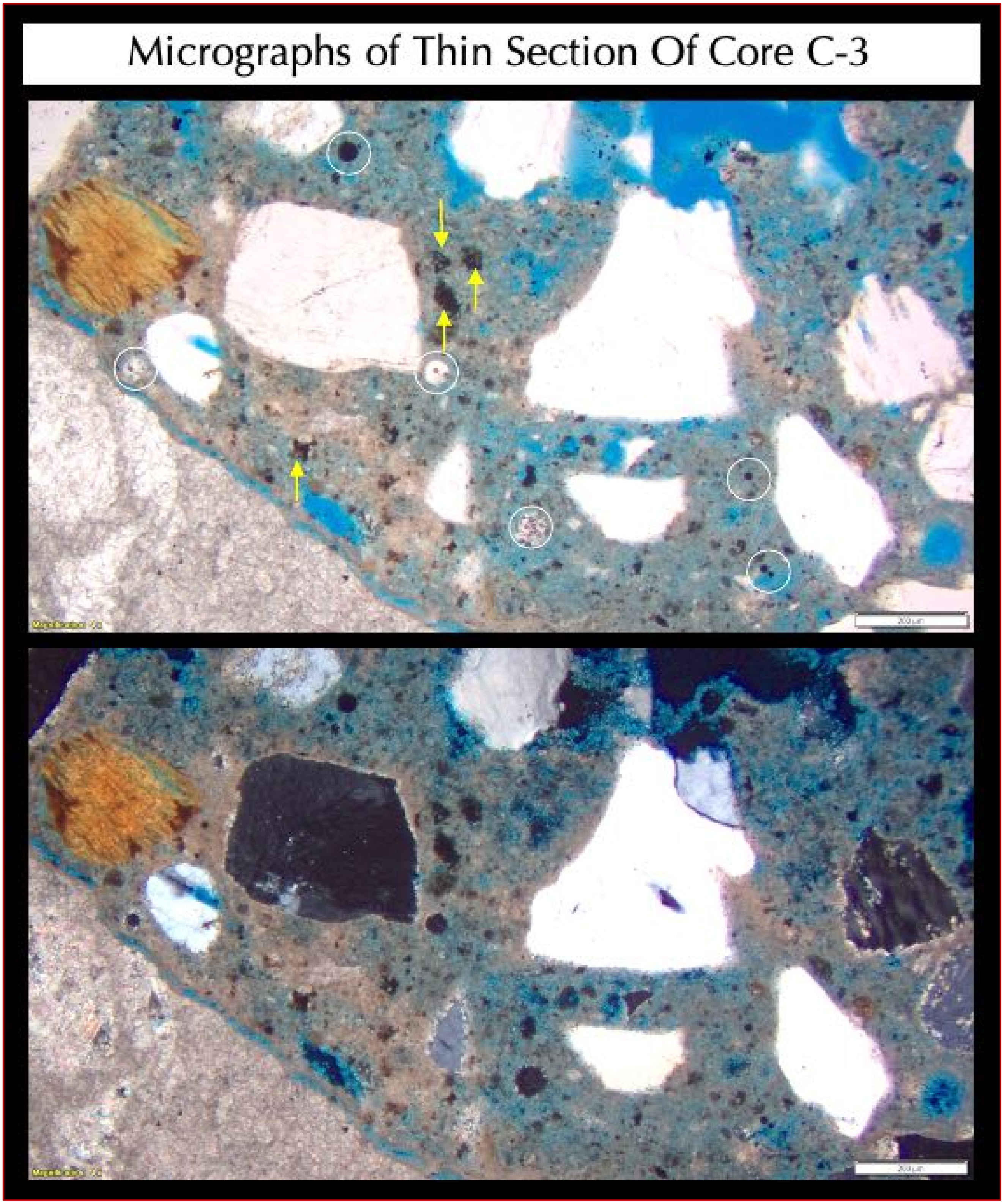

Figure 14: Micrographs of thin section of concrete at two ends showing crushed limestone coarse aggregate particles with interstitial mortar fraction containing silica sand and binary cement and fly ash paste where residual fly ash spheres are circled and a few residual Portland cement particles are marked with arrows. Paste is carbonated to form finely crystalline calcium carbonate deposits.

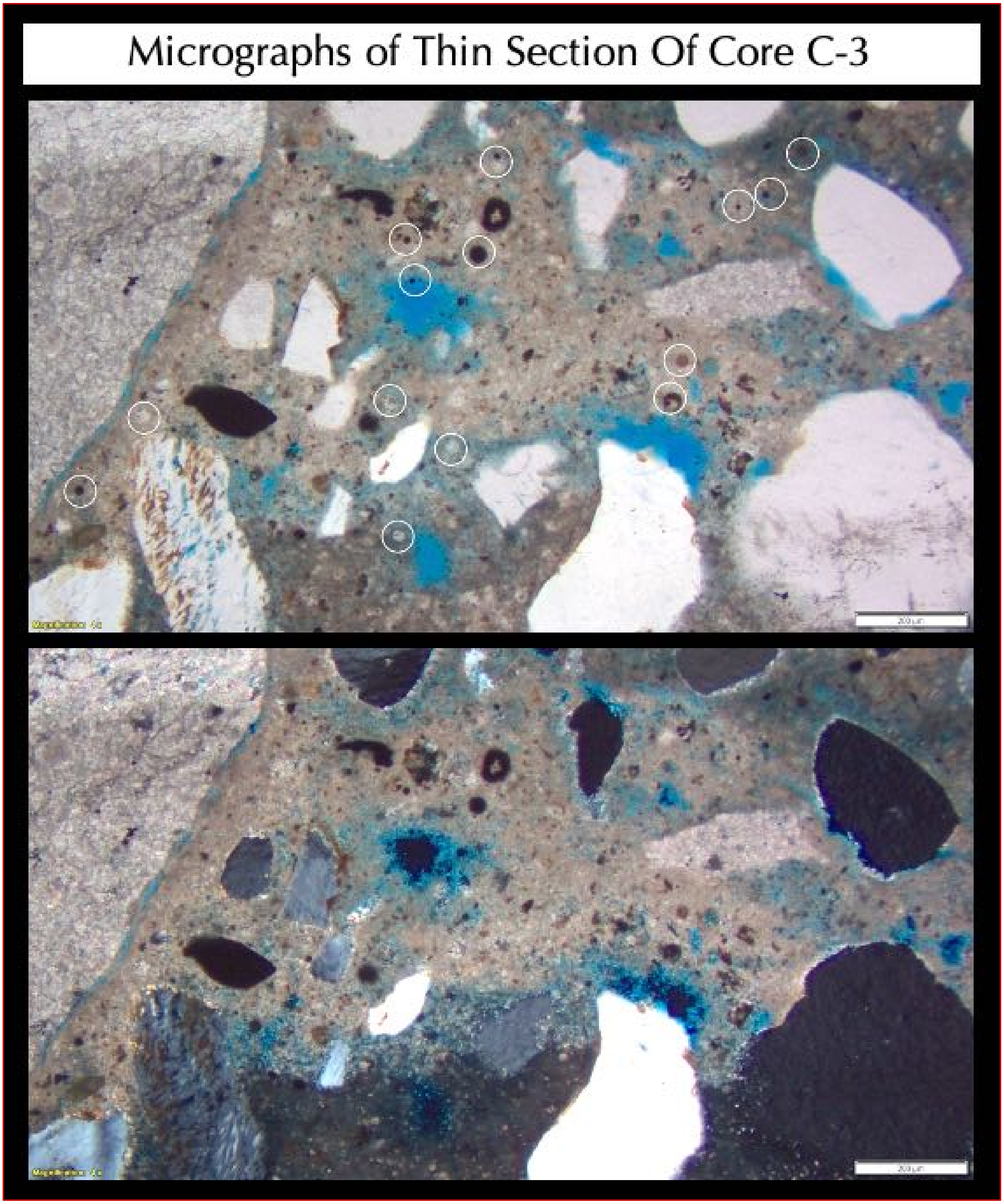

Figure 15: Micrographs of thin section of concrete at two ends showing crushed limestone coarse aggregate particles with interstitial mortar fraction containing silica sand and binary cement and fly ash paste where residual fly ash spheres are circled. Paste is carbonated at the top half to form finely crystalline calcium carbonate deposits whereas interior past at the bottom end of photos is non-carbonated.

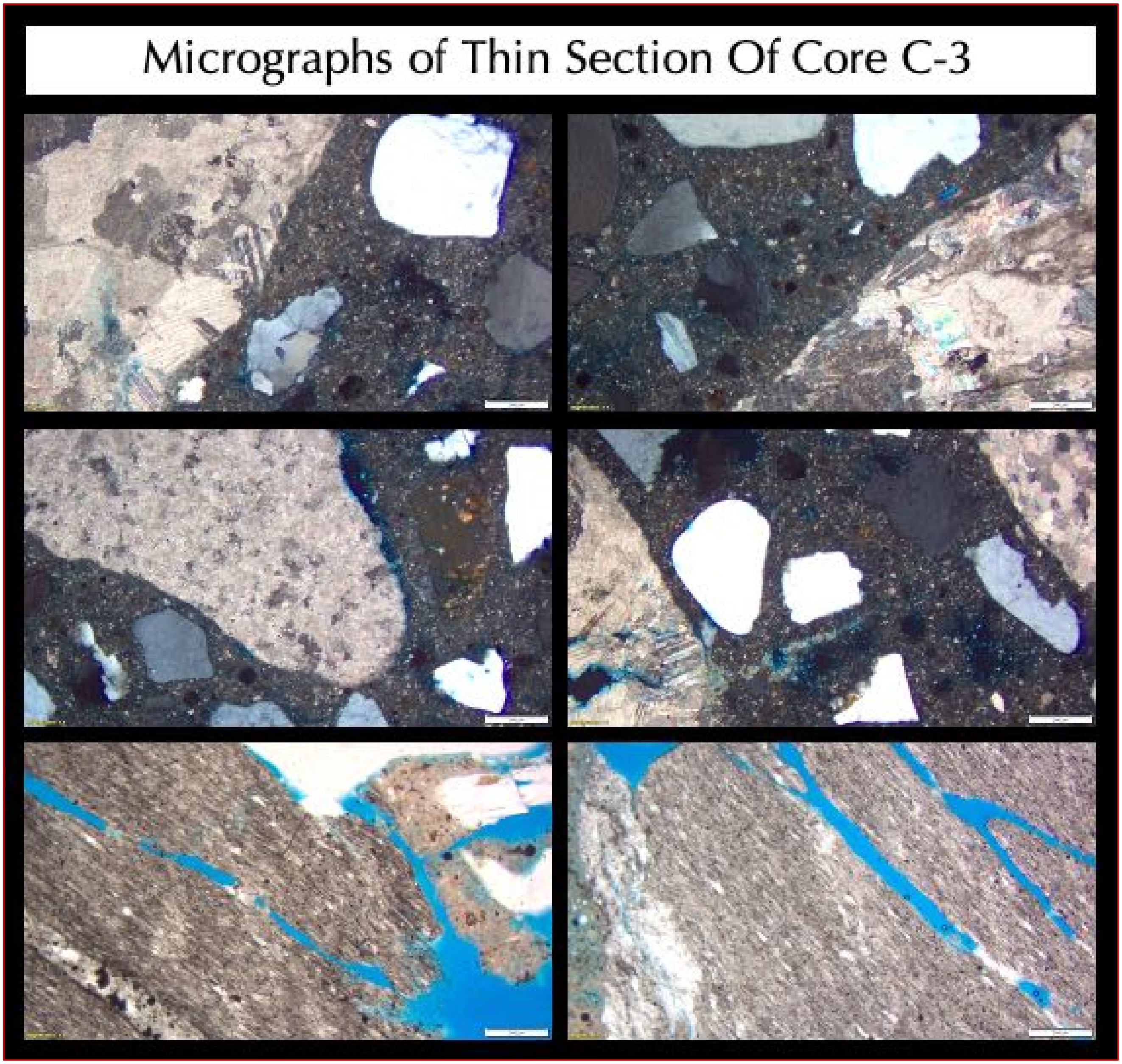

Figure 16: Micrographs of thin section showing crushed limestone coarse aggregate and silica sand fine aggregate in top and middle rows. However, the bottom row shows a near-surface dark gray shale particle in coarse aggregate, which has developed cracking within the particle and in neighboring paste. Such shale particles are potentially deleterious to concrete when exposed to near-surface region where the particles can absorb moisture and expand to cause pop-outs, which can also develop from subsequent freezing at saturated conditions.

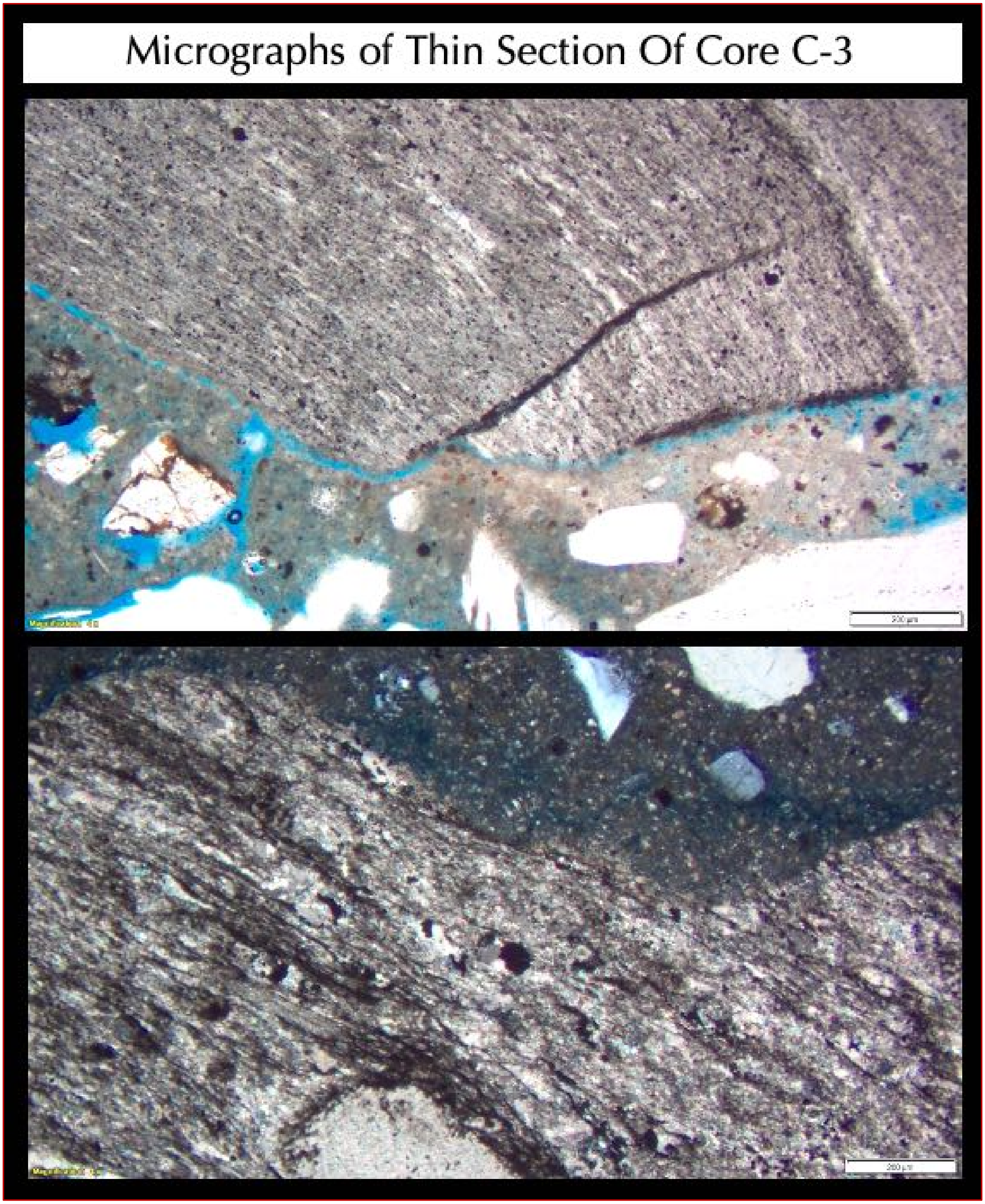

Figure 17: Micrographs of thin section showing a near-surface dark gray shale particle in coarse aggregate, which has developed cracking within the particle and in neighboring paste. Such shale particles are potentially deleterious to concrete when exposed to near-surface region where the particles can absorb moisture and expand to cause pop-outs, which can also develop from subsequent freezing at saturated conditions.

COARSE AGGREGATE

Coarse aggregate is crushed limestone having a nominal maximum size of $^3/_4$ in. (19 mm). Particles are angular, dark gray, dense, hard, massive-textured, equidimensional to elongated, poorly graded (due to the deficiency of some finer and intermediate-sized particles) but well-distributed. There is no evidence of alkali-aggregate reactions of coarse aggregate particles found in the core. Coarse aggregate particles have been sound during their service in the concrete and did not contribute to any distress in the slab.

There are, however, a few dark gray crushed shale particles found near surface region of concrete which has developed potential unsoundness as cracking within the unsound shale particles as well as in the neighboring paste which are judged to be due to expansions associated with absorption of moisture from the surface along with potential additional expansions from freezing at moisture-saturated conditions.

FINE AGGREGATE

Fine aggregate is natural siliceous sand containing major amounts of quartz, and quartzite, and subordinate amounts of feldspar, chert, and quartz siltstone. Fine aggregate has a nominal maximum size of $^3/_8$ in. (9.5 mm). Particles are variably colored, rounded to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and uncracked. Fine aggregate particles are well-graded and well-distributed. There is no evidence of alkali-aggregate reaction of fine aggregate particles. Fine aggregate particles have been sound during their service in the concrete.

The following Table summarizes properties of coarse and fine aggregates in the cores.

Properties and Compositions of Aggregates	Traditions of America
Coarse Aggregate	
Types	Crushed Limestone
Nominal maximum size (in.)	$^3/_4$ in. (19 mm)
Rock Types	Limestone (micritic limestone), argillaceous limestone, shale
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dark gray, dense, hard, massive-textured, equidimensional to elongated
Cracking, Alteration, Coating	Unaltered, Uncoated, and Uncracked
Grading & Distribution	Poorly-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None
Fine Aggregate	
Types	Natural siliceous sand

Properties and Compositions of Aggregates	Traditions of America
Nominal maximum size (in.)	3/8 in. (9.5 mm)
Rock Types	Major amounts of quartz, and quartzite, and subordinate amounts of feldspar, chert, and quartz siltstone
Cracking, Alteration, Coating	Variably colored, rounded to subangular, dense, hard, equidimensional to elongated
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None

Table 1: Properties of coarse and fine aggregates of concrete.

PASTE

Properties and composition of hardened cement paste are summarized in Table 2. Paste is lighter gray at the top 5 mm followed by a relatively darker gray paste immediately beneath the lighter-toned paste, then medium gray paste in the body in the top half, and eventually greenish discolored paste at the bottom half of core. The contrasting color tones of paste from medium gray at the top half of core to greenish-gray at the bottom half is from the presence of sulfide phases in the fly ash used as a supplementary cementitious material, which has imparted the greenish tone, whereas oxidation of binary Portland cement and fly ash paste has changed the original green discoloration to medium gray at the top half (except the very top 5 mm where paste is even lighter gray). Freshly fractured surfaces of interior paste have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 6 to 8 percent of the paste volumes. Distributed throughout the paste are fine, spherical clear, light to dark brown and black glassy particles of fly ash having the fineness of Portland cement. Hydration of Portland cement is normal.

Properties and Compositions of Paste	Traditions of America
Color, Hardness, Porosity, Luster	Lighter gray at the top 5 mm followed by a relatively darker gray paste immediately beneath the lighter-toned paste, then medium gray paste in the body in the top half, and eventually greenish discolored paste at the bottom half of core
Residual Portland Cement Particles	Normal, 6 to 8 percent by paste volume
Calcium hydroxide from cement hydration	Normal, 10 to 14 percent by paste volume
Pozzolans, Slag, etc.	Distributed throughout the paste are fine, spherical clear, light to dark brown and black glassy particles of fly ash having the fineness of Portland cement
Water-cementitious materials ratio (*w/cm*), estimated	0.40 to 0.45 in the interiors but 0.45 to 0.50 at the top 5 mm of scaled surface region
Cement Content (bags per cubic yard)	6 1/2 to 7 bags of which 15 to 20 percent is estimated to be fly ash
Secondary Deposits	None
Depth of Carbonation, mm	1 to 3 mm at the scaled surface

Properties and Compositions of Paste	Traditions of America
Microcracking	No deleterious microcracking is found except some common shrinkage-related microcracks in paste
Aggregate-paste Bond	Tight
Bleeding, Tempering	None
Chemical deterioration	None

Table 2: Proportions and composition of hardened cement paste.

The textural and compositional features of the paste are indicative of cementitious materials contents estimated to be equivalent to $6^{1}/_{2}$ to 7 bags of Portland cement per cubic yard of which 15 to 20 percent is estimated to be fly ash, and, a water-cementitious materials ratio (*w/cm*) estimated to be 0.40 to 0.45 in the interior and slightly higher (0.45 to 0.50) at the top 5 mm of surface region.

There is no evidence of any deleterious deposits found in the core. Carbonation is 5 mm at the scaled surface region. Bonds between the coarse and fine aggregate particles and paste are tight. There is no evidence of microcracking due to any chemical deteriorations, except for some cracking in a few near-surface crushed shale particles in coarse aggregate.

AIR

Air occurs as a few coarse, near-spherical and irregularly-shaped voids of sizes coarser than 1 mm that are characteristic of entrapped air. Air-void system of concrete is suggestive of no intentional addition of an air-entraining agent in the mix. Air content is estimated to be 1 to 2 percent. Concrete in this core is non-air-entrained. Lack of air entrainment as intentionally introduced discrete, fine, spherical, less than 1 mm size entrained air bubbles is contrary to the reported specification of use of an air-entrained concrete and also against common industry recommendation for an outdoor slab exposed to moisture, freezing, salts, and snow.

REPAIR PATCH

Remains of two dark gray 4 to 5 mm thick repair patch are found loosely adhered to the scaled surface at the two ends of exposed surface of core. The patch contains fine silica sand (less than 1 mm in size), and dense Portland cement paste having a water-cement ratio estimated to be less than 0.40.

DISCUSSIONS

Air Contents and Air-Void Systems

Concrete placed at the location of the examined core lacks air entrainment, which is contrary to common industry recommendations for an outdoor concrete exposed to cyclic freezing and thawing and deicing chemicals. Absence of entrained air is judged to have caused the surface scaling, which was potentially aggravated by exposure to chloride-containing deicing chemicals during service.

Aggregates

The crushed limestone coarse aggregate and siliceous sand fine aggregate particles are present in sound conditions and did not contribute to the observed surface distress. There is no evidence of any potentially deleterious alkali-aggregate reaction of coarse or fine aggregate found in the cores. A few crushed shale particles in coarse aggregate, however, have shown potential unsoundness as cracking from moisture absorption and potential freezing at saturated conditions, which are the conditions to cause popups of such aggregate particles situated immediately beneath the finished surface.

Placement, Finishing, and Curing

The lighter-toned higher *w/cm* paste at the top 5 mm of scaled surface is due to finishing in the presence of bleed water at the surface and/or addition of water during finishing where either practice or both can increase the *w/cm* of paste at the surface and decrease the resistance of finished surface to abrasion and salt scaling.

The interior concrete is dense and well-consolidated without any coarse voids or honeycombing, indicating adequate consolidation of concrete during placement. There is also no evidence of any segregation of coarse aggregate particles during placement. There is, therefore, no evidence of any improper consolidation practice of slabs at the location of the examined core.

Curing is essential for adequate cement hydration at the surface, and, thereby, development of the necessary strength of concrete at the surface by providing enough moisture and optimum temperature for cement hydration. Exposed scaled surface of the core shows no evidence of inadequate curing of concrete, e.g., no evidence of restricted cement hydration at the scaled surface at least to cause the reported surface scaling.

Compressive Strengths

For adequate resistance to freezing-related stresses, the common industry (e.g., ACI Committee 201)-recommended compressive strength of concrete exposed to an outdoor environment of moisture and freezing is at least 4000 psi. A concrete having a compressive strength of at least 4500 psi is usually recommended for an outdoor concrete slab exposed to moisture, salts, and snow, where the good strength of concrete provides the necessary resistance against freezing-related tensile stresses in concrete. Reported compressive strength of a companion core from the field is 4070 psi, which is less than the common industry specification of 4500 psi for an outdoor concrete exposed to freezing, moisture, salt, and snow.

Concrete Maturity

The maturity of concrete is defined as: (i) a period of air drying and (ii) a compressive strength of at least 4000 psi – both prior to the first exposure of salts and snow so that the concrete does not contain any 'freezable' water in its capillary pores to freeze, expand, and thus cause distress (hence the importance of at least a period of air drying), and is strong enough to resist freezing-related stresses (hence the importance of adequate strength of at least 4500 psi) both prior to the first exposure of snow and salt (Jana 2004, Jana 2007). A concrete, therefore, needs to be 'matured' prior to the first exposure of freezing, especially during the winter weather constructions.

Potential placement of the slab in early Spring or late Fall may prevent attainment of maturity of concrete at the surface region, especially if concrete at the surface region does not attain a strength of at least 4000 psi at the time of freezing in which case distress may occur from freezing prior to the attainment of at least 4000 psi strength for surface concrete.

Additionally, fly ash in the cementitious components is known to slow down the strength gain, which for a concrete placed in later Fall or early Spring and not protected from freezing can develop scaling issues.

Deicing Salts

Deicing salts, usually, do not cause surface scaling in a properly air-entrained concrete having a good air-void system that is made using sound aggregates, and has been placed, finished, cured, and was matured properly (Jana 2004, 2007), *unless*: (i) salt is applied prior to the attainment of maturity of concrete, and/or (ii) a chemically aggressive (e.g., magnesium or ammonium sulphate or urea-based) salt is applied that can chemically decompose the paste (calcium silicate hydrate, the heart of concrete). A well-designed concrete placed, finished, and cured properly should resist the deleterious action of salt unless salt was brought in too early and/or a chemically corrosive salt (magnesium sulfate or ammonium-based) was present that has caused chemical erosion of paste.

Lack of air entrainment, however, intensifies salt-related scaling due to the lack of necessary air voids to prevent stresses that develop during freezing in the presence of salts. The hygroscopic nature of salts increases the degree of saturation of salt-soaked surface where having adequate air entrainment is essential to prevent salt scaling.

Beneficial Aspect of A Surface Sealer

Exposed scaled surface of core showed no evidence of application of a surface sealer. It is the concrete itself, i.e. an adequately air-entrained concrete made using optimum air content and good air-void system, sound aggregates, good paste, placed, finished, and cured properly, and has been matured prior to the first exposure to freezing, salts, and snow, which should provide the necessary durability in an outdoor environment of freezing, salt, and snow. When all these basic factors are fulfilled from concrete materials to construction practices, having an additional surface sealer is not needed for protection. A surface sealer, however, does provide an additional protection, particularly when the inherent concrete quality and/or construction practices is/are questionable such as in this present case, where concrete is non-air-entrained. There are, however, many incidences of surface scaling in many outdoor slabs that did receive surface sealers, simply because sealer did not provide a long-term protection, and needed repeated applications. On the other hand, there are many incidences of perfectly sound outdoor slabs without any sealer that were exposed to freezing, salts, and snow but no distress at all simply because the concretes were made using sound durable materials and were well-constructed (consolidated, finished, cured), and matured properly. Therefore, having or not having a sealer is not the paramount factor for providing the first-hand protection against the environment. Sealer becomes more important when the inherent quality of concrete is questionable as here for having no air entrainment at all.

Ineffective Repair Patch

Loss of the repair patch from most of the exposed surface of core except only two isolated remains of such patch indicate inadequate bond of the patch to the underlying concrete, which could be due to ineffective surface preparation of concrete before installation of the patch, or thin application of patch or other reasons not evident in the present study.

CONCLUSIONS

Based on detailed laboratory investigations, surface distress of concrete sidewalk are found to be due to:

(a) Lack of air entrainment in the concrete exposed to outdoor environment of cyclic freezing and thawing and potentially deleterious deicing chemicals;

(b) Potentially deleterious effects of some crushed shale particles in coarse aggregate, which can cause pop outs from moisture absorption and subsequent freezing;

(c) Finishing in the presence of bleed water at the surface and/or addition of water during finishing where either practice or both can increase the *w/cm* of paste at the surface and decrease the resistance of finished surface to abrasion and salt scaling;

(d) Potential exposure to freezing and salt prior to the attainment of concrete maturity, especially in early Spring or late Fall placement when the surface region may not have developed at least 4000 psi compressive strength and has gone through a period of air drying; and,

(e) Potentially deleterious effects of various deicing chemicals, which may have been applied which can aggravate the surface distress especially due to the lack of air entrainment.

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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.