CONSTRUCTION MATERIALS CONSULTANTS, INC.

Investigation of Concrete Surface Distress by Petrographic Examinations of Two Concrete Cores

National Cemetery of the Alleghenies Design Build Expansion
1158 Morgan Road
Bridgeville, PA 15017

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CMC 0219106

TABLE OF CONTENTS

Attached 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

Reported herein are the results of detailed petrographic examinations of two hardened concrete cores from an outdoor flatwork slab that has exhibited surface scaling and spalling at multiple locations. The slab was reportedly placed in July to September and winter months of 2018.

Field photographs of concrete slab showed: (a) *thin sheet-like separation of the finished surface from the body and (b) loss of the original finished concrete as eroding or washing away*. The former type of scaling (i.e. *sheet scaling*) is common where bleed water accumulates beneath the finished surface usually from premature finishing operations prior to the cessation of bleeding thus creates a plane of weakness immediately beneath the finished surface causing eventual loss of bond of the top finished surface from the body and subsequent separation of the top finished surface as thin sheets. The latter type of scaling is common when the finished surface is soft, porous, and earthy-textured preferentially at the locations where water accumulated at the finished surface during finishing (e.g., from the bleed water on the surface) and/or from excess water present during finishing (either water added during finishing and/or mixing of bleed water at the surface during finishing). Although both types of scaling, are the consequences of improper finishing operations, either of these two types, however can also occur from cyclic freezing and thawing of a poor quality concrete at critically saturated conditions, e.g., a concrete having improper air-void system and/or inadequate amount of entrained air that is needed for protection of concrete in a moist outdoor environment exposed to freezing.

The cores received show severely scaled top surfaces where coarse aggregate particles are exposed, as well as a coating of dried drilling mud with craze-crack type shrinkage microcracks indicating an inherently soft nature of concrete. The cores were examined by detailed petrographic examinations *a la* ASTM C 856 to evaluate the concrete quality (e.g., aggregates, water-cementitious materials ratio, air contents, air-void systems), construction practices followed (e.g., placement, consolidation, finishing, and curing), and the potentially deleterious effects of salts.

The placed concrete is reportedly of a mix design containing (in a cubic yard): 1105 pounds of #57 crushed stone and 595 pounds of #8 MGQ coarse aggregate, 1110 pounds of Three Rivers' natural sand fine aggregate, 432 pounds of Lafarge Type I/II Portland cement, 108 pounds of Headwaters Resources Class F fly ash, 33.0 gallons of water, 1.0 oz/cwt of Grace Darex II air-entraining admixture, 2.0 oz/cwt Grace WRDA 20 water-reducing admixture, 4.0 to 8.0 oz/cwt Grace ADVA 140M mid-range water-reducer, and optional 2.5 to 4.5 oz/cwt Grace ADVA 190 high-range water-reducer, 4.0 to 24.0 oz/cwt Grace Daraset 400 non-chloride accelerating admixture, 1.0 to 6.0 oz/cwt Grace Daratard 17 retarding admixture - all to have a design slump of 2 to 4 inches (6 in. maximum after mid-range water reducer, and 8 in. maximum after high-range water reducer), a design air content of 4.5 to 7.5 percent, a design water-cementitious materials ratio of 0.51 for a 28-day design compressive strength of 4000-psi.

Based on petrographic examinations the concrete in both cores is determined to be compositionally similar, *non-air-entrained*, and made using: (a) mixtures of #57 and #8 crushed limestone-dolomite having nominal maximum sizes of $^{3}/_{4}$ to 1 in. and containing variably porous limestone, dolomitic limestone, and porous dolomite which are medium to dark gray, variably dense due to the presence of pore spaces, hard, angular, massive textured, equidimensional to elongated, unaltered, uncoated, uncracked, well-graded, well-distributed, and have been sound during their service in the concrete (except the pore spaces in limestone-dolomite that can absorb moisture and expand during freezing to promote popouts); (b) natural siliceous-calcareous sand fine aggregate having major amounts of siliceous components quartz, quartzite, feldspar, chert, siltstone), subordinate amounts of calcareous components (limestone, dolomite), and subordinate amount of argillaceous and ferruginous components (shale, ferruginous and argillaceous siltstone), having nominal maximum sizes of $^{3}/_{8}$ in. (9.5 mm) which are well-graded, well-distributed, and sound; (c) a hardened blended cement paste having Portland cement and fly ash with cementitious materials contents estimated to be equivalent to $5^1/_2$ to 6 bags of Portland cement per cubic yard of which 20 percent is estimated to be fly ash, and, water-cementitious materials ratios (*w/cm*) estimated to be 0.55 to 0.60 at the scaled surface regions and 0.50 to 0.55 in the body; and, most importantly, (d) absence of air entrainment, air contents are similar in both cores and estimated from petrographic examinations to be 1 to 2 percent, as opposed to reported design air contents of 4.5 to 7.5 percent and air entrainment of concrete. Lack of air entrainment in both cores show serious deviations from reported air entrainment in the mix design, which is judged to be the primary factor for observed and reported scaling of concrete due to cyclic freezing and thawing of a non-air-entrained concrete at critically saturated conditions.

The estimated water-cementitious materials ratios (*w/cm*) of concrete at the surface regions of cores are higher than that in their interiors, which is indicative of a soft, porous paste at the surface region, perhaps due to finishing in the presence of bleed water at the surface and/or addition of water during finishing. Interior *w/cm*, though similar to the reported design *w/cm* of 0.51 is still higher than the common industry (e.g., ACI)-recommended maximum ratio of 0.45 (preferably 0.40) for an outdoor concrete exposed to freezing, salt, and snow. Along with air entrainment, the primary defense of an outdoor concrete to stay durable in a moist environment of salt and snow it should also have the lowest possible *w/cm*, preferably around 0.40 and remain workable, especially when the concrete was designed to have multiple water-reducing admixtures, e.g., 2.0 oz/cwt Grace WRDA 20 water-reducing admixture, 4.0 to 8.0 oz/cwt Grace ADVA 140M mid-range water-reducer, and optional 2.5 to 4.5 oz/cwt Grace ADVA 190 high-range water-reducer. Additionally, all those chemical admixtures where water is an integral part of those admixtures requires an adjustment of batch water content without which concrete would end up having a high *w/cm* beyond the industry-recommended maximum limit of 0.45. Despite having a good reported mix design of an air-entrained concrete containing many water-reducing chemicals, the need for a design *w/cm* of 0.51 is unrealistic especially in a moist outdoor environment of freezing, along with total absence of the air entraining chemical in the cores when the concrete was designed to have 1.0 oz/cwt of Grace Darex II air-entraining admixture to stabilize 4.5 to 7.5 percent air.

Based on detailed laboratory investigations, the reported surface scaling of concrete slab from field photographs to examined cores are judged to be due to one or a combination of the following factors:

a. **Lack of air entrainment in concrete**, which has affected the durability of concrete in a moist outdoor environment exposed to cyclic freezing and thawing at critically saturated conditions.

b. **Premature finishing prior to the cessation of bleeding** that has created sheet scaling of the finished surface from the body at some locations as seen in field photos, as well as **finishing with excess water at the surface** to soften the surface region.

c. **Potential exposures to chloride-containing deicing salts**, where non-air-entrained nature of concrete will aggravate salt-scaling distress of concrete, especially if salts were applied at an early stage prior to the attainment of concrete maturity.

Of these three, lack of air entrainment is the primary factor for the observed scaling of concrete surface due to cyclic freezing and thawing at critically saturated conditions, which may have been aggravated in the presence of salts, especially if salt was applied prior to the attainment of concrete maturity.

Due to the lack of air entrainment all throughout the depths of cores, scaling will continue during future winter months of cyclic freezing and thawing at critically saturated conditions, especially in the presence of salts.

INTRODUCTION

Reported herein are the results of detailed petrographic examinations of two hardened concrete cores from an outdoor flatwork slab that has exhibited surface scaling problem in December of 2018.

BACKGROUND INFORMATION

The following background information was received via email:

a. Reason for the Requested Testing – The concrete has been flaking off the top and has spalled after the freeze and thaw. The finish is flaking and unsightly.
b. Nature of the problem – The problem was noticed on December of 2018, the concrete was spalling in multiple locations.
c. Time of Placement – Two separate areas. One was poured in the winter and the other in July-September.
d. Location/Environment – Outdoor flatwork.
e. Mix Design – See the provided mix design in Figure 1.
f. Previous testing results – No additional laboratory testing was reported beyond the field testing of concrete.

PURPOSE OF PRESENT INVESTIGATION

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

a. The compositions, qualities, and overall conditions of concretes in the two cores;
b. Evidence of any physical or chemical deterioration of concrete in the two cores; and,
c. Based on detailed laboratory investigation, investigation of all possible reasons to explain the observed and reported surface distress of concrete.

MIX DESIGN

The following Mix Design was received with the samples. The design showed use of (in a cubic yard): 1105 pounds of #57 crushed stone and 595 pounds of #8 MGQ coarse aggregate, 1110 pounds of Three Rivers' natural sand fine aggregate, 432 pounds of Lafarge Type I/II Portland cement, 108 pounds of Headwaters Resources Class F flay ash, 33.0 gallons of water, 1.0 oz/cwt of Grace Darex II air-entraining admixture, 2.0 oz/cwt Grace WRDA 20 water-reducing admixture, 4.0 to 8.0 oz/cwt Grace ADVA 140M mid-range water-reducer, and optional 2.5 to 4.5 oz/cwt Grace ADVA 190 high-range water-reducer, 4.0 to 24.0 oz/cwt Grace Daraset 400 non-chloride accelerating admixture, 1.0 to 6.0 oz/cwt Grace Daratard 17 retarding admixture - all to have a design slump of 2 to 4 inches (6 in. maximum after mid-range water reducer, and 8 in. maximum after high-range water reducer), a design air content of 4.5 to 7.5 percent, a design water-cementitious materials ratio of 0.51 for a 28-day design compressive strength of 4000-psi.

Mix Design

LAFARGE NORTH AMERICA

Mix #: RMXUD4067 4000 AE

[redacted]

MIX DESIGN COMPONENT (1 CUBIC YARD)

COMPONENTS	SUPPLIER	TYPE / NAME	QTY. lb/yd3	VOLUME ft3
Cement	LAFARGE NA	LAFARGE TYPE I/II	432	2.20
Mineral Add	HEADWATERS RESOURCES	CLASS F FLY ASH	108	0.73
		TOTAL CEMENTITIOUS	**540**	**2.93**
Sand	THREE RIVERS	CONCRETE SAND	1110	6.76
Stone #57	MGQ	COARSE AGG ASTM #57	1105	6.63
Stone #8	MGQ	COARSE AGG ASTM #8	595	4.77
Water (gal)	WATER MUNICIPAL	WATER	33.00 gal	4.41
Volume of Air			6.0 %	1.68
TOTAL:			**3626**	**27.18**

ADMIXTURES

AEA	GRACE	DAREX II	1.0 oz/cwt (As Required)
WR	GRACE	WRDA 20	2.0 oz/cwt (As Required)
MRWR	GRACE	ADVA 140M	4.0 to 8.0 oz/cwt (As Required)
HRWR	OPTIONAL	GRACE ADVA 190	2.5 to 4.5 oz/cwt (As Required)
NCA	OPTIONAL	GRACE DARASET 400	4.0 to 24.0 oz/cwt (As Required)
RET	OPTIONAL	GRACE DARATARD 17	1.0 to 6.0 oz/cwt (As Required)
TOTAL:			**27.20**

Slump: 3.0" +/- 1.0"
Slump: 6.0" Max. (After MRWR)
Slump: 8.0" Max. (After HRWR)
Air Content: 6.0% +/- 1.5%
Required W/CM: 0.51

Remarks: Lafarge Mix UD4067 performs based on the standard deviation data attached. (Slumps in excess of the 4" specified are indicative of the use of the OPTIONAL MRWR/HRWR.) Testing shall be performed by ACI certified technicians. Test specimens that are not fabricated, site cured, transported and tested in strict conformance with stated specifications shall not be used for evaluation of concrete acceptance. In accordance with ACI Building Code (re: ASTM C 94) we respectfully request copies of all concrete test reports on a timely basis. Should you have any questions please contact us at 505-5307. ** The MRWR, HRWR, NCA, RET, FIBERS and COLOR depicted are OPTIONAL and must be requested at time of order.

Prepared By: Colin Bailey — Date: October 25, 2017
Mix Submitted by Lafarge North America — Unit Weight: 140.9 #/cf

Figure 1: Reported mix design for the concrete for a design slump of 2 to 4 inches (6 in. maximum after mid-range water reducer, and 8 in. maximum after high-range water reducer), a design air content of 4.5 to 7.5 percent, a design water-cementitious materials ratio of 0.51 for a 28-day design compressive strength of 4000-psi.

FIELD PHOTOGRAPHS

Figure 2: Field photographs of concrete slab showing surface scaling problem as loss of the original finished surface.

Figure 2 shows overall conditions of concrete slab. A close examination of distress in these field photos shows ***thin sheet-like separation of the finished surface from the body in the top photo*** as opposed *to* ***loss of the original finished concrete as eroding or washing away at isolated locations in the slab*** which is common in the bottom photo. The latter type of scaling in the bottom photo is common when the finished surface is soft, porous, and earthy-textured preferentially at the locations where water was accumulated at the finished surface during finishing (e.g., from the bleed water on the surface) and/or from excess water present during finishing (either water added during finishing and/or mixing of bleed water at the surface during finishing). The former type of scaling (i.e. *sheet scaling*) in the top photo is common where bleed water accumulates beneath the finished surface usually from premature finishing operations prior to the cessation of bleeding thus creates a plane of weakness immediately beneath the finished surface causing eventual loss of bond of the top finished surface from the body and subsequent separation of the top finished surface as thin sheets.

Although both types of scaling, as described above are the consequences of **improper finishing operations**, either of these two types, however can also occur from **cyclic freezing and thawing of a poor quality concrete at critically saturated conditions**, e.g., a concrete having improper air-void system and/or inadequate amount of entrained air that is needed for protection of concrete in a moist outdoor environment exposed to freezing.

The latter type of scaling in the bottom photo can also occur from **premature application of salt on a concrete surface that has: (a) not been matured, or (b) a concrete that has inadequate air and/or improper air-void system at the surface or (c) has a soft, porous surface that is not resistant to the potentially deleterious actions of salts**. A chemically corrosive salt (magnesium sulfate, ammonia based salt) can also cause chemical erosion of paste from the surface apparently creating a distress similar to local loss of the original finished surface as seen in the field photos.

As opposed to **scaling** (i.e. loss of original finished surface), two other types of distresses usually found in scaled surfaces but not found in Figure 2 are: (a) **popout,** which usually occur from moisture saturation of porous, unsound aggregates situated immediately beneath the surface and thus expansion of those near-surface particles often aggravated by freezing at saturated conditions, or as (b) **mortar lift-off** over flat top sides of near-surface aggregate particles where exposed aggregate itself is sound but finished surface did not bond adequately to the aggregate, eventually lifted off thus exposing the flat topsides of near-surface aggregate that resembles popout. Both types of distress could have also appeared but cannot be evaluated from the field photos provided.

Therefore, a detailed petrographic examination is needed to investigate all these possible factors, from: (a) concrete quality (e.g., soundness of aggregates, paste, and air content and air void system) to (b) workmanship (finishing and curing procedures and their effect on the durability of the finished surface) to (c) potentially deleterious actions of deicing chemicals and determine which of these factors either independently or in combination may have caused the observed surface scaling.

SAMPLES

PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figures 3 and 4 show the cores, identified as Nos. 1 and 2 as received. The cores have nominal diameters of $2^3/_4$ in. (70 mm) and total nominal lengths of 5 in. (130 mm) and 4 in. (100 mm) for Nos. 1 and 2, respectively.

END SURFACES

Both cores show severely scaled surfaces at the top and formed, wavy bottom surfaces (Figures 3 and 4).

The top end of core 1 has a thin layer of soft, hardened mud-like layer of paste with closed polygonal-shaped mud cracks covering almost 50 percent of the top scaled surface, which is judged to have formed from drilling operation, where drilling mud that came out of the core has dried on the scaled top when received in the lab with mud cracks.

Core 2 also has some of this coat. Scaled surfaces in both cores show exposed coarse aggregate particles, indicating severe scaling of the concrete. Both cores represent full thicknesses of the slab at their respective locations.

CRACKING & OTHER VISIBLE DISTRESS, IF ANY

Both cores were received in broken conditions where each has a crack at mid-depth location that broke the core into two pieces. Cracking is judged to have occurred during the coring operation rather than representing any pre-existing cracks since no other visible crack is found in the cores.

There are no other visible cracks, joints, or large voids observed in the cores, as received.

EMBEDDED ITEMS

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

RESONANCE

The cores have a ringing resonance, when hammered.

Figure 3: Photographs of Core 1 as received – Top left – Exposed surface with severe scaling and complete loss of the finished surface with exposed coarse and fine aggregate particles and a thin coating of drilling mud with fine hair-like mud cracks covering almost 50 percent of the scaled top; Top right – smooth formed wavy bottom surface with a thin layer of fine subbase, and bottom row - cylindrical side view of the core with identification showing a crack at the mid-depth location probably formed during the coring operation.

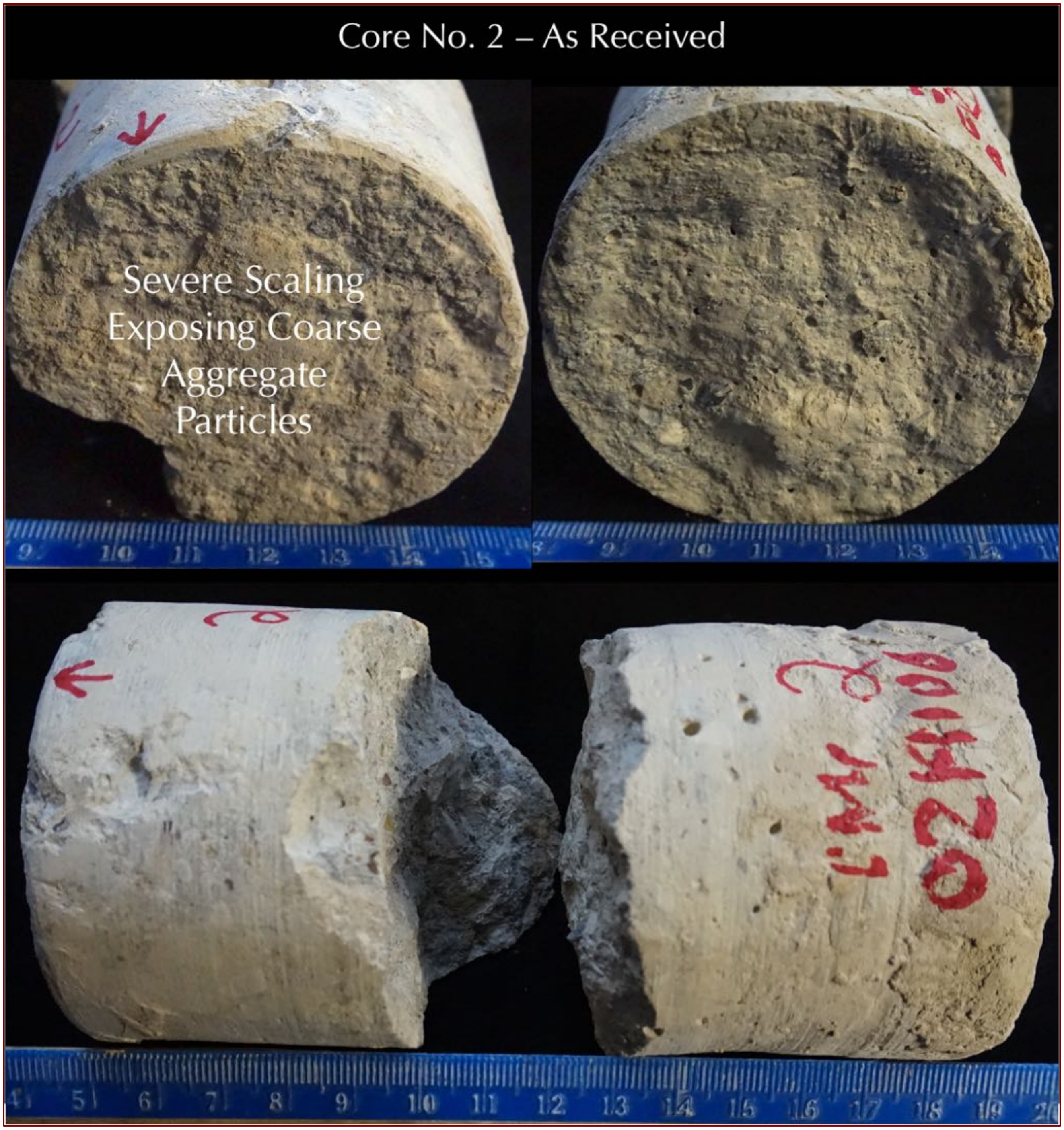

Figure 4: Photographs of Core 2 as received – Top left – Exposed surface with severe scaling and complete loss of the finished surface with exposed coarse and fine aggregate particles and a thin coating of drilling mud with fine hair-like mud cracks covering almost 50 percent of the scaled top; Top right – smooth formed wavy bottom surface with a thin layer of fine subbase, and bottom row - cylindrical side view of the core with identification showing a crack at the mid-depth location probably formed during the coring operation.

METHODOLOGIES

PETROGRAPHIC EXAMINATIONS

The cores were 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 (1997a, b, 2001, 2004a, b, 2005a, b, 2006, 2007).

The steps of petrographic examinations include (Jana 2006):

i. Visual examinations of samples, as received;
ii. Low-power stereomicroscopical examinations of as-received, saw-cut and freshly fractured sections, and lapped cross sections of cores for evaluation of textures, and composition;
iii. Low-power stereomicroscopical examinations of air contents and air-void systems of concrete in the cores;
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. Photomicrographs of lapped section and thin section of sample taken from stereomicroscope and petrographic microscope (Figure 5), respectively to provide detailed compositional and mineralogical information of concrete.

Figure 5: Nikon Eclipse E600POL Petrographic Microscope with Jenoptik Gryphax Camera (left), Olympus SZH (middle), and Nikon SMZ-10A Stereomicroscope (right) used for petrographic examinations.

PETROGRAPHIC EXAMINATIONS

LAPPED AND SAW-CUT CROSS SECTIONS OF CORES

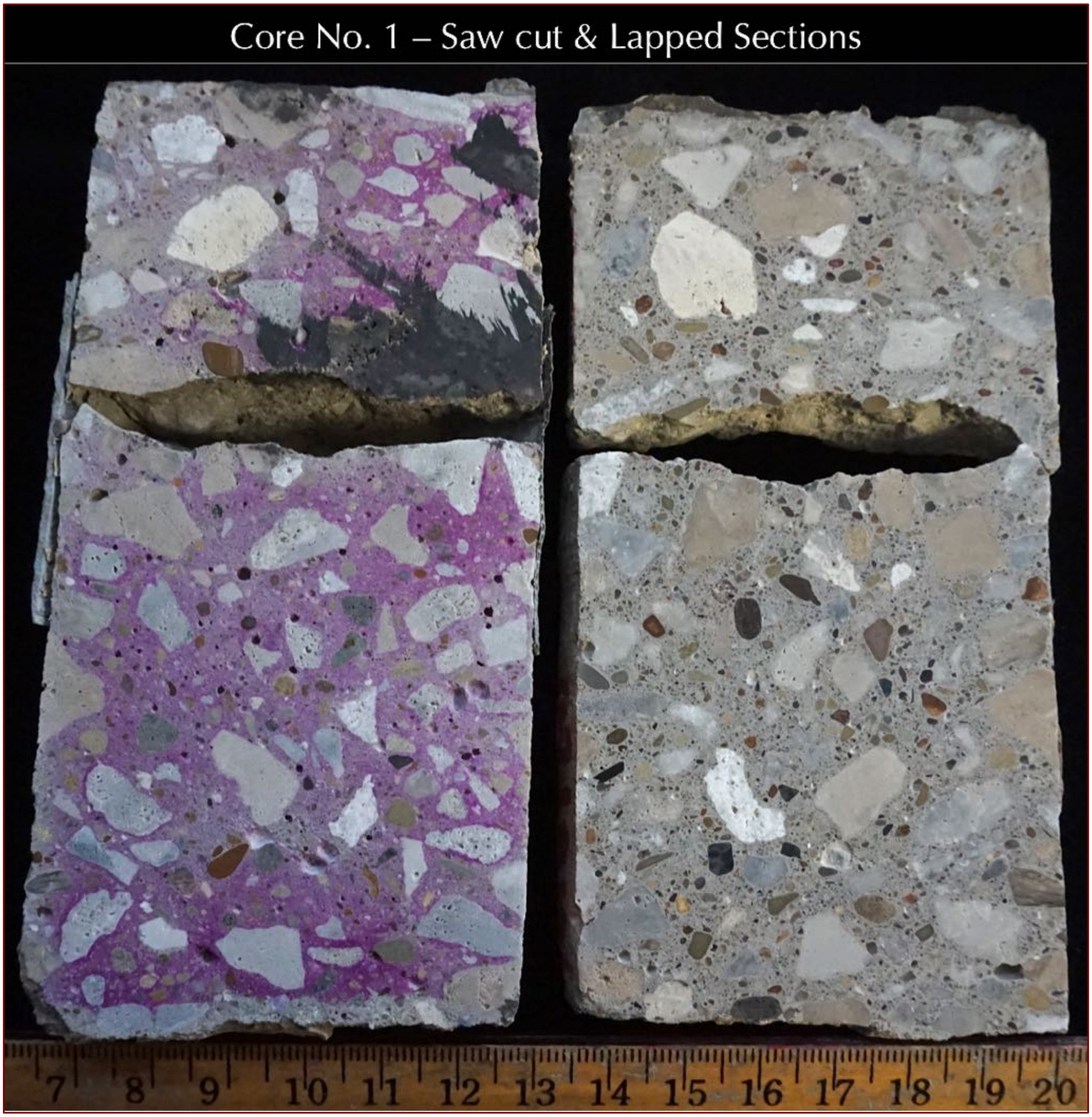

Figure 6: Saw-cut cross section at left after treatment with phenolphthalein alcoholic solution to show minimal carbonation of concrete at the surface region where concrete remains gray as opposed to interior non-carbonated concrete that turned pink, and, a lapped cross section at right of Core No. 1 showing distribution of crushed stone coarse aggregate, good grading and well-distribution of aggregates, and good consolidation of concrete.

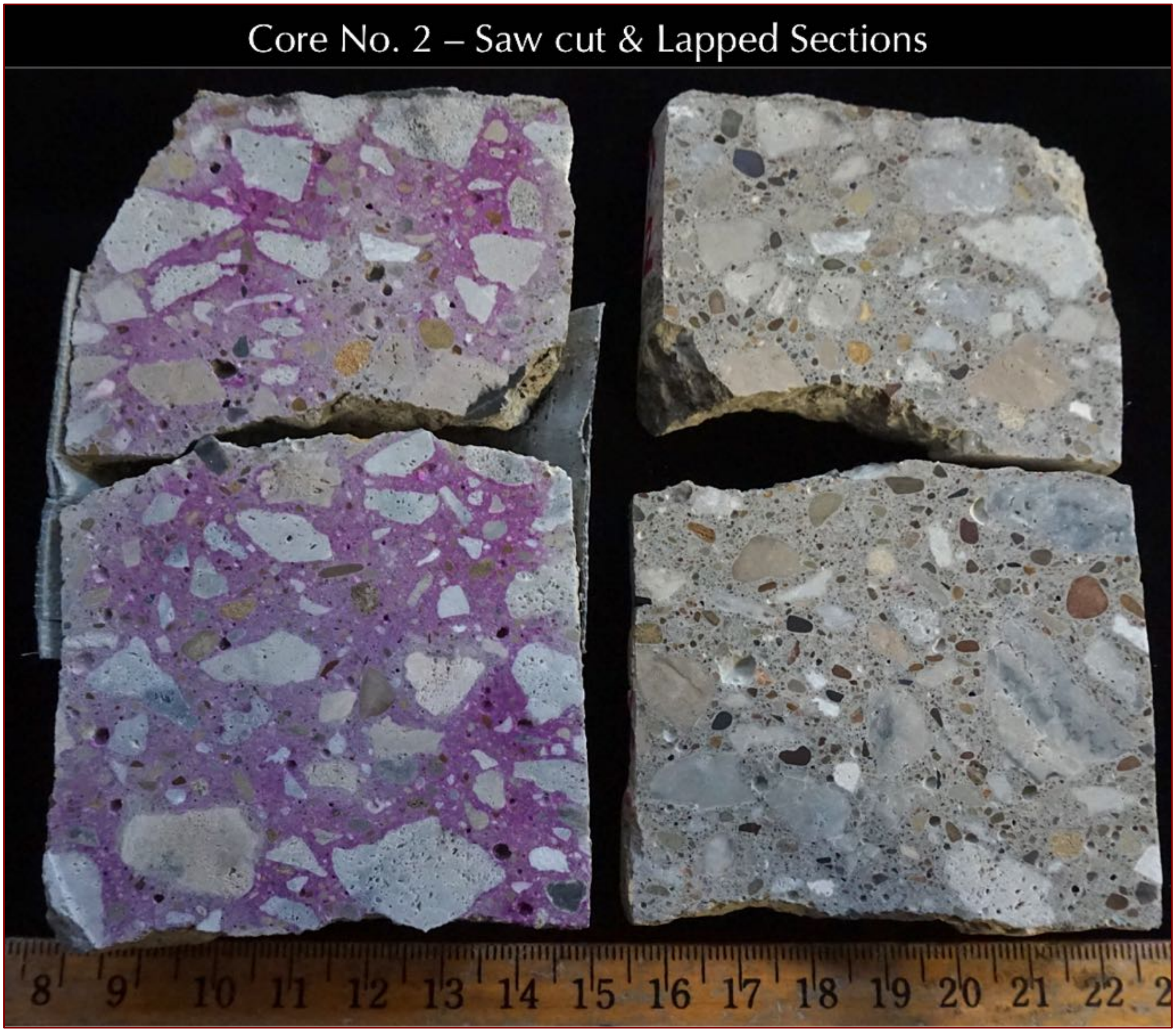

Figure 7: Saw-cut cross section at left after treatment with phenolphthalein alcoholic solution to show minimal carbonation of concrete at the surface region where concrete remains gray as opposed to interior non-carbonated concrete that turned pink, and, a lapped cross section at right of Core No. 2 showing distribution of crushed stone coarse aggregate, good grading and well-distribution of aggregates, and good consolidation of concrete.

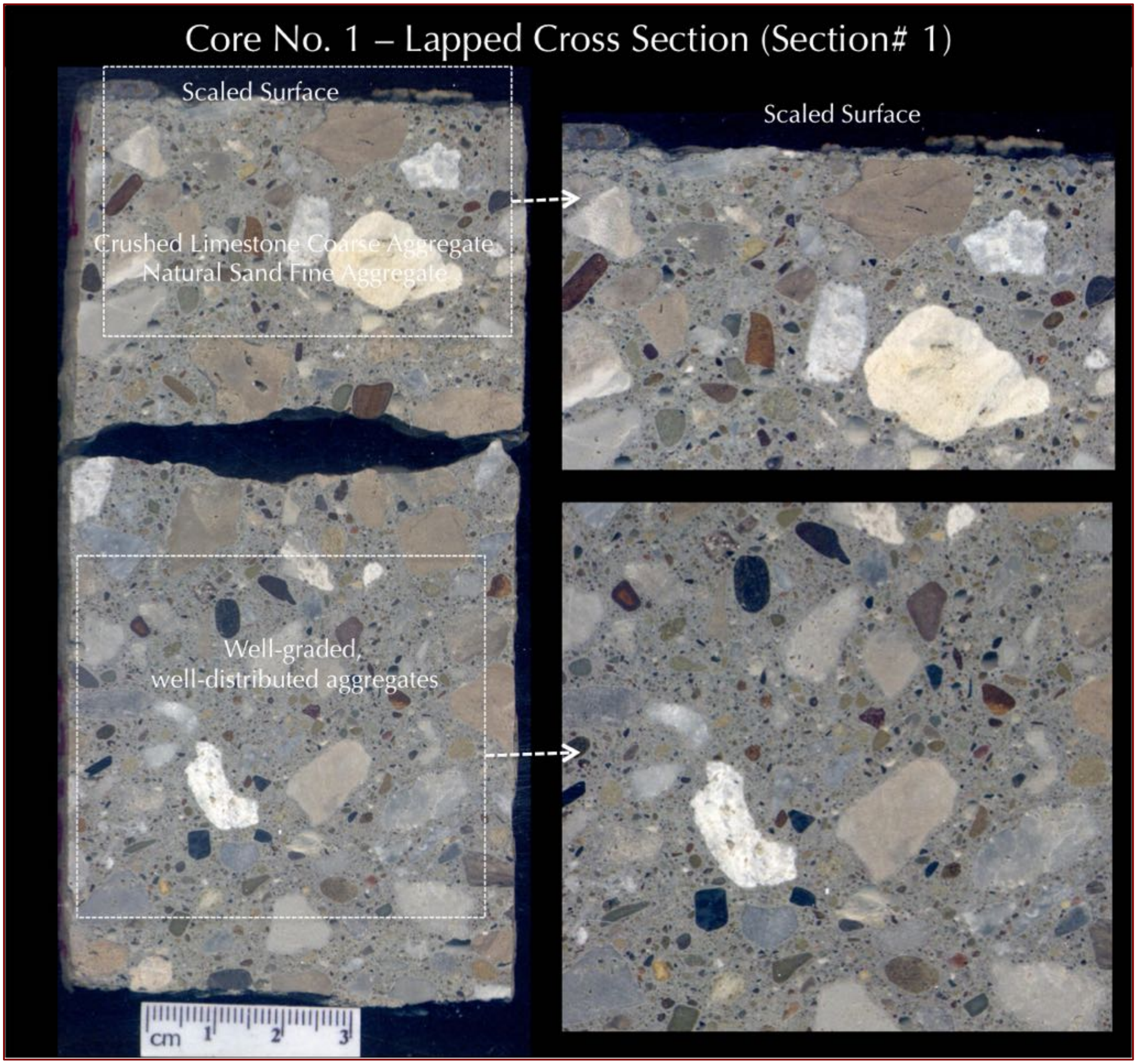

Figure 8: Lapped cross section of Core 1 showing #57 crushed stone coarse aggregate having a nominal maximum size of ¾ to 1 in., natural siliceous-calcareous sand fine aggregate, good grading and well-distribution of aggregates, and the overall sound, dense, well-consolidated nature of the concrete in the body. Right photographs are enlarged views of boxed areas from the left.

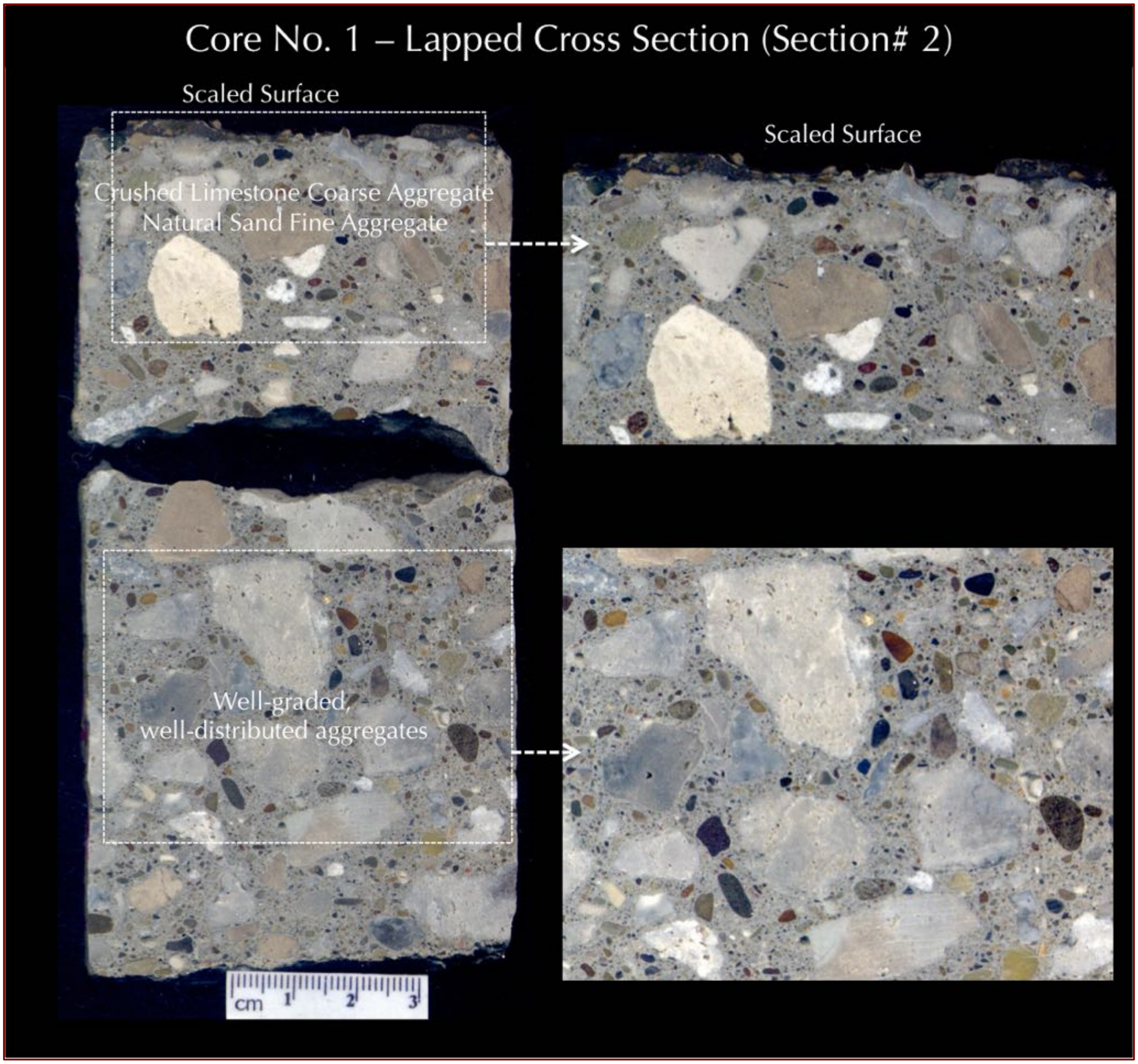

Figure 9: A second lapped cross section of Core 1 sectioned parallel to the first one shown in Figure 8 showing #57 crushed stone coarse aggregate having a nominal maximum size of $^3/_4$ to 1 in., natural siliceous-calcareous sand fine aggregate, good grading and well-distribution of aggregates, and the overall sound, dense, well-consolidated nature of the concrete in the body. Right photographs are enlarged views of boxed areas from the left.

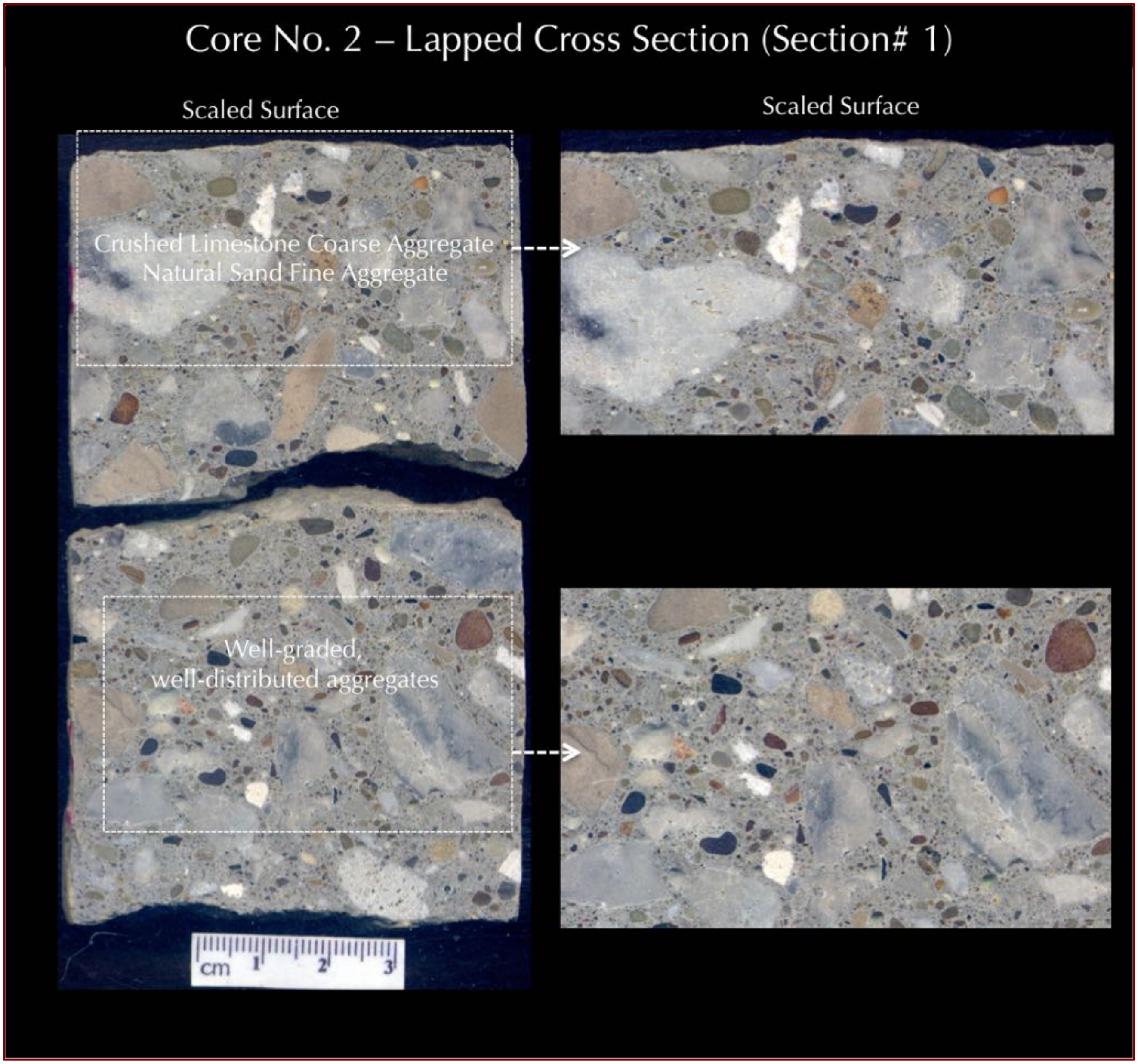

Figure 10: Lapped cross section of Core 2 showing #57 crushed stone coarse aggregate having a nominal maximum size of $^3/_4$ to 1 in., natural siliceous-calcareous sand fine aggregate, good grading and well-distribution of aggregates, and the overall sound, dense, well-consolidated nature of the concrete in the body. Right photographs are enlarged views of boxed areas from the left.

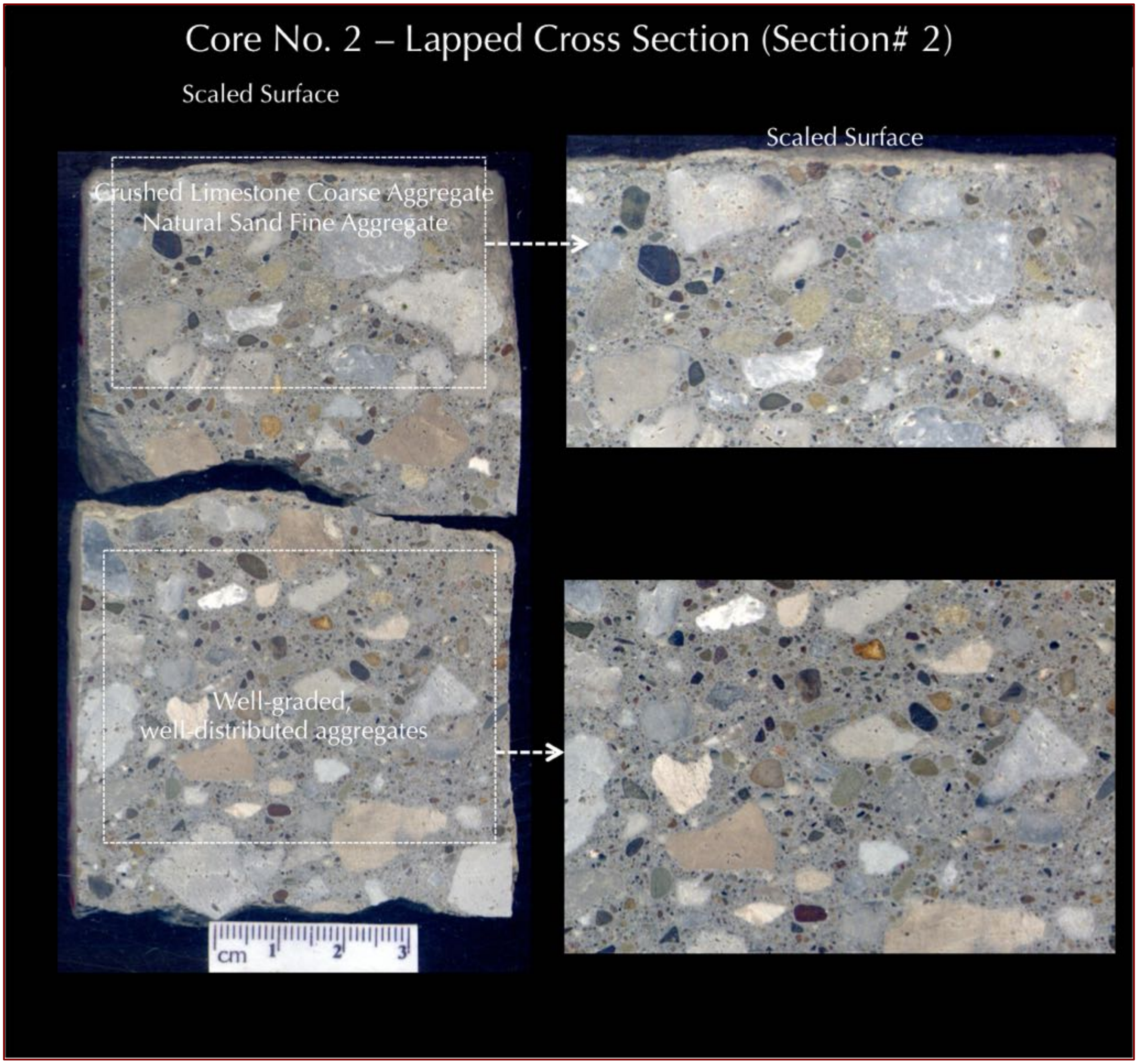

Figure 11: A second lapped cross section of Core 2 sectioned parallel to the first one shown in Figure 10 showing #57 crushed stone coarse aggregate having a nominal maximum size of $^{3}/_{4}$ to 1 in., natural siliceous-calcareous sand fine aggregate, good grading and well-distribution of aggregates, and the overall sound, dense, well-consolidated nature of the concrete in the body. Right photographs are enlarged views of boxed areas from the left.

PHOTOMICROGRAPHS OF LAPPED CROSS SECTIONS

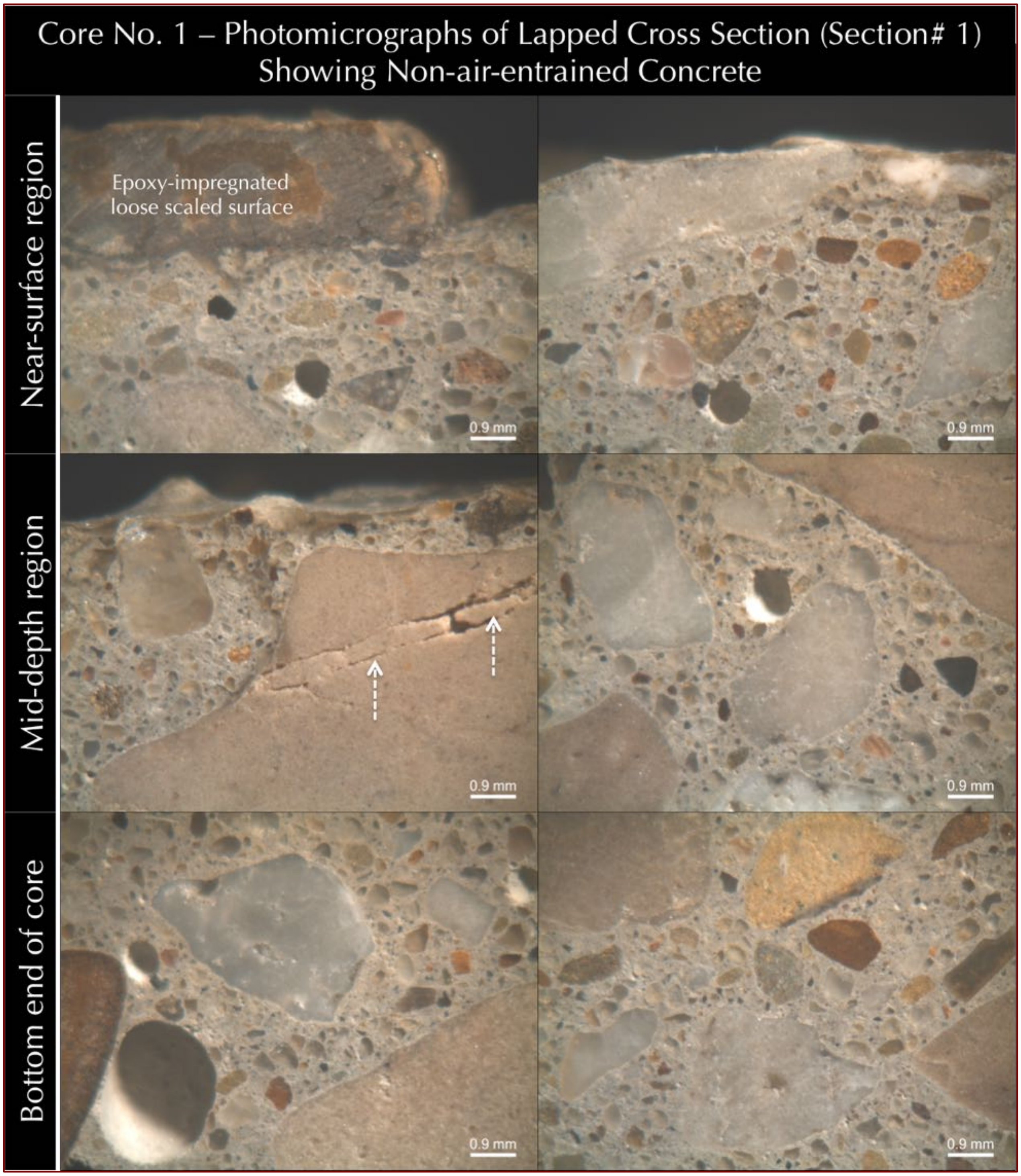

Figure 12: Photomicrographs of lapped cross section of Core 1 showing: (a) a thin coat of paste and aggregates in mud-cracked loose dried drill mud encapsulated in clear epoxy (top left), (b) scaled surface at the top (top row), (c) lack of air entrainment all throughout the depth of core showing absence of fine, discrete spherical entrained air voids except a few coarse entrapped air voids (all photos), and (d) near-surface fine microcracks (middle left).

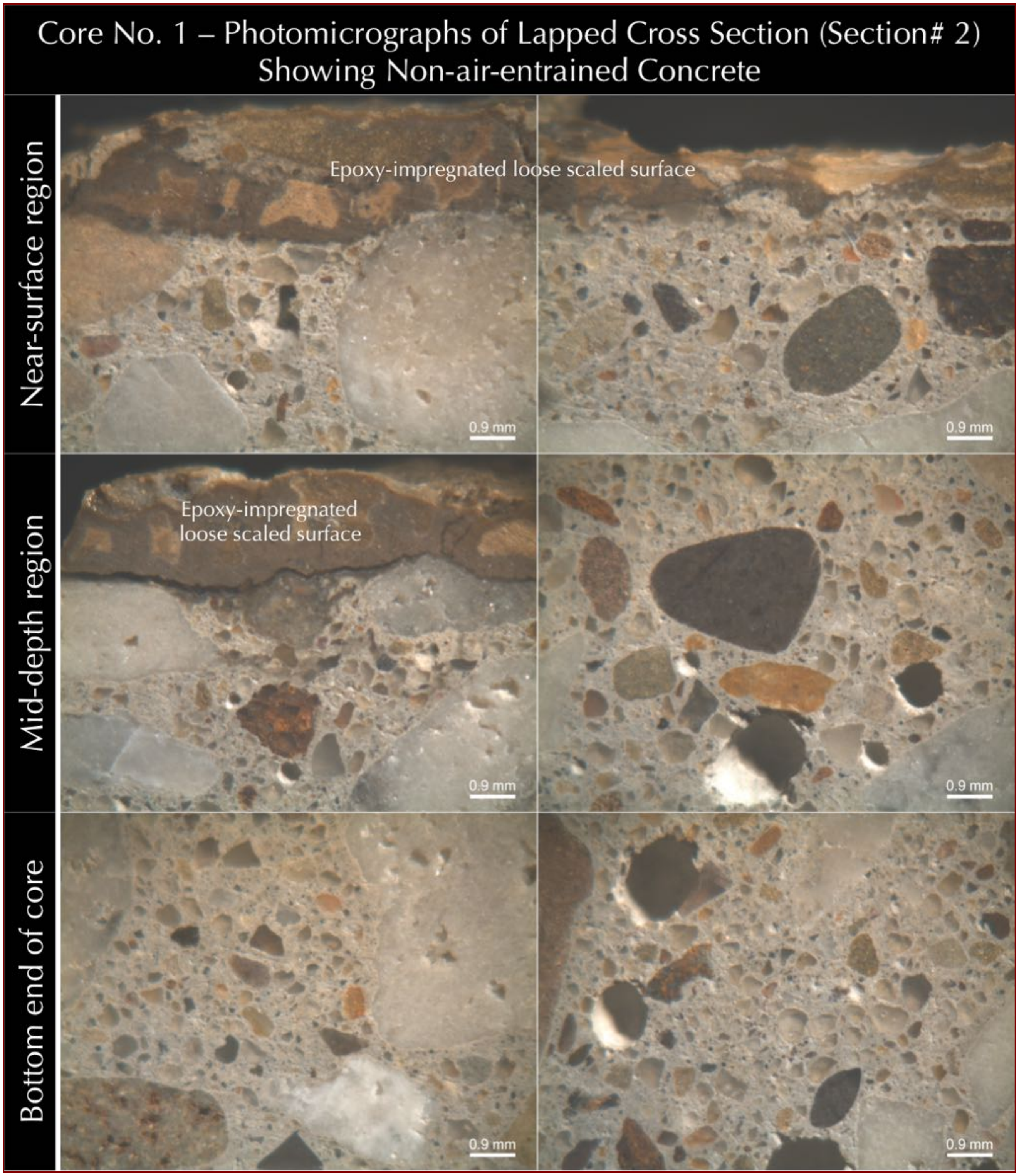

Figure 13: Photomicrographs of lapped cross section of Core 1 showing: (a) a thin coat of paste and aggregates in mud-cracked loose dried drill mud encapsulated in clear epoxy (top row and middle left photos), (b) scaled surface at the top (top row), and (c) lack of air entrainment all throughout the depth of core showing absence of fine, discrete spherical entrained air voids except a few coarse entrapped air voids (all photos).

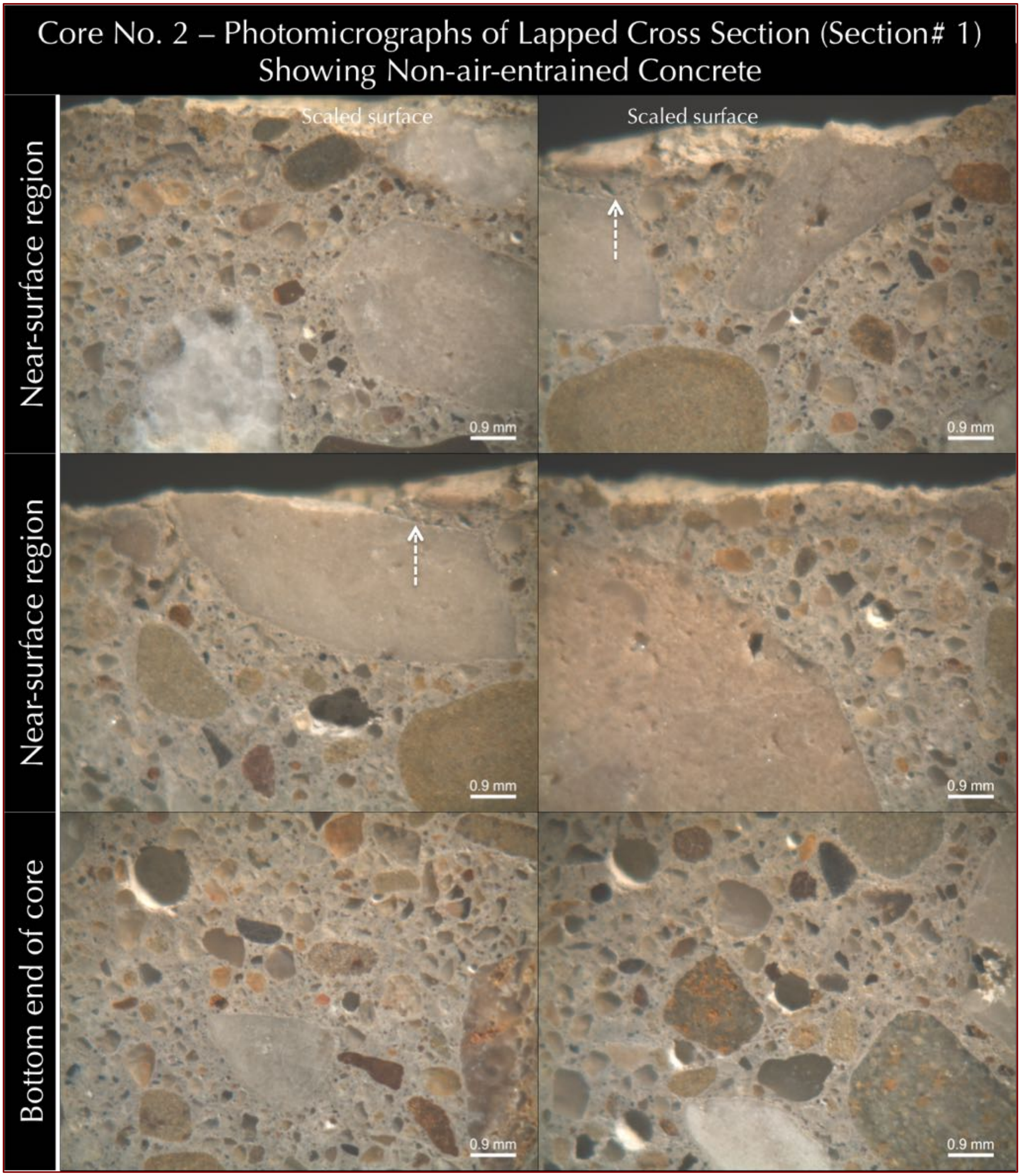

Figure 14: Photomicrographs of lapped cross section of Core 2 showing: (a) scaled surface at the top (top row), (b) lack of air entrainment all throughout the depth of core showing absence of fine, discrete spherical entrained air voids except a few coarse entrapped air voids (all photos), and (c) near-surface fine microcracks (top right and middle left photos).

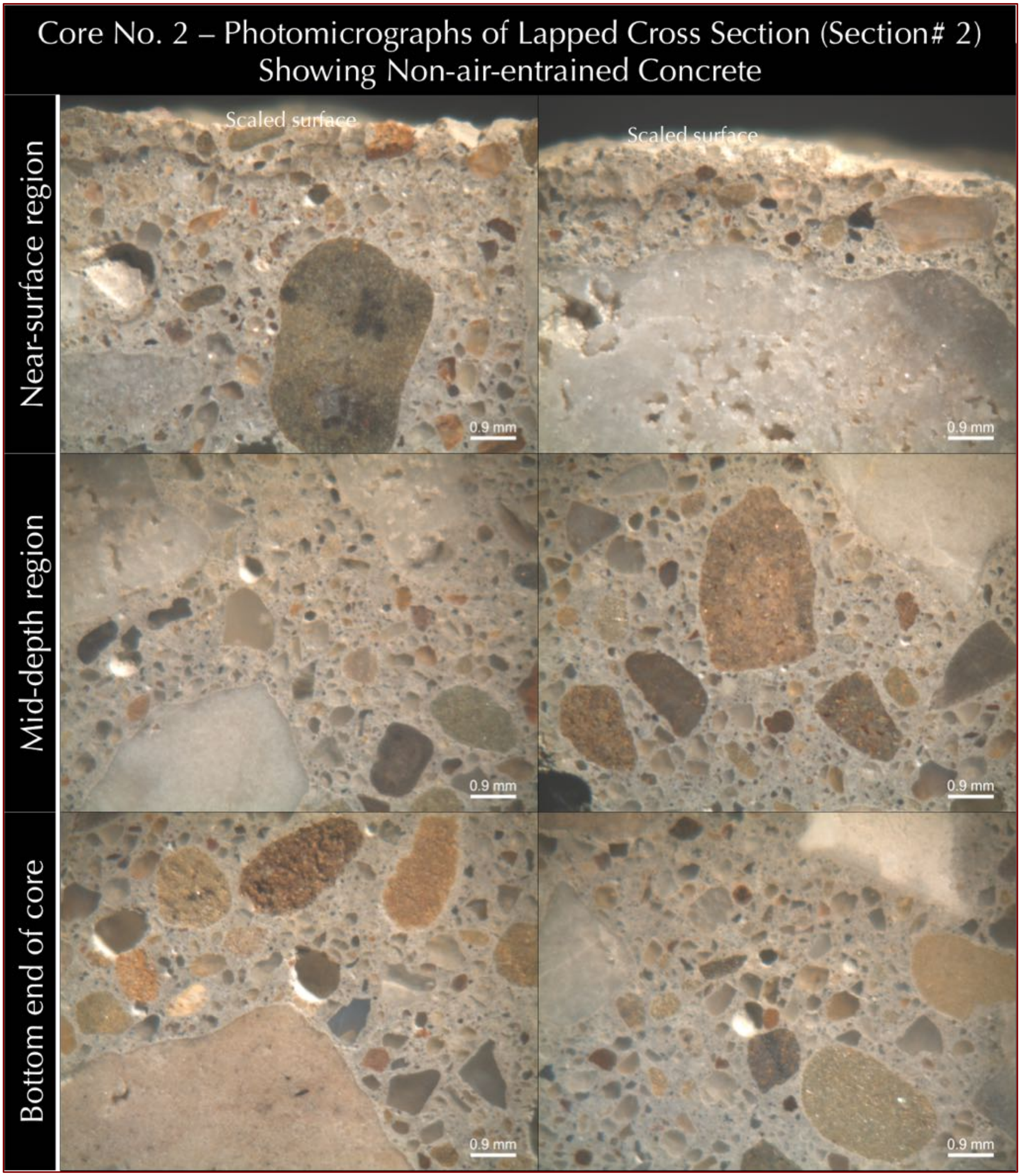

Figure 15: Photomicrographs of lapped cross section of Core 2 showing: (a) scaled surface at the top (top row), and (b) lack of air entrainment all throughout the depth of core showing absence of fine, discrete spherical entrained air voids except a few coarse entrapped air voids (all photos).

BLUE DYE-MIXED EPOXY-IMPREGNATED THIN SECTIONS

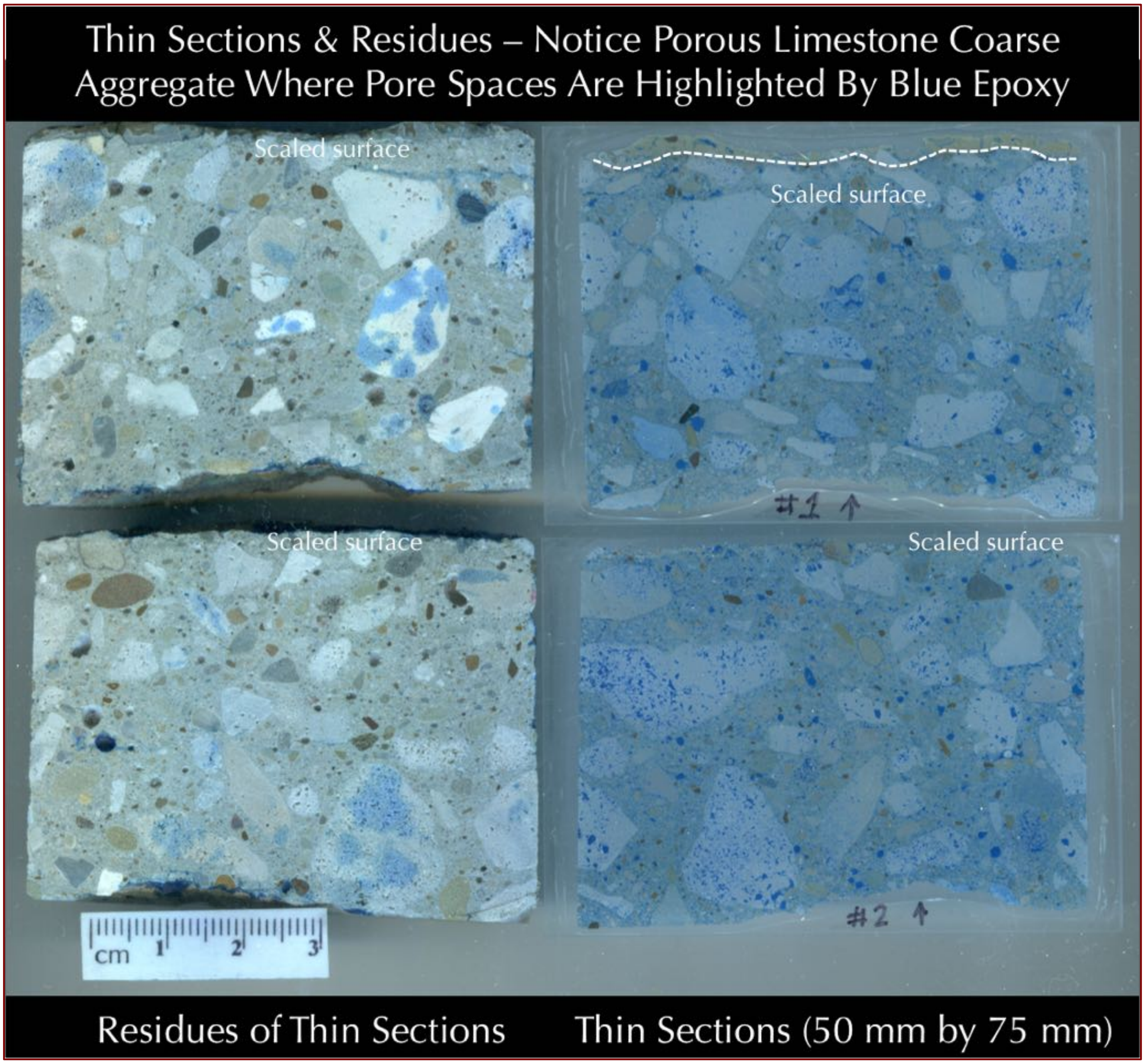

Figure 16: Blue dye-mixed epoxy-impregnated thin sections (right) and corresponding solid residues (left) after thin section preparation of the cores where lack of air entrainment and pore spaces in crushed stone coarse aggregate particles are revealed by highlighting the air voids and pore spaces that are filled with blue epoxy.

PHOTOMICROGRAPHS OF THIN SECTIONS

Core No. 1 – Photomicrographs of Thin Section Showing Porous Limestone Coarse Aggregate & Lack of Air Entrainment in Concrete

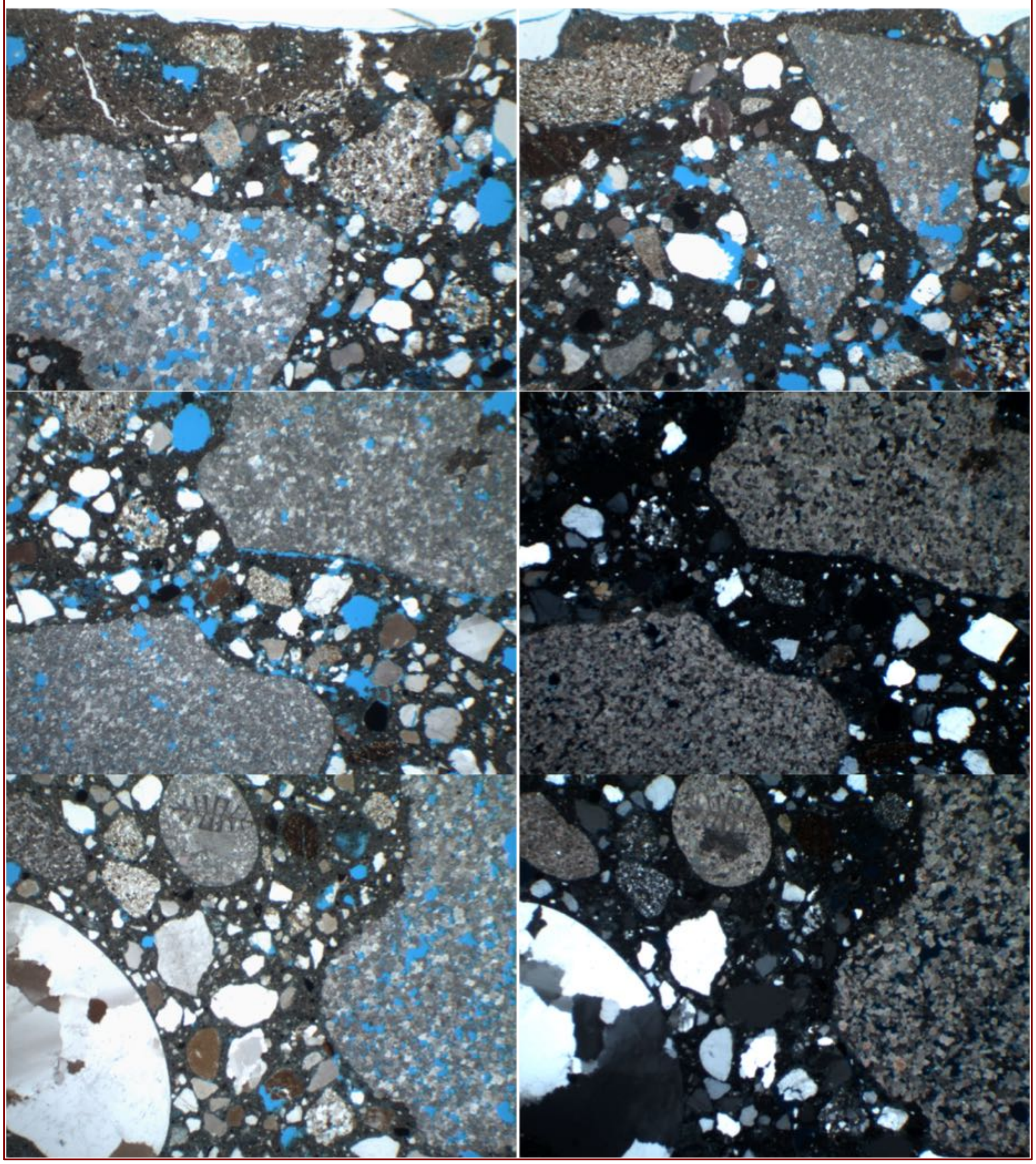

Figure 17: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of concrete in Core 1 taken from a transmitted-light Stereozoom microscope showing: (a) neat paste coat in dried mud layer with vertical shrinkage microcracks above the scaled surface (top row) (top row); (b) lack of air entrainment in concrete and pore spaces in crushed stone coarse aggregate particles highlighted by the blue epoxy, and (c) natural siliceous-calcareous sand fine aggregate.

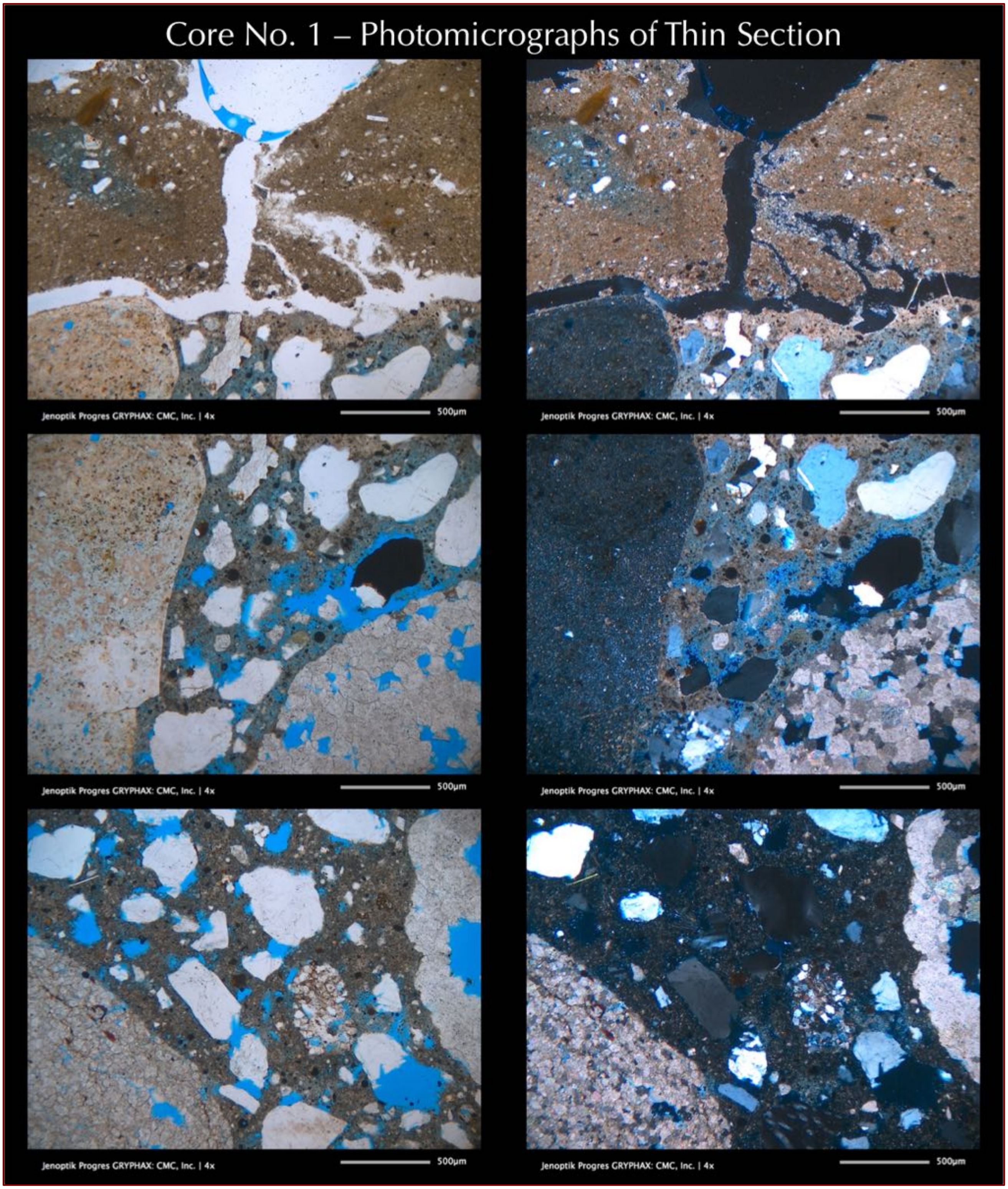

Figure 18: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of concrete in Core 1 taken from a petrographic microscope showing: (a) carbonated paste in dried mud-cracked coating above the scaled surface with shrinkage microcracks (top row); (b) carbonated concrete beneath the scaled surface (top and middle rows); (c) lack of entrained air but many irregularly-shaped and coarse voids in concrete highlighted by blue epoxy; and (d) crushed limestone-dolomite coarse aggregate and natural siliceous-calcareous sand fine aggregate. Right column photos are crossed polarized-light views of corresponding left column photos.

Core No. 2 – Photomicrographs of Thin Section Showing Porous Limestone Coarse Aggregate & Lack of Air Entrainment in Concrete

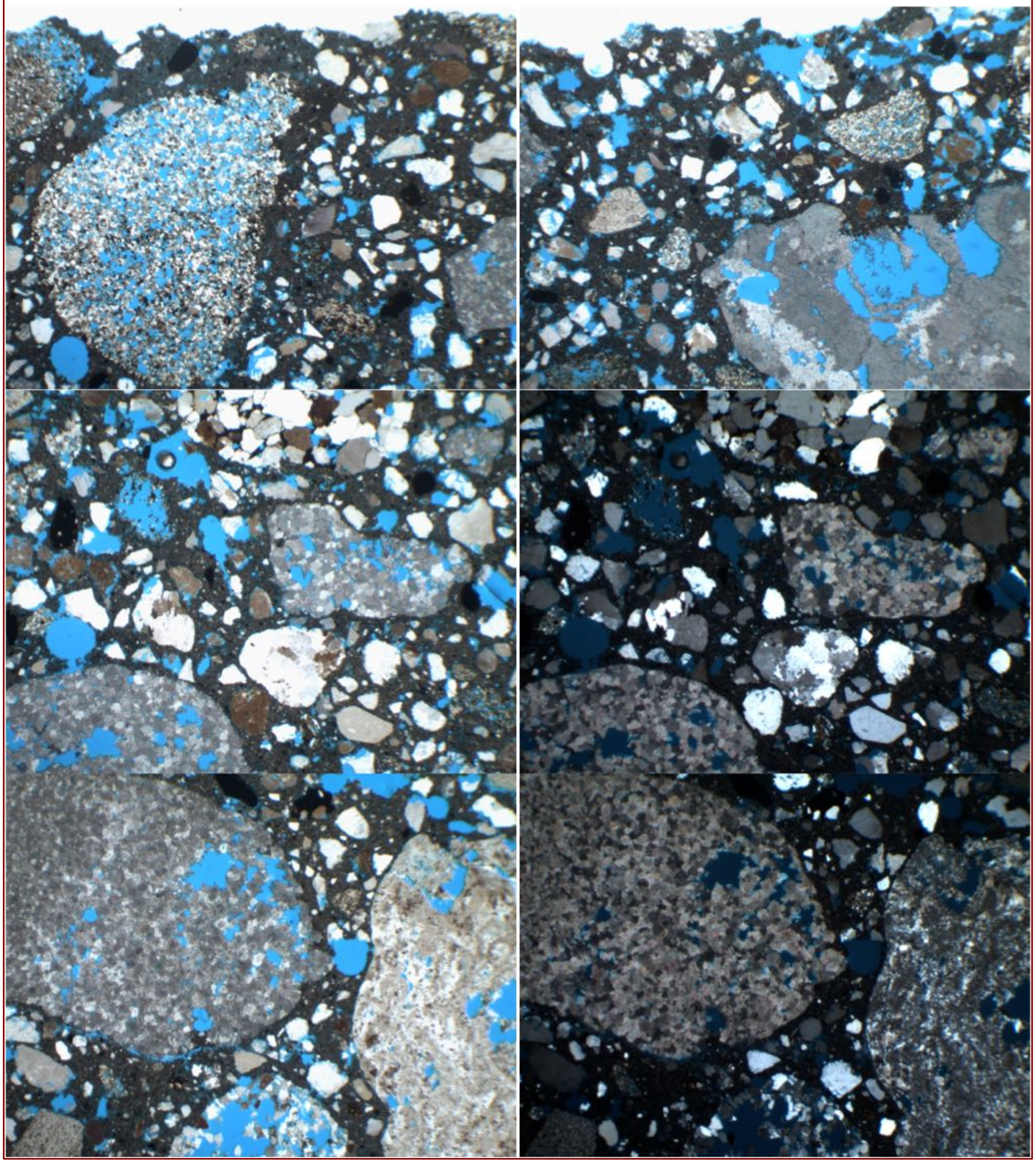

Figure 19: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of concrete in Core 2 taken from a transmitted-light Stereozoom microscope showing: (a) the scaled surface region (top row) (top row); (b) lack of air entrainment in concrete and pore spaces in crushed stone coarse aggregate particles highlighted by the blue epoxy, and (c) natural siliceous-calcareous sand fine aggregate.

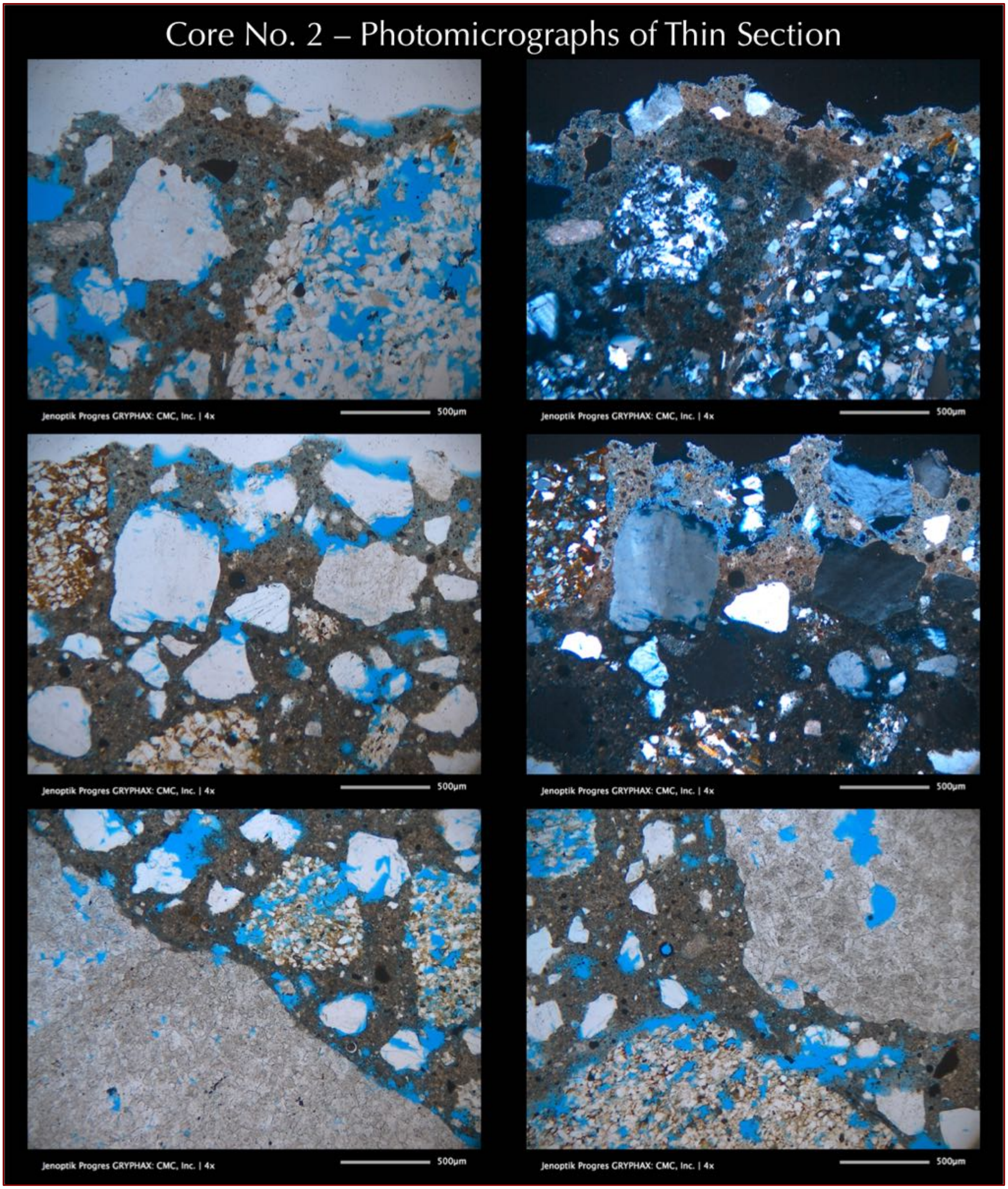

Figure 20: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of concrete in Core 2 taken from a petrographic microscope showing: (a) carbonated paste of concrete at the scaled surface region (top and middle rows); (b) lack of entrained air but many irregularly-shaped and coarse voids in concrete highlighted by blue epoxy; and (c) crushed limestone-dolomite coarse aggregate and natural siliceous-calcareous sand fine aggregate. Right column photos are crossed polarized-light views of corresponding left column photos.

COARSE AGGREGATE

Coarse aggregates are compositionally similar in both cores and made using mixtures of #57 and #8 crushed limestone-dolomite having nominal maximum sizes of $^3/_4$ to 1 in. and containing variably porous limestone, dolomitic limestone, and porous dolomite. Particles are medium to dark gray, variably dense due to the presence of pore spaces, hard, angular, massive textured, equidimensional to elongated, unaltered, uncoated, and uncracked. Coarse aggregate particles are well-graded and well-distributed. There is no evidence of alkali-aggregate reactions of coarse aggregate particles in the cores. Coarse aggregate particles have been sound during their service in the concrete. The presence of pore spaces within many particles, however, make them vulnerable to distress such as popout during freezing at saturated conditions, especially for the particles situated immediately beneath the surface that can absorb moisture within the pore spaces and expand during freezing. Field photos and top scaled surfaces of two cores, however, did not show any popout-type distress.

FINE AGGREGATE

Fine aggregates are compositionally similar natural siliceous-calcareous sands in both cores having major amounts of siliceous components (quartz, quartzite, feldspar, chert, siltstone), subordinate amounts of calcareous components (limestone, dolomite), and subordinate amount of argillaceous and ferruginous components (shale, ferruginous and argillaceous siltstone). Fine aggregates have nominal maximum sizes 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.

Properties and Compositions of Aggregates	Core No. 1	Core No. 2
Coarse Aggregate		
Types	Crushed Limestone-Dolomite	
Nominal maximum size (in.)	$^3/_4$ to 1 in. (19 to 25 mm)	
Rock Types	Variably porous limestone, dolomitic limestone, and porous dolomite	
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dense, hard, dark gray, massive textured, equidimensional to elongated	
Cracking, Alteration, Coating	Unaltered, Uncoated, and Uncracked	
Grading & Distribution	Well-graded and Well-distributed	
Soundness	Sound	
Alkali-Aggregate Reactivity	None	

Properties and Compositions of Aggregates	Core No. 1	Core No. 2
Fine Aggregate		
Types	Natural siliceous-calcareous sand	
Nominal maximum size (in.)	3/8 in. (9.5 mm)	
Rock Types	Major amounts of siliceous components quartz, quartzite, feldspar, chert, siltstone), subordinate amounts of calcareous components (limestone, dolomite), and subordinate amount of argillaceous and ferruginous components (shale, ferruginous and argillaceous 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 in two cores.

PASTE

Properties and composition of hardened cement pastes are summarized in Table 2. Paste in both cores is compositionally similar, light gray at the top 1 to 2 mm of scaled surface due to atmospheric carbonation, and light to medium gray in the interior body, moderately dense and moderately hard; freshly fractured surfaces of interior pastes 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 pastes in both cores are fine, discrete, spherical clear to light to dark brown to black glassy particles of fly ash having the fineness of Portland cement. Hydration of Portland cement is normal.

Properties and Compositions of Paste	Core No. 1	Core No. 2
Color, Hardness, Porosity, Luster	Light gray at the top 1 to 2 mm of scaled surface due to atmospheric carbonation, and light to medium gray in the interior body, moderately dense and moderately hard; freshly fractured surfaces of interior pastes have subvitreous lusters and subconchoidal textures	
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.	Fly ash	
Water-cementitious materials ratio (*w/cm*), estimated	0.55 to 0.60 at the scaled surface, 0.50 to 0.55 in the body	
Cementitious Materials Contents (bags per cubic yard)	5 1/2 to 6 bags of which 20 percent is estimated to be fly ash	
Secondary Deposits	None	

Properties and Compositions of Paste	Core No. 1	Core No. 2
Depth of Carbonation, mm	2 to 3 mm	1 to 2 mm
Microcracking	None except in the top mud-cracked coat of dried drill mud	A few at the scaled surface
Aggregate-paste Bond	Tight	
Bleeding, Tempering	None	
Chemical deterioration	None	

Table 2: Proportions and composition of hardened cement paste in two cores.

The textural and compositional features of the pastes are indicative of cementitious materials contents estimated to be equivalent to $5^1/_2$ to 6 bags of Portland cement per cubic yard of which 20 percent is estimated to be fly ash, and, water-cementitious materials ratios (*w/cm*) estimated to be 0.55 to 0.60 at the scaled surface regions and 0.50 to 0.55 in the body.

There is no evidence of any deleterious deposits found in the cores. Carbonation is shallow 1 to 3 mm, which, however, does not represent the true depth due to loss of the original finished surface. Bonds between the coarse and fine aggregate particles and paste are tight. There is no evidence of microcracking in the interior bodies of the cores due to deleterious reactions.

The overall quality and condition of the concrete in the interior bodies of the cores i.e. beneath the scaled surface are judged to be sound (except lack of air entrainment described below which makes concrete vulnerable to scaling) with no evidence of any physical or chemical deterioration in the bodies of the cores.

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. There is no evidence of the presence of any entrained air voids in the concrete in any of the two cores that are characterized by fine, discrete, spherical and near-spherical voids of sizes 1 mm or less. Air-void systems of concretes in the cores are suggestive of lack of intentional addition of an air-entraining agent in the mix, as opposed to the reported mix design that calls for addition of an air-entraining agent.

Air contents are similar in both cores and estimated from petrographic examinations to be 1 to 2 percent, as opposed to reported design air contents of 4.5 to 7.5 percent and air entrainment of concrete. Lack of air entrainment in both cores show serious deviations from reported air entrainment in the mix design, which is judged to be the primary factor for observed and reported scaling of concrete due to cyclic freezing and thawing of a non-air-entrained concrete at critically saturated conditions.

Figures 12 through 15 show numerous photomicrographs of concrete in both cores throughout the depths where lack of air entrainment and overall non-air-entrained natures of concrete through depths are obvious.

DISCUSSIONS

The following paragraphs discuss various factors that are important for investigation of concrete surface scaling.

AIR CONTENTS AND AIR-VOID SYSTEMS

Concrete in the examined cores showed evidence of lack of an air-entraining agent to have only 1 to 2 percent estimated air content, as opposed to reported design air contents of 4.5 to 7.5 percent and air entrainment of concrete. Lack of air entrainment in both cores show serious deviations from reported air entrainment in the mix design, which is judged to be the primary factor for observed and reported scaling of concrete due to cyclic freezing and thawing of a non-air-entrained concrete at critically saturated conditions.

The non-air-entrained nature of concrete in both cores is contrary to the reported mix design, which indicates use of an air-entrained concrete having an estimated air content range of 4.5 to 7.5 percent. By contrast, concrete in both cores show no evidence of addition of any air entraining agent, which makes the concrete vulnerable to scaling during cyclic freezing and thawing at critically saturated conditions, especially in the presence of deicing chemicals.

AGGREGATES

The crushed limestone-dolomite coarse aggregates and natural sand fine aggregates are present in sound conditions and did not contribute to the observed surface issues. The presence of pore spaces within many particles, however, make them vulnerable to distress such as popout during freezing at saturated conditions, especially for the particles situated immediately beneath the surface that can absorb moisture within the pore spaces and expand during freezing. Field photos and top scaled surfaces of two cores, however, did not show any popout-type distress

PLACEMENT, FINISHING, AND CURING

Field photographs of concrete scaling showed sheet-type scaling where original finished surface is loosely bonded at some locations to the body, which is due to premature finishing operations prior to the cessation of bleeding. A non-air-entrained concrete bleeds more and longer than an air-entrained concrete and thus increases the potential for bleed water accumulation beneath the finished surface if finishing operation starts prior to the cessation of bleeding. Such bleed water accumulation can cause sheet-like scaling of the finished surface due to the weak bond between the finished surface and the body.

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 aggregates during placement. There is, therefore, no evidence of any improper consolidation practice of slab at the locations of the examined cores.

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. The scaled surface of examined cores show no evidence of inadequate curing of concrete, e.g., no evidence of restricted cement hydration at the surfaces at least to cause the reported surface issues, however, cannot be examined properly due to the loss of the original finished surface.

COMPRESSIVE STRENGTH & 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 is, therefore, needed to be 'matured' prior to the first exposure of freezing, especially during the winter weather constructions. Due to the reported placement of slab in July to September the concrete is judged to have achieved the necessary maturity in terms of the amount of freezable water prior to the first exposure to freezing, salt, and snow. Portions of slab reportedly placed in the winter months, however are susceptible to scaling if freezing has occurred at critically saturated conditions prior to the attainment of maturity. Lack of air entrainment would aggravate the situation.

WATER-CEMENTITIOUS MATERIALS RATIO AND DURABILITY

The estimated water-cementitious materials ratios (*w/cm*) of concrete at the surface regions of cores are higher than that in their interiors, which is indicative of a soft, porous paste at the surface region, perhaps due to finishing in the presence of bleed water at the surface and/or addition of water during finishing. Interior *w/cm*, though similar to the reported design *w/cm* of 0.51 is still higher than the common industry (e.g., ACI)-recommended maximum ratio of 0.45 (preferably 0.40) for an outdoor concrete exposed to freezing, salt, and snow. Along with air entrainment, the primary defense of an outdoor concrete to stay durable in a moist environment of salt and snow it should also have the lowest possible *w/cm*, preferably around 0.40 and remain workable, especially when the concrete was designed to have multiple water-reducing admixtures, e.g., 2.0 oz/cwt Grace WRDA 20 water-reducing admixture, 4.0 to 8.0 oz/cwt Grace ADVA 140M mid-range water-reducer, and optional 2.5 to 4.5 oz/cwt Grace ADVA 190 high-range water-reducer. Addition all those chemical admixtures where water is an integral part of those admixtures requires an adjustment of batch water content without which concrete would end up having a high *w/cm* beyond the industry-recommended maximum limit of 0.45. Despite having a good reported mix design of an air-entrained concrete containing many water-reducing chemicals, the need for a design *w/cm* of 0.51 is unrealistic especially in a moist outdoor environment of freezing, along with total absence of the air entraining chemical in the cores when the concrete was designed to have 1.0 oz/cwt of Grace Darex II air-entraining admixture to stabilize 4.5 to 7.5 percent air.

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).

Premature exposures to salts i.e. prior to the attainment of maturity of concrete (i.e. a period of air drying and a compressive strength of at least 4000 psi before first exposure of salt and snow) can enhance surface scaling especially when finishing operations may have forced some water addition to improve workability of a sticky unworkable high-air concrete mass. However, 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 from the concrete surface.

Due to the lack of air entrainments in both cores deicing salts can aggravate surface scaling. Portions of slab placed in the winter month can cause scaling from premature applications of salts prior to the attainment of maturity.

BENEFICIAL ASPECT 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 adequate durability. 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 from the absence of air entrainment. 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 constructed 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 when concrete surface has poor scaling resistance. The examined cores examined showed no evidence of any sealer, which, however, is not possible to examine due to the total loss of the original finished surface in the scaled top of the cores received.

CONCLUSIONS

Based on detailed laboratory investigations, the reported surface scaling of concrete slab from field photographs to examined cores are judged to be due to a combination of one of several of the following factors:

a. **Lack of air entrainment in concrete**, which has affected the durability of concrete in a moist outdoor environment exposed to cyclic freezing and thawing at critically saturated conditions.

b. **Premature finishing prior to the cessation of bleeding** that has created sheet scaling of the finished surface from the body at some locations as seen in field photos, as well as **finishing with excess water at the surface** to soften the surface region.

c. **Potential exposures to chloride-containing deicing salts**, where non-air-entrained nature of concrete will aggravate salt-scaling distress of concrete, especially if salts were applied at an early stage prior to the attainment of concrete maturity.

Due to the lack of air entrainment all throughout the depths of cores, scaling will continue during future winter months of cyclic freezing and thawing at critically saturated conditions.

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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.