CONSTRUCTION MATERIALS CONSULTANTS, INC.

Investigation of Surface Distress Of Concrete Slabs – A Comprehensive Study From Petrography, Chloride-Sulfate Profiles, and Compressive Strength Tests

Norbeck Crossing HOA
Silver Spring, Maryland

May 18, 2021
CMC 0421119

TABLE OF CONTENTS

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

The present investigation involves premature degradation of concrete sidewalks and roadway curbs in a residential development located at Norbeck Crossing in Silver Spring, Maryland. The alleged surface distress of concrete has ranged from: (a) various degrees of *surface scaling* of concrete as loss of the original finished surface of concrete and exposures of near-surface coarse aggregate particles, to (b) isolated occurrences of exposures of near-surface coarse aggregate particles as *mortar lift-offs* and/or *pop outs*, to (c) thin *sheet-like scaling* of the original finished surface where many such 'sheets' of finished surfaces are only loosely adhered to the main body. All these distress have reportedly occurred within two years of concrete placement between 2015 and 2017.

As a result, eight concrete cores were collected from different areas and provided for various laboratory tests. Locations of cores and the observed surface conditions in the field at the core locations as well as on the core top surface received are as follows:

Core ID	Core Location	Slab Surface Condition in Field Photos	Core Top Surface
1	3606 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles	Sound, fine broom-finished surface despite retrieval from a severely scaled area
2	3628 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles	Broom-finished, with 3 mortar lift-offs, $^3/_8$ in. size
3	Mailbox near 15711 Murpheys Tin	Isolated mortar lift-off and/or pop out	Finished, 1 small pop-out ($^1/_8$ in. size) otherwise sound
4	Near dog waste station at Doc Berlin tot lot	Severe surface scaling and exposures of near-surface coarse aggregate particles and thin sheets of original finished surface loosely adhered to the main body	Sound, fine broom-finished surface but the entire surface is detached from the main body, only loosely adhered as a thin sheet to the main body
5	3624 Summer House	Severe surface scaling and exposures of near-surface coarse aggregate particles	Sound, fine broom-finished surface despite retrieval from a severely scaled area
6	Corner of Maven and Clara Downey	Sound, fine broom-finished surface	Sound, fine broom-finished surface for collection from a sound area, with beige discoloration of paste at top 2 mm
7	3710 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles	Finished, 1 small mortar lift-off or pop out ($^1/_8$ in. size) otherwise sound
8	3500 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles	Isolated mortar lift-off with exposure of near-surface coarse aggregate particles

Cores 2 and 6 were requested for detailed petrographic examinations according to the procedures of ASTM C 856. Core 3 was requested for compressive strength test according to the procedures of ASTM C 42. Cores 1, 2, 5, 6, 7, and 8 were selected for water-soluble chloride and sulfate content analyses by ion chromatography according to the procedures of ASTM D 4327. Core 4 was kept in reserve.

Based on detailed petrographic examinations of concretes in Cores 2 and 6, concretes in both cores are found to be compositionally similar and made using the same solid ingredients of coarse and fine aggregates, and binary Portland cement and ground slag based cementitious materials indicating use of the same or similar concrete mix.

Coarse aggregates are compositionally similar in both Cores 2 and 6, which are #57 crushed limestone. Limestone particles are angular, dense, hard, $^3/_4$ in. (19 mm) in nominal size, often contain fine dark brown argillaceous veins. Particles are equidimensional to elongated, unaltered, uncoated, uncracked, well-graded, and well-distributed. There is no evidence of alkali-aggregate reactions or any other potentially deleterious reactions of limestone aggregates found in the concrete to cause the observed surface distress. Therefore, coarse aggregate particles have been sound during their service in the concrete and did not contribute to the distress. The argillaceous impurities detected in the limestone are judged inefficient to cause pop out or other distress in the near-surface particles at least at the locations of Nos. 2 and 6.

Fine aggregates are compositionally similar natural siliceous sands having nominal maximum sizes of $^3/_8$ in. (9.5 mm) and made using major amount of quartz and subordinate amounts of quartzite, feldspar, siltstone, shale and other particles. Particles are variably colored, rounded to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and mostly 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 and did not contribute to the distress.

Hardened pastes are dense, hard, medium gray. Freshly fractured surfaces have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 10 to 12 percent of the paste volumes in the interior bodies. Distributed throughout the paste are angular, shard-like, glassy particles of ground granulated blast furnace slag having the fineness of Portland cement. Hydration of Portland cement is normal. The textural and compositional features of paste are indicative of total cementitious materials contents estimated to be equivalent to 7 to $7^1/_2$ bags of Portland cement per cubic yard of which 25 to 30 percent is estimated to be ground granulated blast furnace slag, and water-cementitious materials ratios (*w/cm*) estimated to be 0.40 to 0.44 except at the top 5 to 6 mm of the wearing surface, where *w/cm* is estimated to be higher than that in the interior, estimated to be around 0.45 to 0.50. Compared to the interior, the higher *w/cm* at the wearing surface regions are judged to be due to either finishing in the presence of excess bleed water at the surface and/or addition of water during finishing. Both practices reduce the overall wear resistance and freeze-thaw durability of the surface. Depth of carbonation of concrete is measured to be 5 to 6 mm from the exposed ends. Bonds between aggregates and paste are tight. There is no evidence of any potentially deleterious secondary deposits or evidence of any deleterious chemical reactions found. There is also no evidence of any microcracking due to any deleterious reactions found in the pastes.

Concrete in both Cores 2 and 6 are air-entrained having air contents similar in both cores and through the depths and estimated to be 6 to 7 percent by volume. Air occurs as: (i) numerous very fine (< 100 micron) to fine (100 micron to 1 mm) discrete, spherical and near-spherical voids having sizes of up to 1 mm, and (ii) a few coarse, near-spherical and irregularly shaped voids of sizes coarser than 1 mm. The former voids are characteristic of entrained air and the latter ones are characteristic of entrapped air. Air-void systems in both cores are judged to be excellent for providing the necessary protection of concrete against distress due to cyclic freezing and thawing at critically saturated conditions, particularly in the presence of deicing chemicals. The observed surface distress of concrete is judged at least not due to the lack of entrained air, or inadequate entrained air in the concrete at least at the locations of Core Nos. 2 and 6 where the air-void systems were examined in detail.

Water-soluble chloride and sulfate contents of concretes are determined from ion chromatography (*a la* ASTM D 4327) on pulverized sections from the top exposed ends, and at mid-depth locations of Cores 1, 2, 5, 6, 7, and 8. All cores showed clear evidence of distinctly higher chloride and sulfate contents at the exposed surface ends compared to results obtained from the interiors, indicating exposures to chloride and sulfate salts during service.

Compressive strength of concrete in Core 3 is determined to be 4910 psi. 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. The 4910-psi compressive strength of Core 3 is adequate for attainment of maturity as long as the concrete received at least 4000 psi strength within the first month of placement and a period of air drying prior to the first exposure of winter, salt, and snow.

Air-void parameters are judged in conformance to the common industry requirements for concretes from an outdoor environment exposed to freezing, thawing, and deicing chemicals in a moist environment, where the concrete should have a total air content in the range of 4.5 to maximum 7.5 percent. The other air-void parameters that are more crucial for freeze-thaw durability of concrete than the total air are the air-void specific surface, which measures the 'fineness' of air-voids, and, air-void spacing factor, which measures the 'closeness' of voids. Both these parameters are judged satisfactory and in conformance to common industry recommendations.

The crushed limestone coarse aggregate and natural siliceous (quartz-quartzite) sand fine aggregate particles in Cores 2 and 6 are present in sound conditions and did not contribute to the observed distress. These coarse and fine aggregate should not cause any pop out from unsoundness unless the amount of argillaceous impurities are higher in the near-surface particles than the ones found in Cores 2 and 6. Therefore, any distress that resembles pop outs i.e., having fractured remains of underlying near-surface aggregate could possibly be a mortar lift-off rather than a pop out, where the original finished surface was lifted off from the flat topside of underlying sound limestone aggregates due to the weak bond between the finished surface and the underlying aggregate than any expansion or unsoundness of the aggregate itself. Aggregates, therefore, are not responsible for the distress.

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 location of this 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. Cores 2 and 6 showed 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 scaling.

Petrographic examinations of Cores 2 and 6, however, found evidence of higher *w/cm* at the very top 5 to 6 mm resulting in lighter toned paste from the interior which could have formed from addition of water during finishing and/or finishing in the presence of bleed water at the surface. Such practices can reduce the overall freeze-thaw durability and wearing resistance of surface despite having a good air entrainment.
Additionally, there is evidence of premature finishing, i.e., finishing prior to the cessation of bleeding as sheet-scaling, which forms due to accumulation of bleed water beneath the finished surface eventually causing separation of the top thin sheet of finished surface from the main body of concrete to cause sheet-scaling.

Results of water-soluble chloride and sulfate profile analyses from the top wearing surface regions and the interior bodies of Cores 1, 2, 5, 6, 7, and 8 showed higher chloride and sulfate contents at the wearing surface regions compared to bodies indicating exposures to chloride and sulfate salts at the surface during service, which can potentially cause and/or aggravate the distressed wearing surfaces.

Based on detailed laboratory investigations, the observed and reported surface distress of concrete slab are judged to be due to one or a combination of the following factors:

a. Improper finishing practices leading to less durable wearing surface compared to interiors in having higher *w/cm* pastes at the exposed surfaces compared to interiors, at least at the locations of Cores 2 and 6;
b. Premature finishing prior to the cessation of bleeding causing accumulation of bleed water beneath the finished surface, at least at the location of Core 4;
c. Inadequate embedding of the near-surface coarse aggregate particles causing exposures of flat topsides of near-surface crushed limestone particles due to the presence of weak bonds between the flat topsides of near-surface coarse aggregate and the thin sheet of finished surface above those particles to cause mortar lift-offs, at least at the locations of Cores 2, 3, 5, 7, and 8;
d. Pop outs due to moisture-induced expansions of near-surface argillaceous limestone coarse aggregate particles can also occur, which, however, is not found in the cores examined here; and,
e. Exposures to potentially deleterious chloride and sulfate-based salts during service, which can cause and/or aggravate the surface conditions especially during cyclic freezing and thawing.

Due to the presence of sound, air-entrained good interior concretes at least in Cores 2 and 6 that were examined by petrography, majority of the interior of the slab is still serviceable and durable as long as the distressed surface regions can be repaired with sound, durable repair materials well-bonded to the interior concrete. All cores tested for potential exposures of chloride showed clear evidence of application of deicing salts, which can interfere with the performance and durability of concrete unless the distressed surfaces are protected with a durable repair coat. Presence of good air-void systems in the concretes in Cores 2 and 6 justify keeping the slabs without replacement with some necessary repairs of the distressed areas, at least at the locations of 2 and 6 where air-void systems were examined.

INTRODUCTION

Reported herein are the results of detailed laboratory studies of eight (8) concrete cores received from outdoor distressed residential concrete sidewalks and curbs at Norbeck Crossing HOA in Silver Spring, Maryland.

BACKGROUND INFORMATION

Premature degradation of concrete sidewalks and roadway curbs in a residential development has initiated this investigation. The alleged surface distress of concrete has ranged from: (a) various degrees of *surface scaling* of concrete as loss of the original finished surface of concrete and exposures of near-surface coarse aggregate particles, to (b) isolated occurrences of exposures of near-surface coarse aggregate particles as *mortar lift-offs* and/or *pop outs*, to (c) thin *sheet-like scaling* of the original finished surface where many such 'sheets' of finished surfaces are only loosely adhered to the main body. All these distress have reportedly occurred within two years of concrete placement between 2015 and 2017.

FIELD PHOTOGRAPHS

Figure 1 provides locations of eight cores collected across residential concrete sidewalks and curbs.

Core ID	Core Location	Slab Surface Condition in Field Photos	Core Top Surface
1	3606 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles (Figures 2 and 4)	Sound, fine broom-finished surface despite retrieval from a severely scaled area (Figure 8)
2	3628 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles (Figures 2 and 4)	Broom-finished, with 3 mortar lift-offs, $^3/_8$ in. size (Figure 9)
3	Mailbox near 15711 Murpheys Tin	Isolated mortar lift-off and/or pop out (Figure 2 and 5)	Finished, 1 small pop-out ($^1/_8$ in. size) otherwise sound (Figure 10)
4	Near dog waste station at Doc Berlin tot lot	Severe surface scaling and exposures of near-surface coarse aggregate particles and thin sheets of original finished surface loosely adhered to the main body (Figures 3 and 5)	Sound, fine broom-finished surface but detached from the main body with only loose adherence as a thin sheet to the main body (Figure 11)
5	3624 Summer House	Severe surface scaling and exposures of near-surface coarse aggregate particles (Figures 3 and 6)	Sound, fine broom-finished surface despite retrieval from a severely scaled area (Figure 12)
6	Corner of Maven and Clara Downey	Sound, fine broom-finished surface (Figures 2 and 6)	Sound, fine broom-finished surface for collection from a sound area (Figure 13)
7	3710 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles (Figure 7)	Finished, 1 small mortar lift-off or pop out ($^1/_8$ in. size) otherwise sound (Figure 14)
8	3500 Doc Berlin	Severe surface scaling and exposures of near-surface coarse aggregate particles (Figures 3 and 7)	Isolated mortar lift-off with exposure of near-surface coarse aggregate particles (Figure 18)

Table 1: Conditions of original finished surfaces of concrete at the locations of cores in the field as well as conditions on core top surfaces. See Figure 1 for locations of cores and 2 through 18 for conditions of surfaces at the core locations in the field as well as on the top wearing surface ends of the cores.

PURPOSE OF PRESENT INVESTIGATION

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

a. The composition, quality, and overall condition of concretes in two cores, 2 and 6, selected for detailed petrographic examinations;
b. Evidence of any physical or chemical deterioration of concretes in Cores 2 and 6;
c. Compressive strength of concrete in Core 3;
d. Water-soluble chloride and sulfate contents of concrete at the exposed surface regions and in the interiors in Cores 1, 2, 5, 6, 7, and 8 to investigate potential exposures of sidewalks to chloride and/or sulfate containing deicing chemicals and their potentially deleterious effects on the performance and durability of concrete, especially at the locations that have shown surface distress; and,
e. Based on detailed laboratory investigation, investigation of all possible reasons to explain the observed and reported surface distress of concrete across the core locations at the sidewalks and roadway curbs.

TESTING STRATEGY

Cores 2 and 6 were requested for detailed petrographic examinations according to the procedures of ASTM C 856. Core 3 was requested for compressive strength according to the procedures o ASTM C 42. Cores 1, 2, 5, 6, 7, and 8 were selected for water-soluble chloride and sulfate content analyses by ion chromatography according to the procedures of ASTM D 4327. Core 4 was requested to keep in reserve without any testing.

Cores 2 and 6 were sectioned longitudinally with a water-cooled diamond saw; then sectioned surfaces were lapped to smooth fine surfaces with horizontal cast iron lapping wheels with various magnetically attached grinding discs from coarse to fine abrasive sizes until surfaces suitable for examinations in a low-power stereo-microscope are achieved. An important aspect of this investigation is to determine the air void systems of concretes at the exposed surface regions and in the interiors and estimate air contents and any variations in air contents through depths. Sections parallel to the lapped section were obtained for encapsulation with a blue dye-mixed epoxy for preparation of polarized light-transmitted thin sections (about 30 micron in thickness) for examinations in a petrographic microscope for determinations of aggregates, paste, and products of any potentially deleterious constituents in the concrete.

Core 3 was trimmed at both ends to smooth flat surfaces, sulfur-capped, and tested in air-dry condition for compressive strength.

For water-soluble chloride, sulfate and other anions, Cores 1, 2, 5, 6, 7, and 8 were sectioned about 10 mm thick portions from the exposed surface regions and from mid-depth locations.

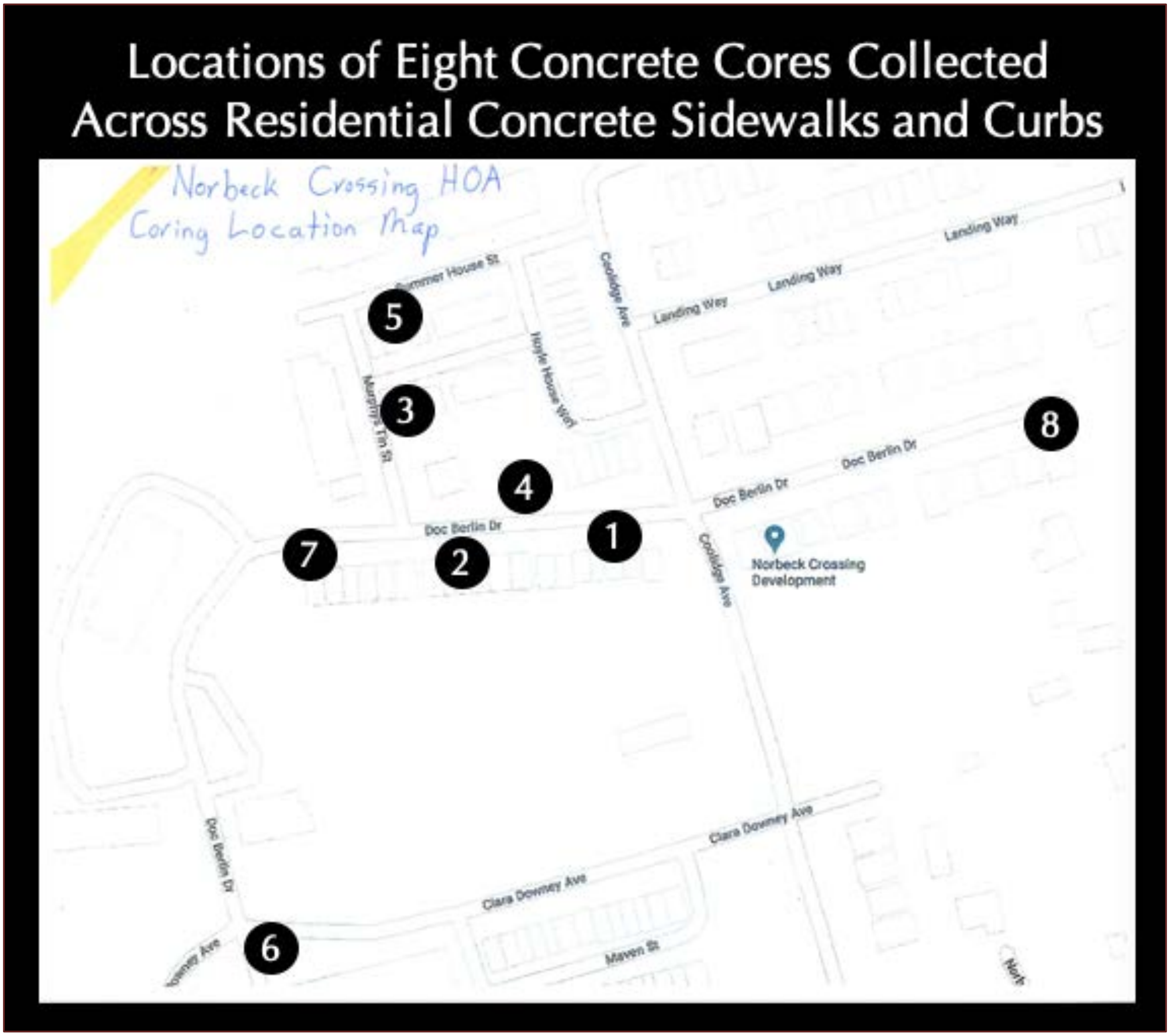

Figure 1: Locations of eight concrete cores collected across residential concrete sidewalks and curbs.

Figure 2: Field photographs showing surface scaling of concrete slab surface at the locations of Cores 1, 2, 3, and 6.

Figure 3: Field photographs showing surface scaling of concrete slab surface at the locations of Cores 4, 5, and 8.

Figure 4: Severe surface scaling and exposures of coarse aggregate particles at the locations of Cores 1 and 2.

Figure 5: Isolated occurrences of surface distress as exposures of near-surface coarse aggregate particles as mortar lift-offs and/or pop-outs at the location of Core 3, but severe sheet-style surface scaling due to accumulation of bleed water underneath prematurely finished surface at the location of Core 4.

Figure 6: Severe scaling at the location of Core 5 whereas sound visually distress-free surface at the location of Core 6.

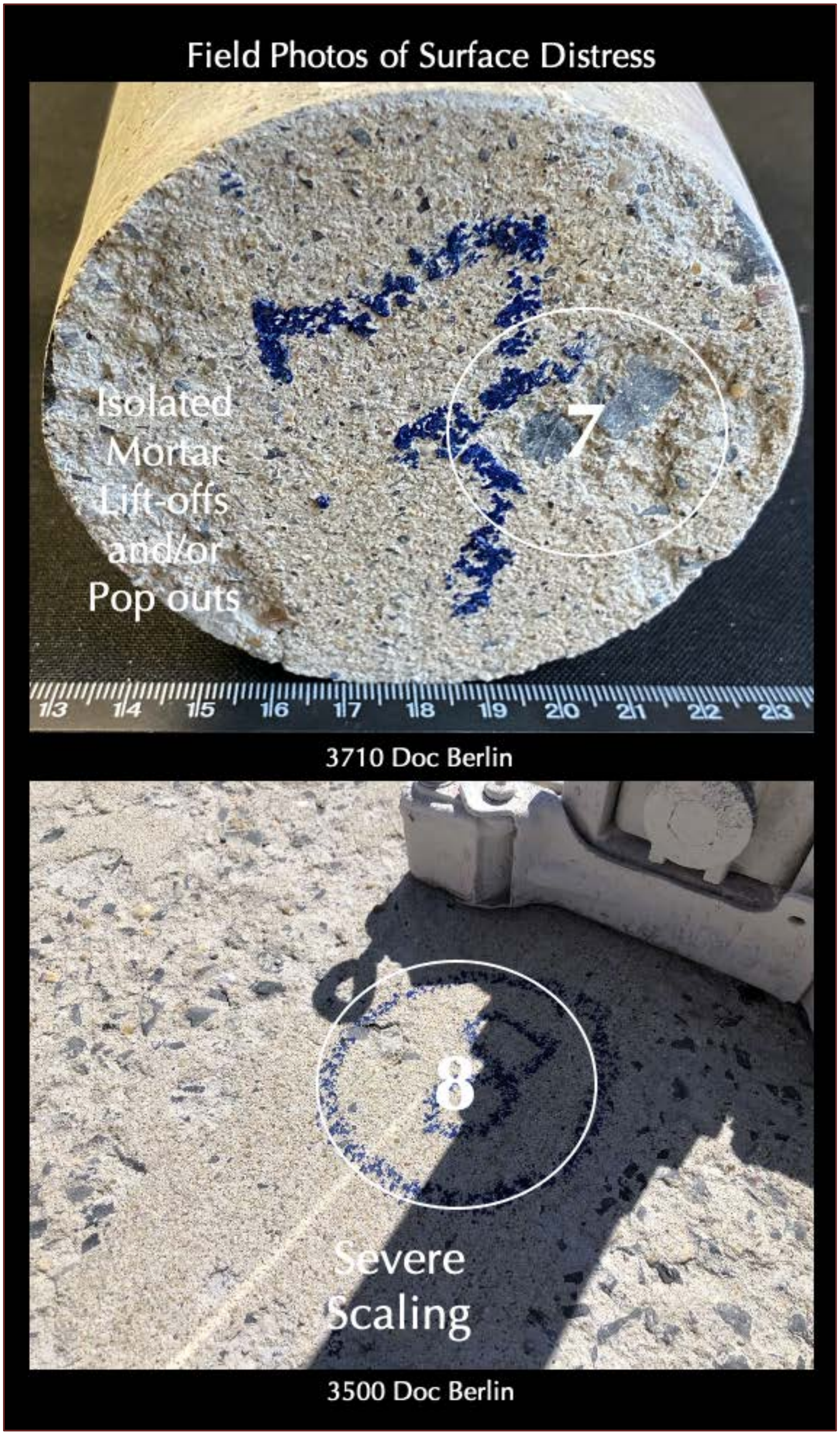

Figure 7: Scaling at the top exposed surface of Core 7 with exposure of coarse aggregate particles and similar severe scaling with coarse aggregate exposures at the location of Core 8.

SAMPLES

Core ID	Core Location	Core Diameter (in.)	Core Length (in.)	Top Exposed Surface	Bottom Surface	Cracking	Reinforcing Steel	Core Condition
1	3606 Doc Berlin	$3^{3}/_{4}$ in. (95 mm)	$7^{1}/_{4}$ in. (185 mm)	Broom-finished, Sound	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
2	3628 Doc Berlin	$3^{3}/_{4}$ in. (95 mm)	7 in. (180 mm)	Broom-finished, 3 mortar lift-offs, $^{3}/_{8}$ in. size	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
3	Mailbox near 15711 Murpheys Tin	$3^{3}/_{4}$ in. (95 mm)	$3^{3}/_{4}$ in. (95 mm)	Finished, 1 small pop-out ($^{1}/_{8}$ in. size) otherwise sound	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
4	Near dog waste station at Doc Berlin tot lot	$3^{3}/_{4}$ in. (95 mm)	$4^{1}/_{4}$ in. (110 mm)	Sheet Scaling with Fine Aggregate Exposure, 1 mm thick sheet of finished surface loosely bonded to body	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
5	3624 Summer House	$3^{3}/_{4}$ in. (95 mm)	$4^{1}/_{4}$ in. (105 mm)	Broom-finished, Sound	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
6	Corner of Maven and Clara Downey	$3^{3}/_{4}$ in. (95 mm)	$3^{1}/_{2}$ in. (90 mm)	Broom-finished, Sound, with beige discoloration of paste at top 2 mm	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
7	3710 Doc Berlin	$3^{3}/_{4}$ in. (95 mm)	$7^{1}/_{2}$ in. (190 mm)	Finished with 2 pop outs, $^{3}/_{8}$ in. size	Crushed Stone of Subbase	None	None	Intact, Dry, Ring
8	3500 Doc Berlin	$3^{3}/_{4}$ in. (95 mm)	$7^{1}/_{2}$ in. (185 mm)	Partially Scaled (10%), Fine Broom-finish	Crushed Stone of Subbase	None	$^{3}/_{16}$ in. mesh at 6 in. depth and $6^{1}/_{2}$ in. depth.	Intact, Dry, Ring

Table 2: Description of cores, as received.

PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figures 8 through 18 show cores as received as well as surface conditions of slab at the field locations of cores. Table 1 provides preliminary descriptions of the cores as received.

END SURFACES

All eight cores show variably distressed surfaces from fine found broom-finished top surfaces to surfaces showing evidence of mortar lift-off and/or pop outs, variable degrees of scaling exposing the near-surface coarse aggregate particles, and sheet-scaling of the original finished surface from the main body. Surface distresses as seen on the core tops are described in Table 1. Field locations of cores are shown in Figures 1 to 6, 8 to 12, and 16 to 18.

CRACKING & OTHER VISIBLE DISTRESS, IF ANY

Besides surface distress from scaling to mortar lift-off to pop out to sheet-scaling, however, there are no major cracks, joints, or large voids present in any of the eight cores received.

EMBEDDED ITEMS

Core No. 8 contains $^{3}/_{16}$ in. wire mesh at depths of 6 in. and $6^{1}/_{2}$ in. No reinforcing steel, wire mesh, or other embedded items are present in the cores.

RESONANCE

All eight cores have a ringing resonance, when hammered.

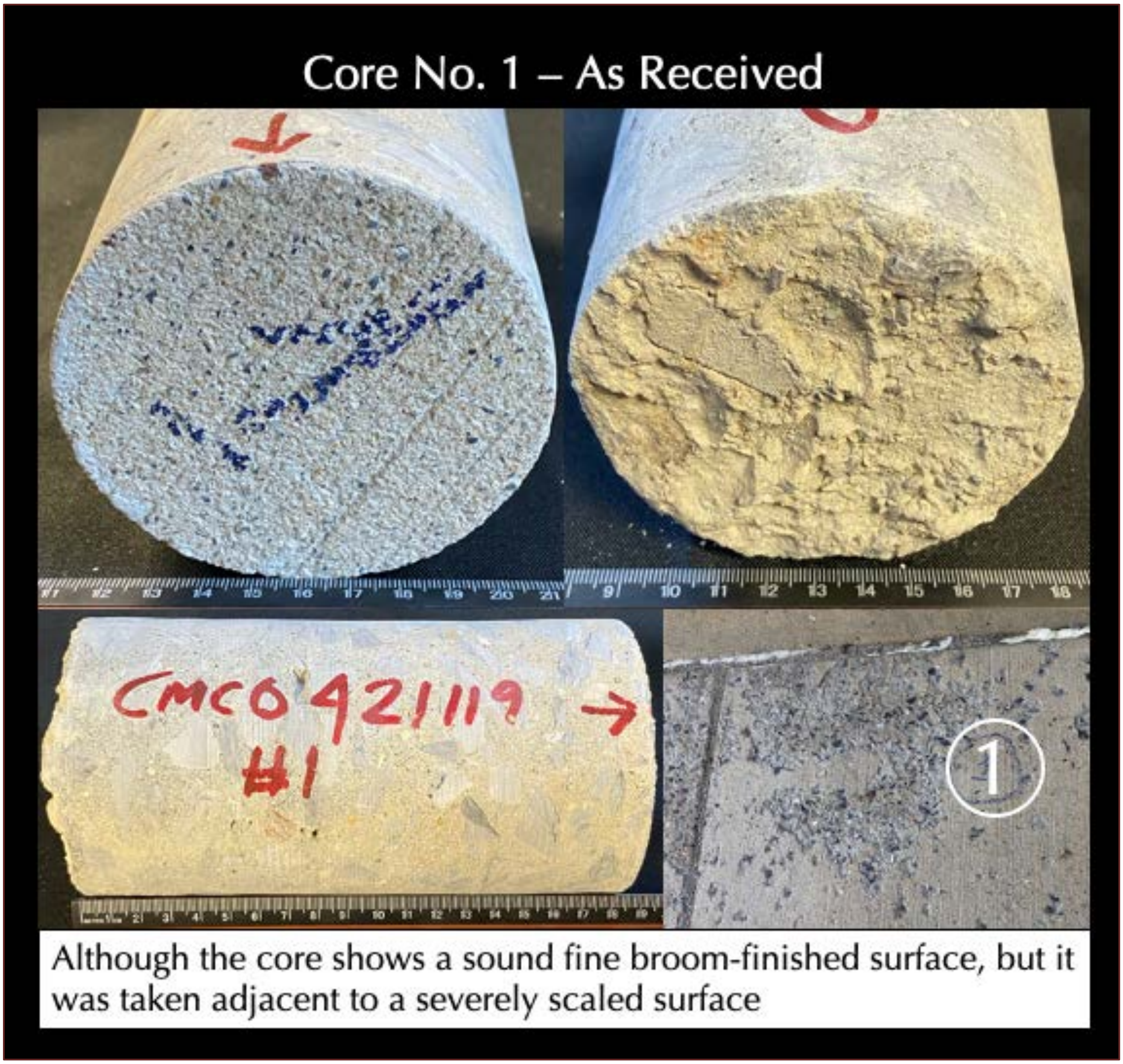

Figure 8: Core 1 as received showing fine broom-finished surface at the top left photo even though the core was taken from a scaled area (see Figures 1 and 3 and at the bottom right inset), bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

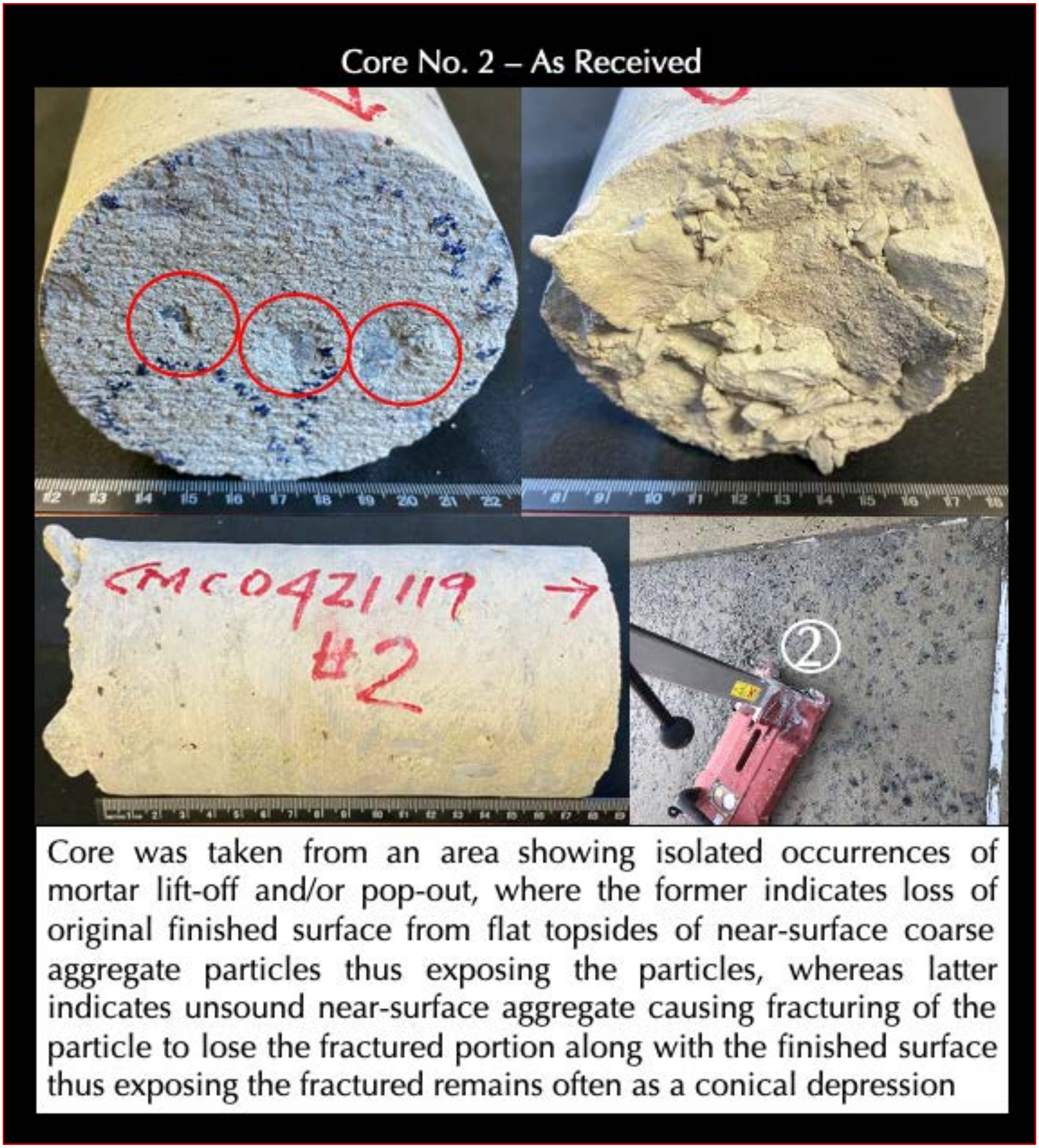

Figure 9: Core 2 as received showing isolated occurrences of scaling as loss of the original finished surface over flat topsides of near-surface coarse aggregate particles as mortar lift-offs (circled), which is consistent with the severely scaled surface of core location in Figures 1 and 3 and at the bottom right inset, bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

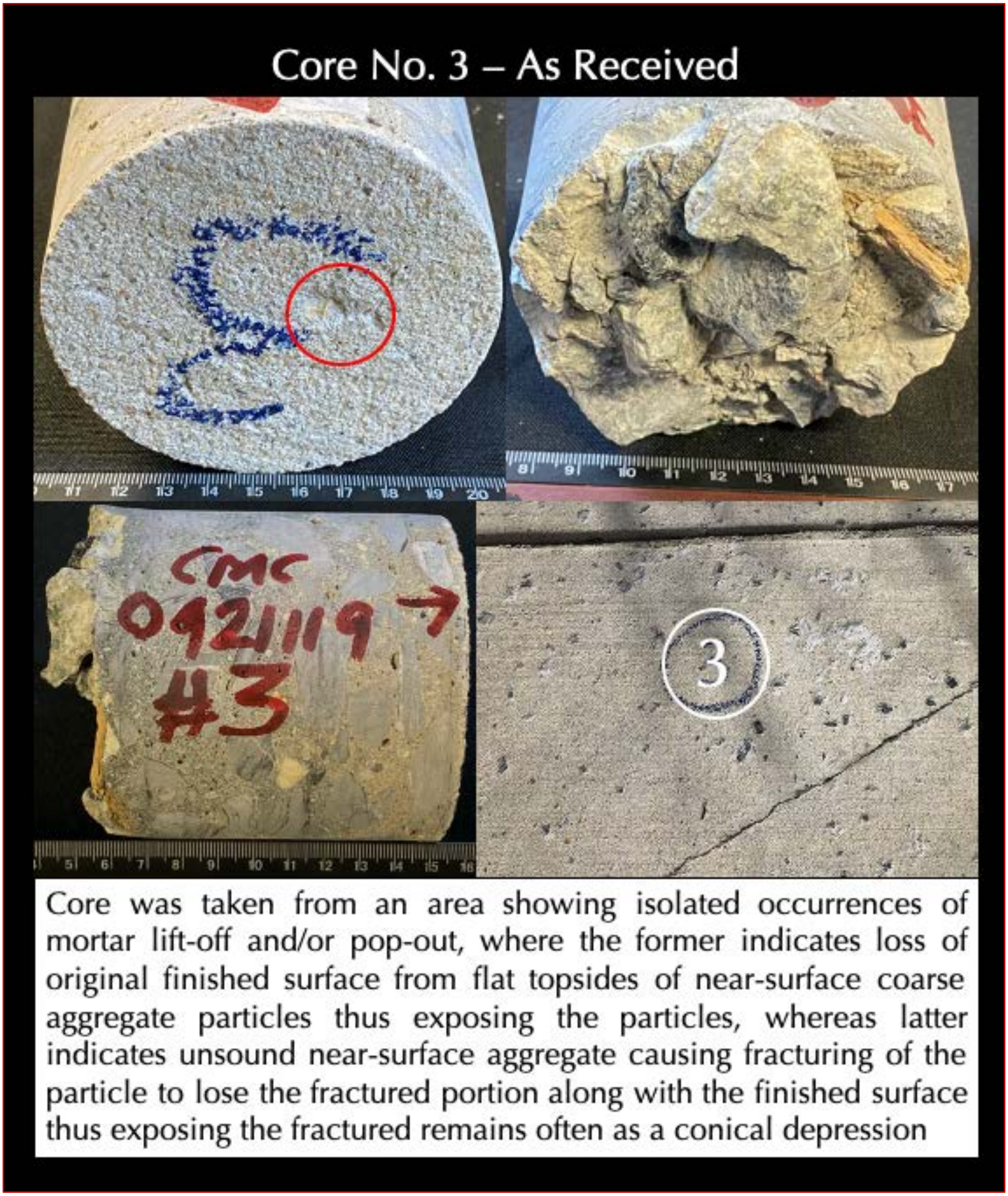

Figure 10: Core 3 as received showing isolated occurrences of scaling as loss of the original finished surface over flat topsides of near-surface coarse aggregate particles as mortar lift-offs (circled), which is consistent with isolated occurrences of small mortar lift-offs and/or pop-outs at the core location at the bottom right inset, bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

Figure 11: Core 4 as received showing thin sheet-style incipient scaling where the original finished surface is loosely adhered to the main body with a weak bond marked by arrows in the middle row, which is consistent with sheet-scaling at the core location at the bottom right inset due to accumulation of bleed water underneath the prematurely finished surface, bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

Figure 12: Core 5 as received showing sound fine broom-finished surface even though the core was taken from a scaled area as shown in the bottom right inset of field photo, bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

Figure 13: Core 6 as received showing the sound fine broom-finished surface, which is consistent with its collection from a sound location of slab as seen in the bottom right inset, bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

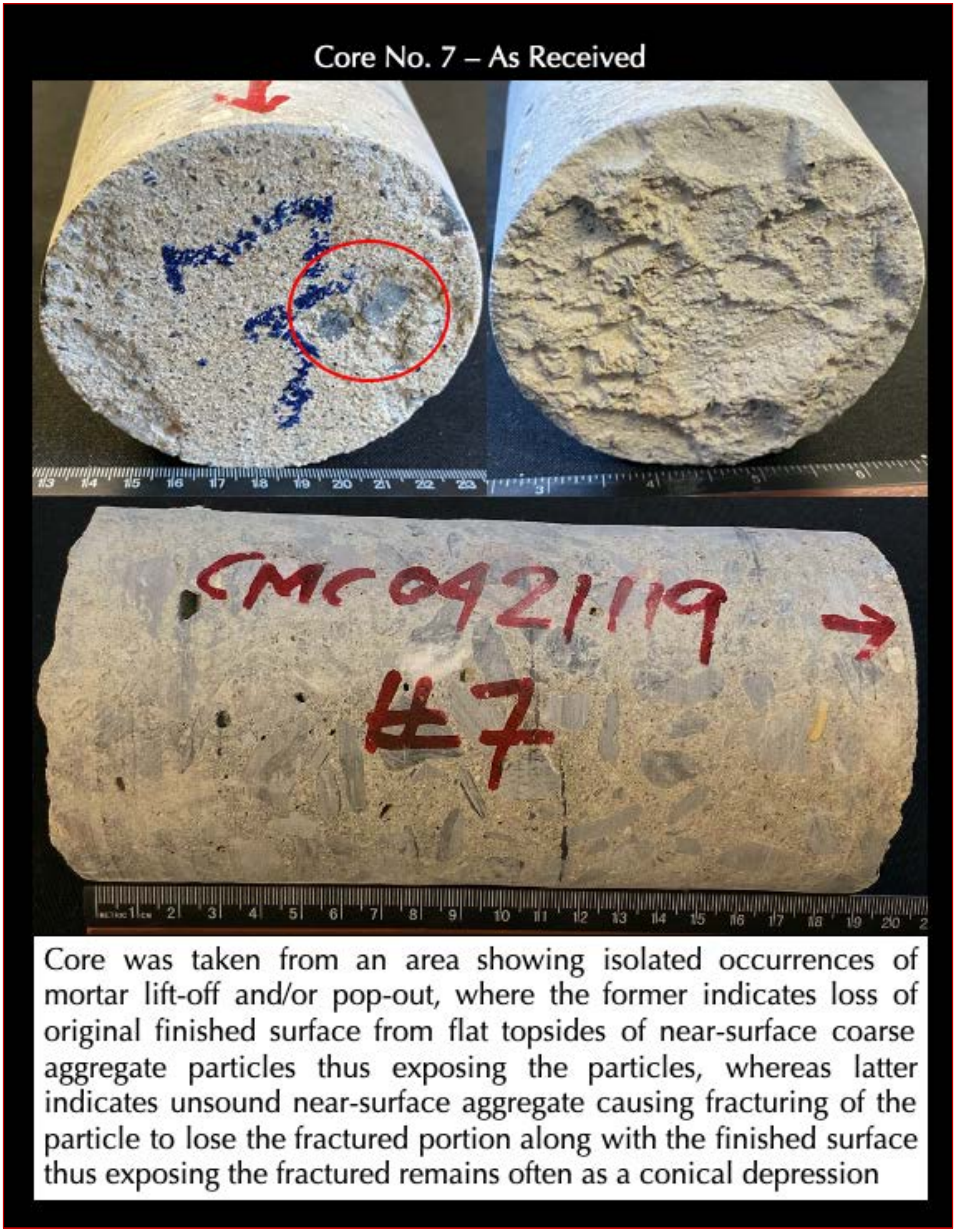

Figure 14: Core 7 as received showing scaled exposed surface with exposure of near-surface coarse aggregate particle as mortar lift-off (circled), bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

Figure 15: Core 8 as received showing scaled surface with exposures of near-surface coarse aggregate particles, which is consistent with its severely scaled field location shown at the bottom right inset, bottom surface of core at the top right, and side cylindrical surface at the bottom left photo.

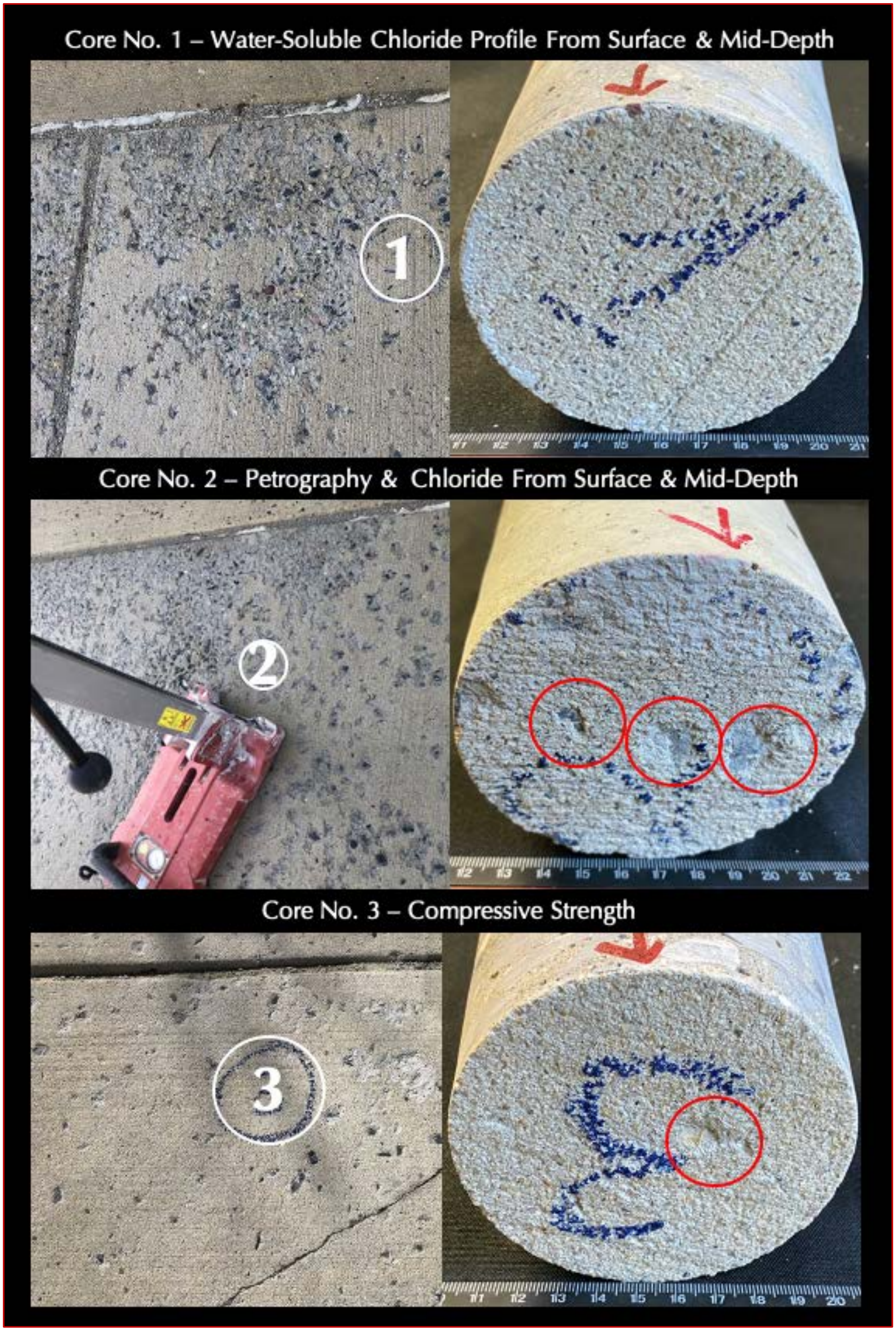

Figure 16: Water-soluble chloride contents of concrete were determined from the top distressed surface locations and at mid-depth locations of Cores 1, 2, and 3. Additionally, Core 2 was selected for detailed petrographic examinations.

Figure 17: Water-soluble chloride contents of concrete were determined from the top distressed surface locations and at mid-depth locations of Cores 4, 5, and 6. Additionally, Core 6 was selected for detailed petrographic examinations.

Figure 18: Water-soluble chloride contents of concrete were determined from the top distressed surface locations and at mid-depth locations of Cores 7 and 8.

METHODOLOGIES

PETROGRAPHIC EXAMINATIONS

Core Nos. 2 and 6 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 cores, as received;
ii. Low-power stereo microscopical 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 stereo microscopical examinations of air contents and air-void systems of concretes 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 concretes in a petrographic microscope for detailed compositional and microstructural analyses;
vi. Photographing cores, as received and at various stages of sample preparation with a digital camera, and flatbed and film scanners; and,
vii. Photomicrographs of lapped sections and thin sections of samples taken with stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information of concrete.

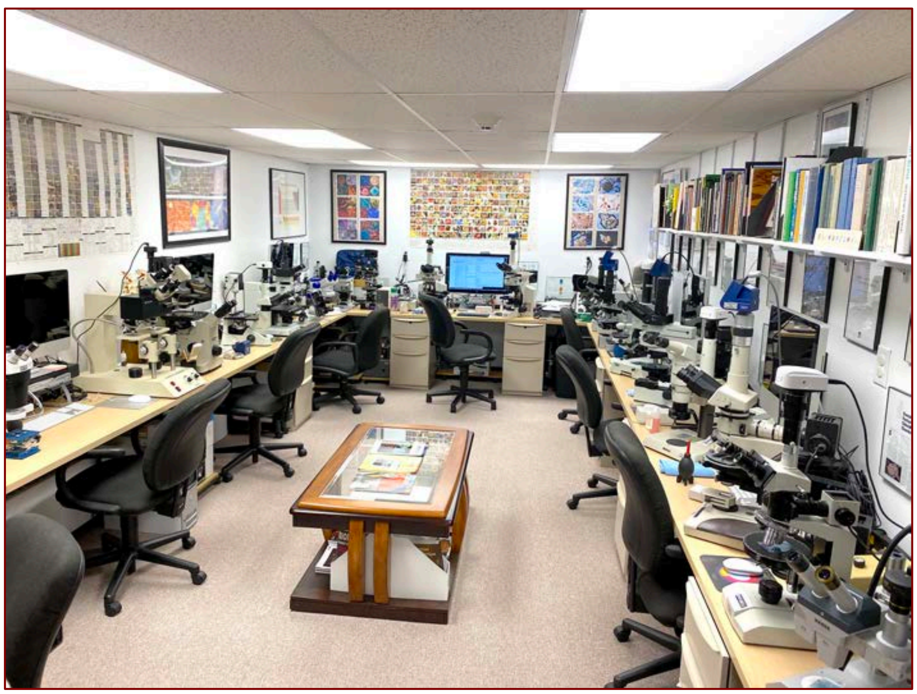

Figure 19: Optical microscopy laboratory in CMC that houses various stereo-microscopes, and petrographic microscopes used in this study.

CHEMICAL PROFILES OF CHLORIDE, SULFATE, AND OTHER WATER-SOLUBLE ANIONS

Portions of pulverized concrete sectioned from the exposed surface, and mid-depth locations of Core Nos. 1, 2, 5, 6, 7, and 8 were digested in deionized water for 24 hours at room temperature, and then filtered to collect the filtrate for determination of various anions by ion chromatography by following the methods of ASTM D 4327, particularly for water-soluble chloride and sulfate ion contents in concrete.

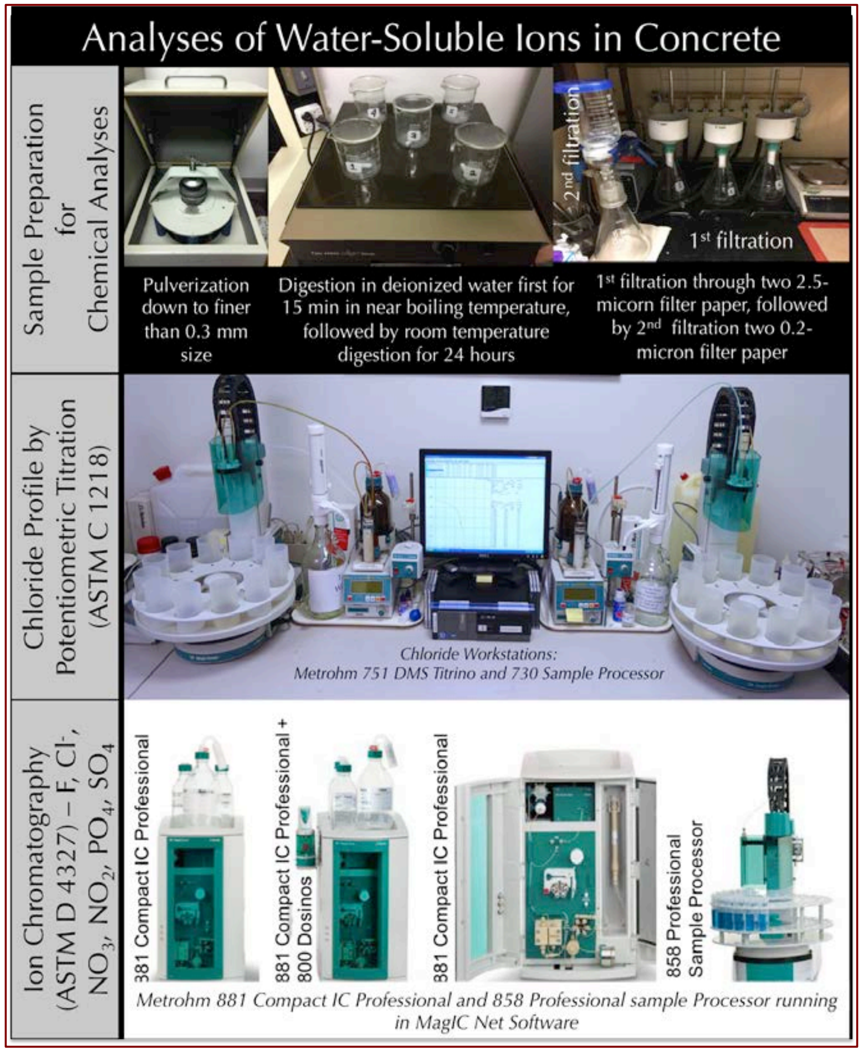

Figure 20: Sample preparation and analyses of water-soluble ions of concrete in potentiometric titration and ion chromatography.

Sections were pulverized down to finer than 0.3 mm size. Approximately 1 gram of pulverized concrete from each section was thoroughly digested in 100 ml deionized water first in near-boiling temperature for 15 minutes with magnetic stirrer, followed by further room-temperature digestion for 24 hours. The digested sample solution was then filtered under vacuum, first through two 2.5-micron filter papers, followed by another filtration through two 0.2-micron filter papers to collect the filtrate. The filtrate thus obtained was diluted to a final volume of 200 ml in a volumetric flask.

Filtrate thus prepared was used for anion chromatography, *a la* ASTM D 4327 for water-soluble fluoride, chloride, nitrate, nitrite, bromide, phosphate, and sulfate ions by using Metrohm 881 Compact IC Professional with attached 858 Professional Sample Processor with a sodium carbonate-bicarbonate eluent (Figure 20).

COMPRESSIVE STRENGTH

A cylindrical portion from Core 3 was sectioned for compressive strength testing according to the procedures of ASTM C 42.

PETROGRAPHIC EXAMINATIONS

LAPPED CROSS SECTIONS

Figure 21: Two parallel lapped cross sections of Core 2 showing: (a) lightened gray toned paste at the top 5 to 6 mm of exposed surface (boxed) compared to relatively darker toned paste in the interior body, which occurs due to addition of water during finishing operations and/or finishing in the presence of bleed water at the surface, either practice would increase the porosity and water-cementitious materials ratio of paste and decrease the wear resistance and durability of exposed surface; (b) crushed limestone coarse aggregate particles, which are well-graded but show slight segregation at the top inch of the finished surface; (c) overall dense, and well-consolidated nature of concrete in the body; and greenish-gray discoloration of paste at the bottom 1 to 2 inches (boxed) due to the presence of ground granulated blast furnace slag as a cementitious component in the paste.

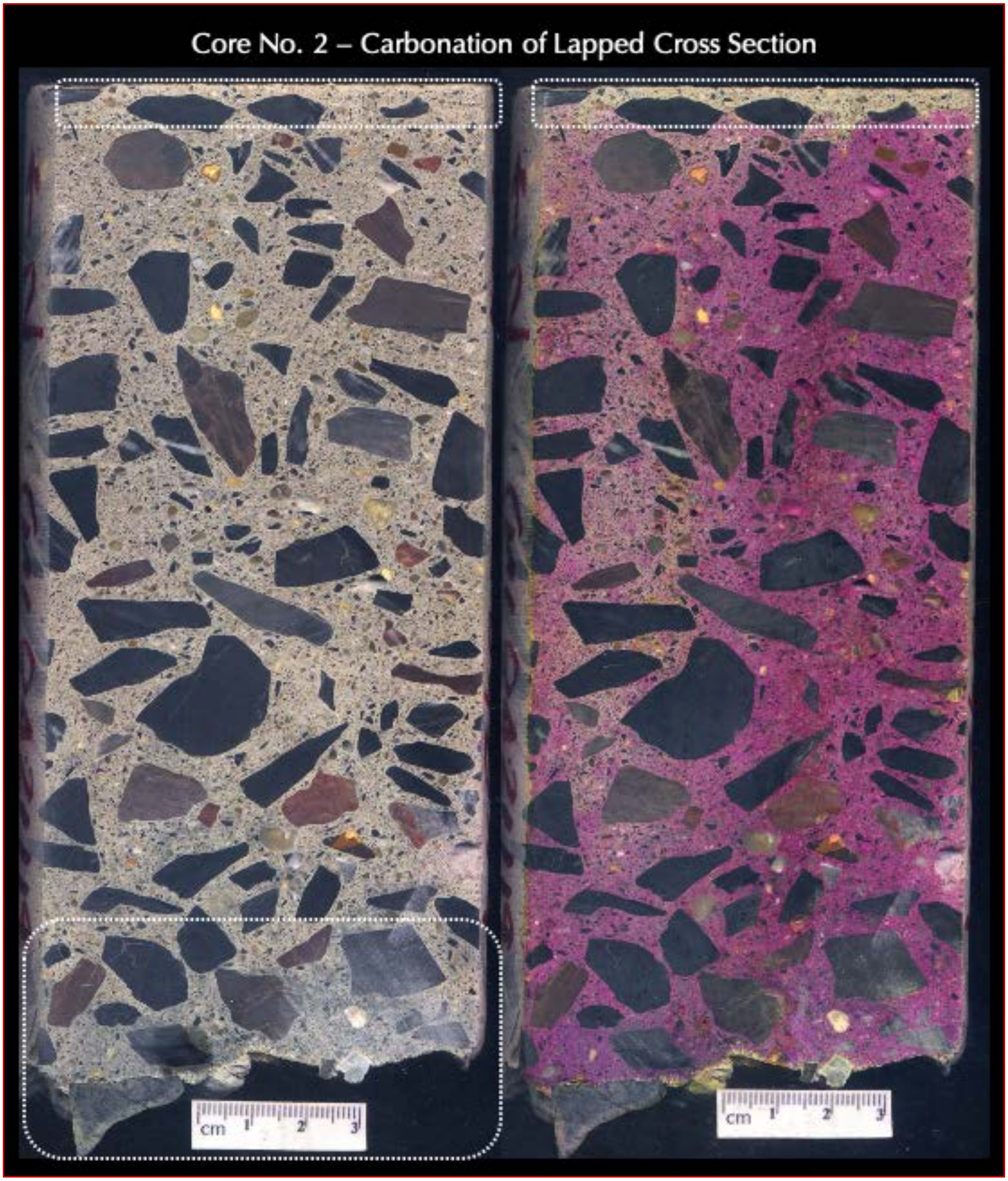

Figure 22: Lapped cross section of Core 2 shown in the previous Figure and at left, but before (left) and after (right) treatment with a phenolphthalein alcoholic solution, which turns the majority of the section to pink as shown in the right photo due to non-carbonated nature of most of the interior concrete except the top 5 to 6 mm of exposed surface, which was porous and light-toned in previous Figure and shows carbonated nature as well where phenolphthalein treatment did not turn the paste color to pink.

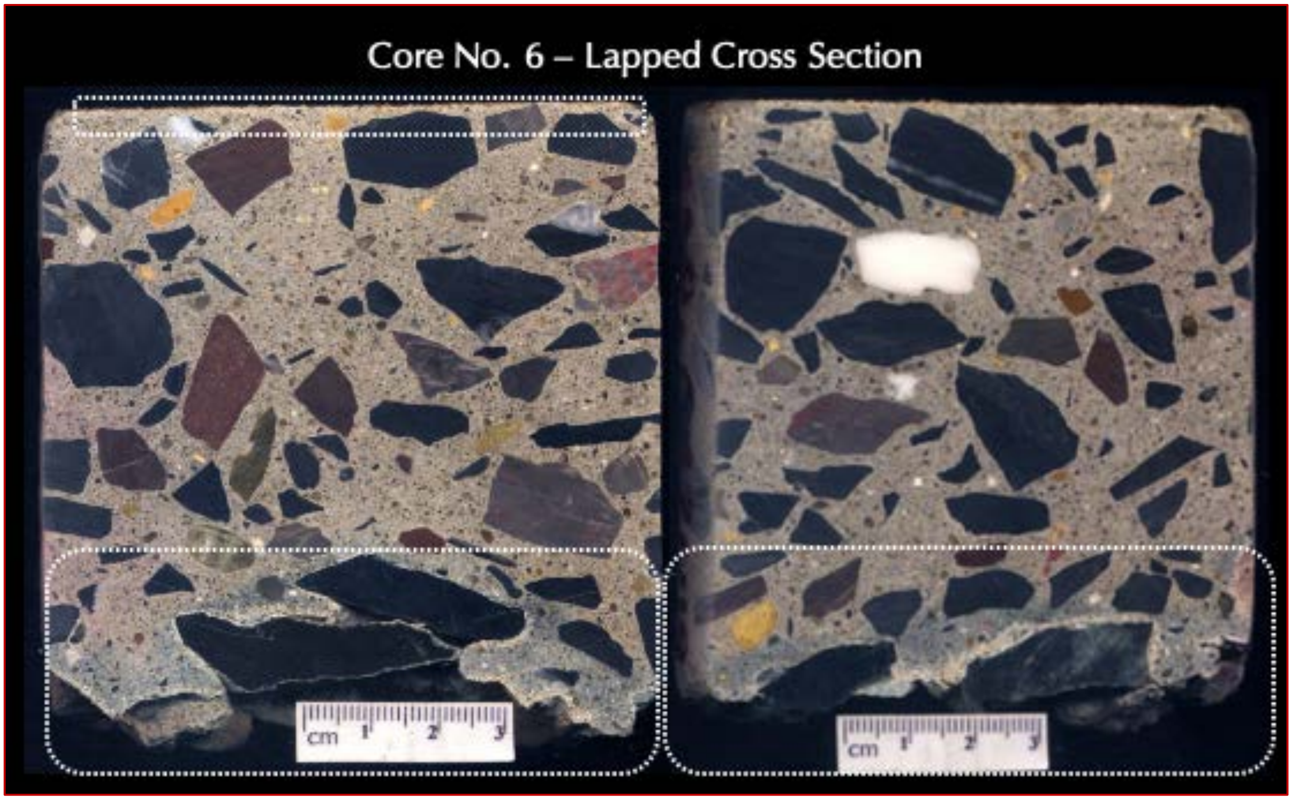

Figure 23: Two parallel lapped cross sections of Core 6 showing: (a) lightened gray toned paste at the top 5 to 6 mm of exposed surface (boxed) compared to relatively darker toned paste in the interior body, which, however, is not as contrasting as seen in Core 2, which occurs due to addition of water during finishing operations and/or finishing in the presence of bleed water at the surface, either practice would increase the porosity and water-cementitious materials ratio of paste and decrease the wear resistance and durability of exposed surface; (b) crushed limestone coarse aggregate particles, which are well-graded and well-distributed; (c) overall dense, and well-consolidated nature of concrete in the body; and greenish-gray discoloration of paste at the bottom 1 inch (boxed) due to the presence of ground granulated blast furnace slag as a cementitious component in the paste.

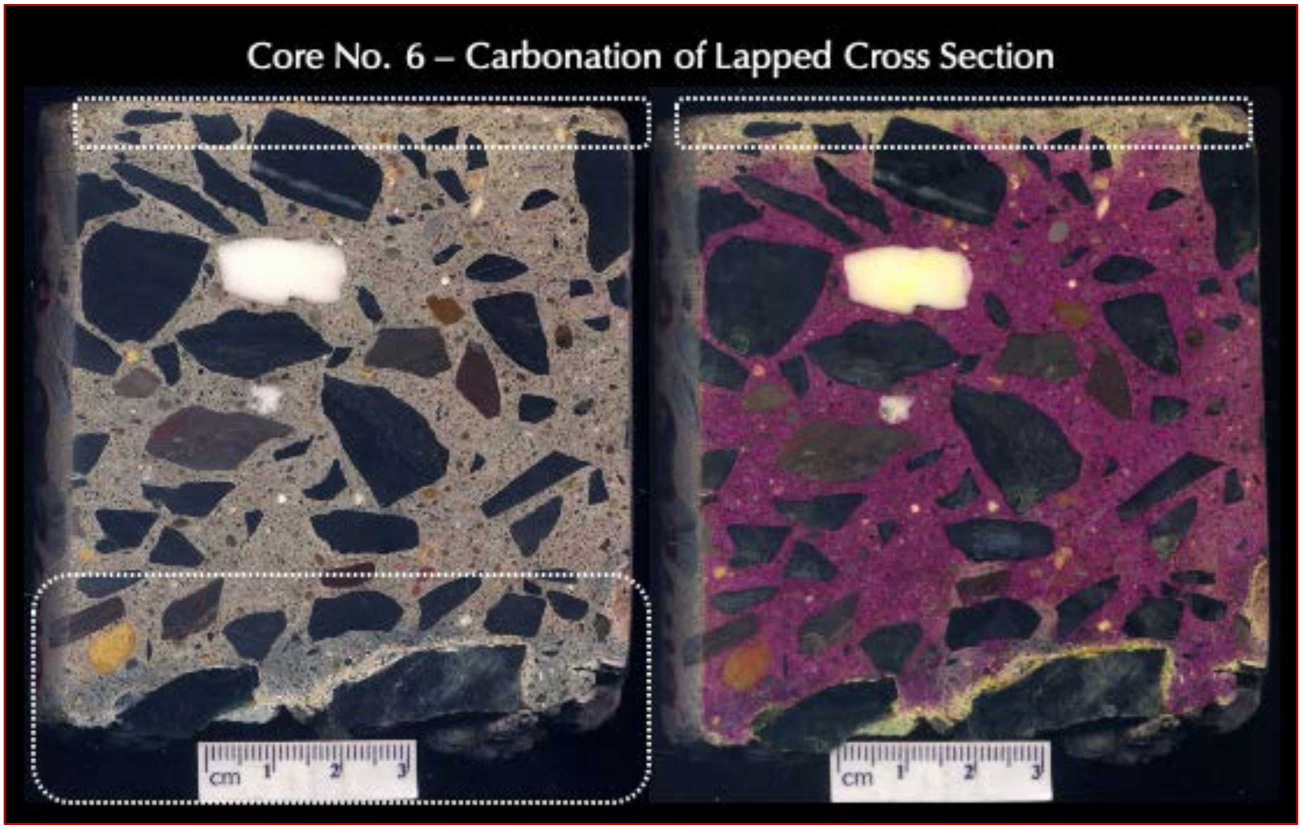

Figure 24: Lapped cross section of Core 6 shown in the previous Figure and at left, but before (left) and after (right) treatment with a phenolphthalein alcoholic solution, which turns the majority of the section to pink as shown in the right photo due to non-carbonated nature of most of the interior concrete except the top 5 to 6 mm of exposed surface, which was porous and light-toned in previous Figure and shows carbonated nature as well where phenolphthalein treatment did not turn the paste color to pink. Also notice some carbonation of paste at the rim of a crushed limestone adhered to the bottom of core.

MICROGRAPHS OF LAPPED CROSS SECTIONS

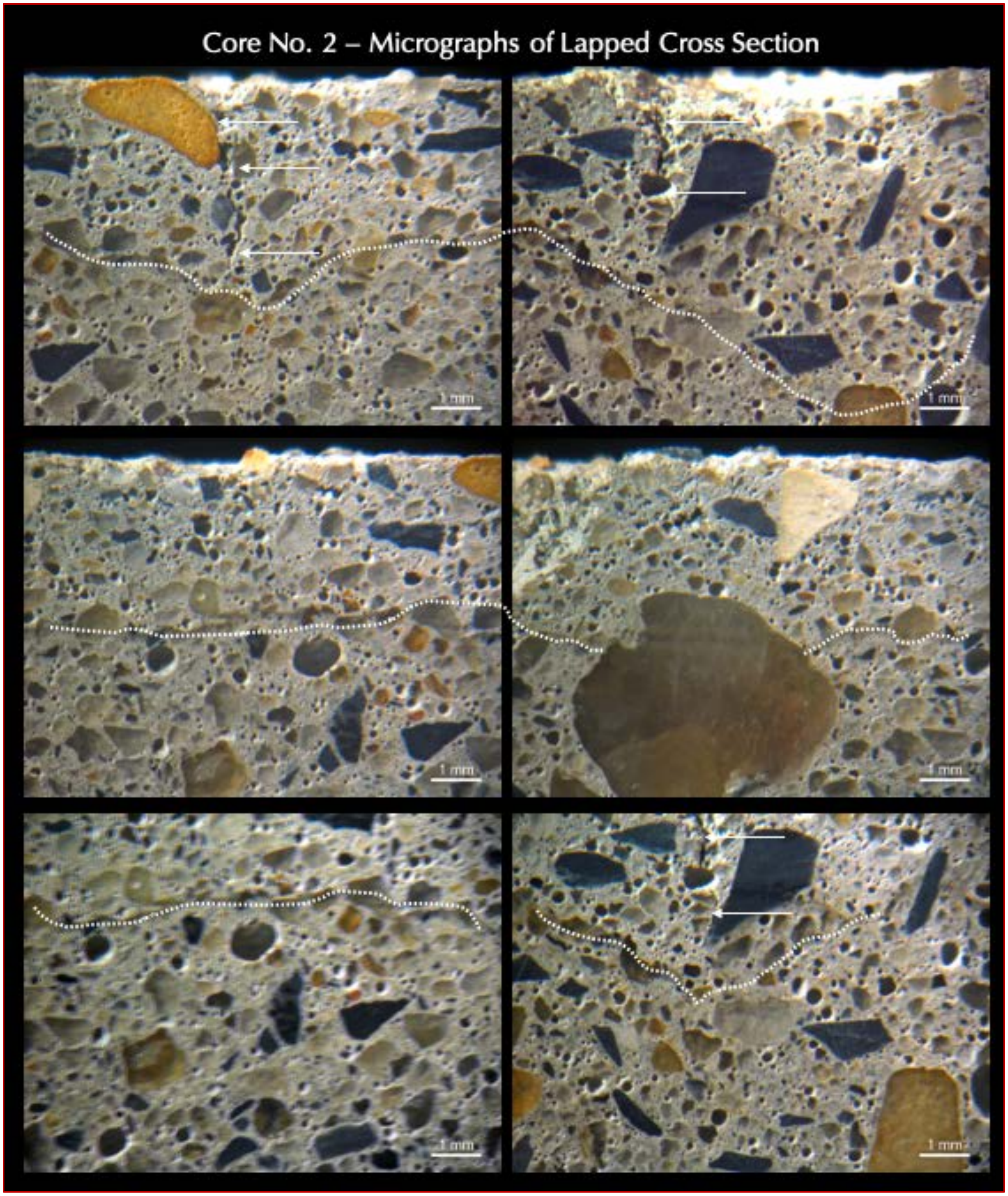

Figure 25: Micrographs of lapped cross section of Core 2 from the surface region showing: (a) a light-toned paste at the top 5 to 6 mm, which is separated from the rest of the interior by the white dotted lines; (b) a few fine, vertical shrinkage microcracks at the exposed surface extended to depths of 5 to 6 mm, one such is marked with arrows in the top row; and (c) excellent air entrainment in concrete at the surface region consisting of numerous, fine, discrete, spherical and near-spherical entrained air voids.

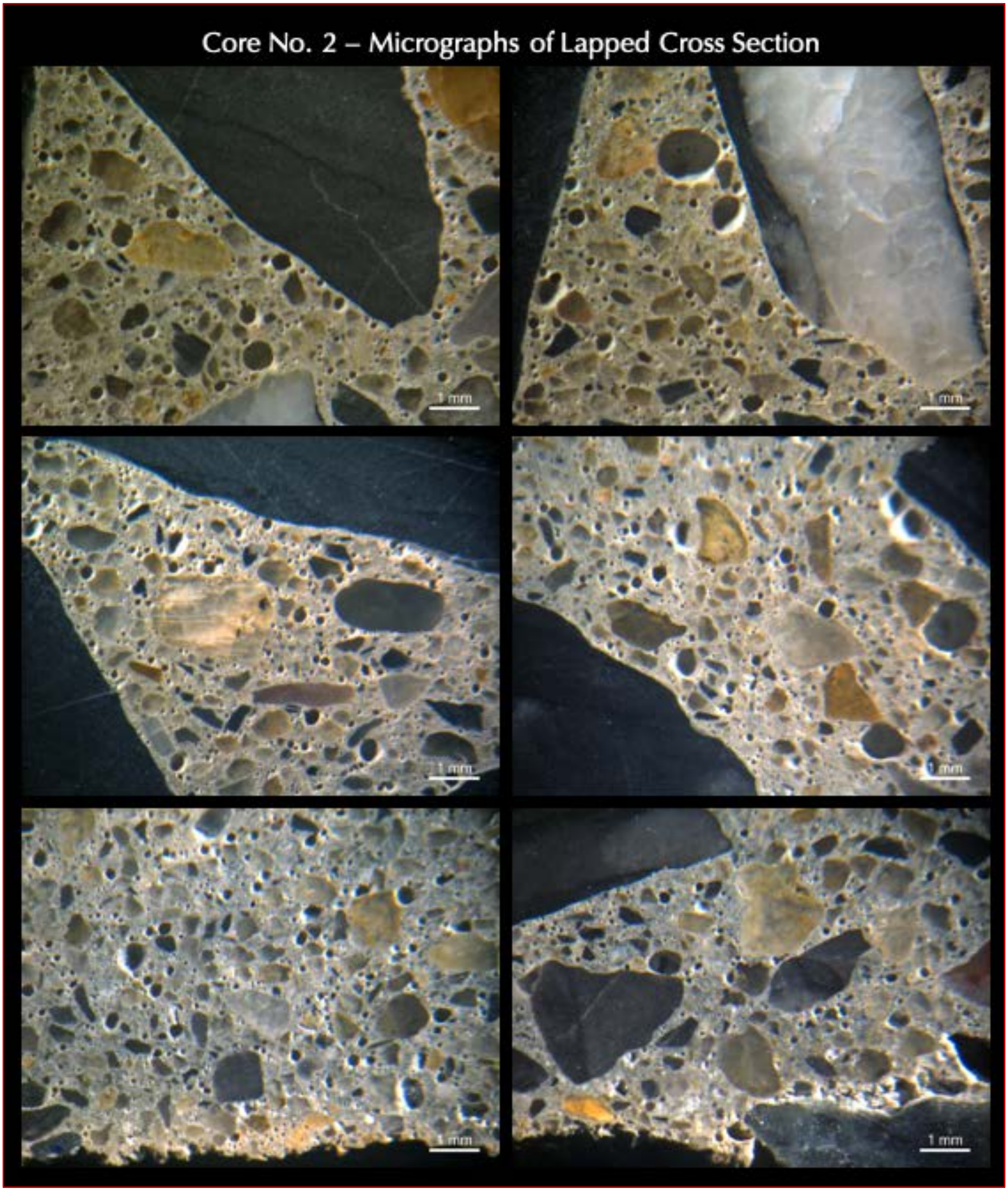

Figure 26: Micrographs of lapped cross section of Core 2 from the interior body showing excellent air entrainment in concrete in the body consisting of numerous, fine, discrete, spherical and near-spherical entrained air voids.

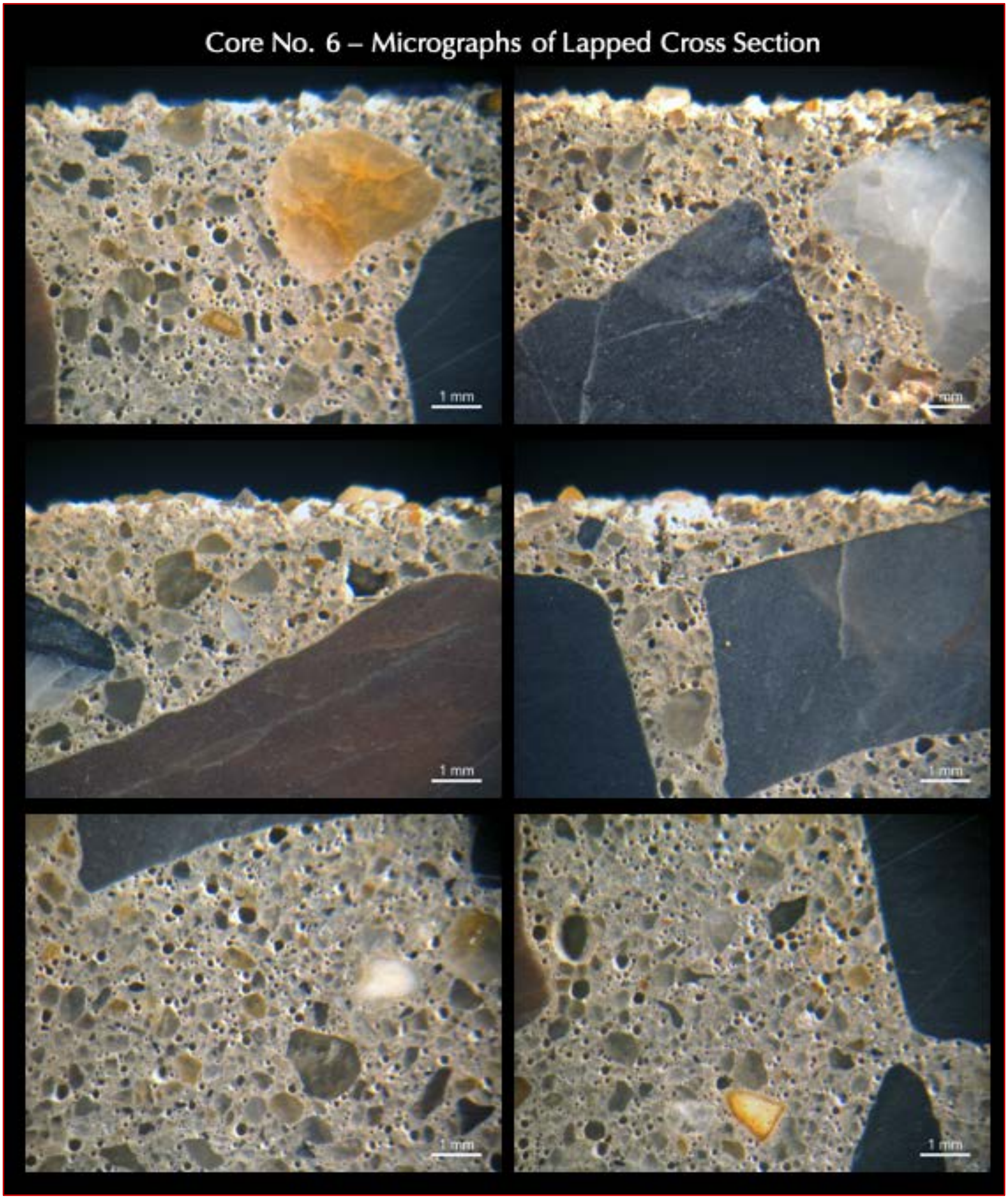

Figure 27: Micrographs of lapped cross section of Core 6 from the surface region showing: (a) a light-toned paste at the top 5 to 6 mm; and (b) excellent air entrainment in concrete at the surface region consisting of numerous, fine, discrete, spherical and near-spherical entrained air voids.

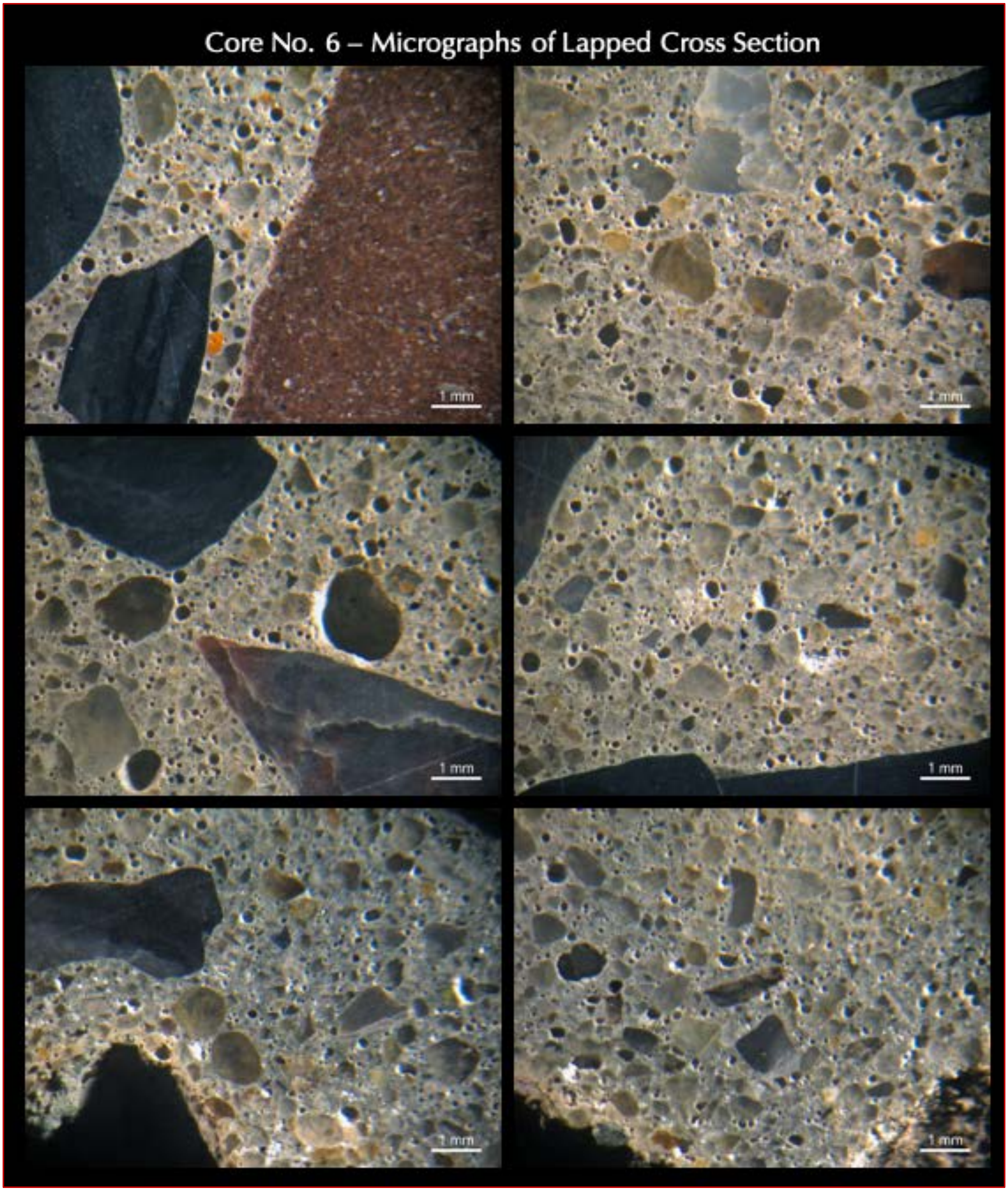

Figure 28: Micrographs of lapped cross section of Core 6 from the interior body showing excellent air entrainment in concrete in the body consisting of numerous, fine, discrete, spherical and near-spherical entrained air voids.

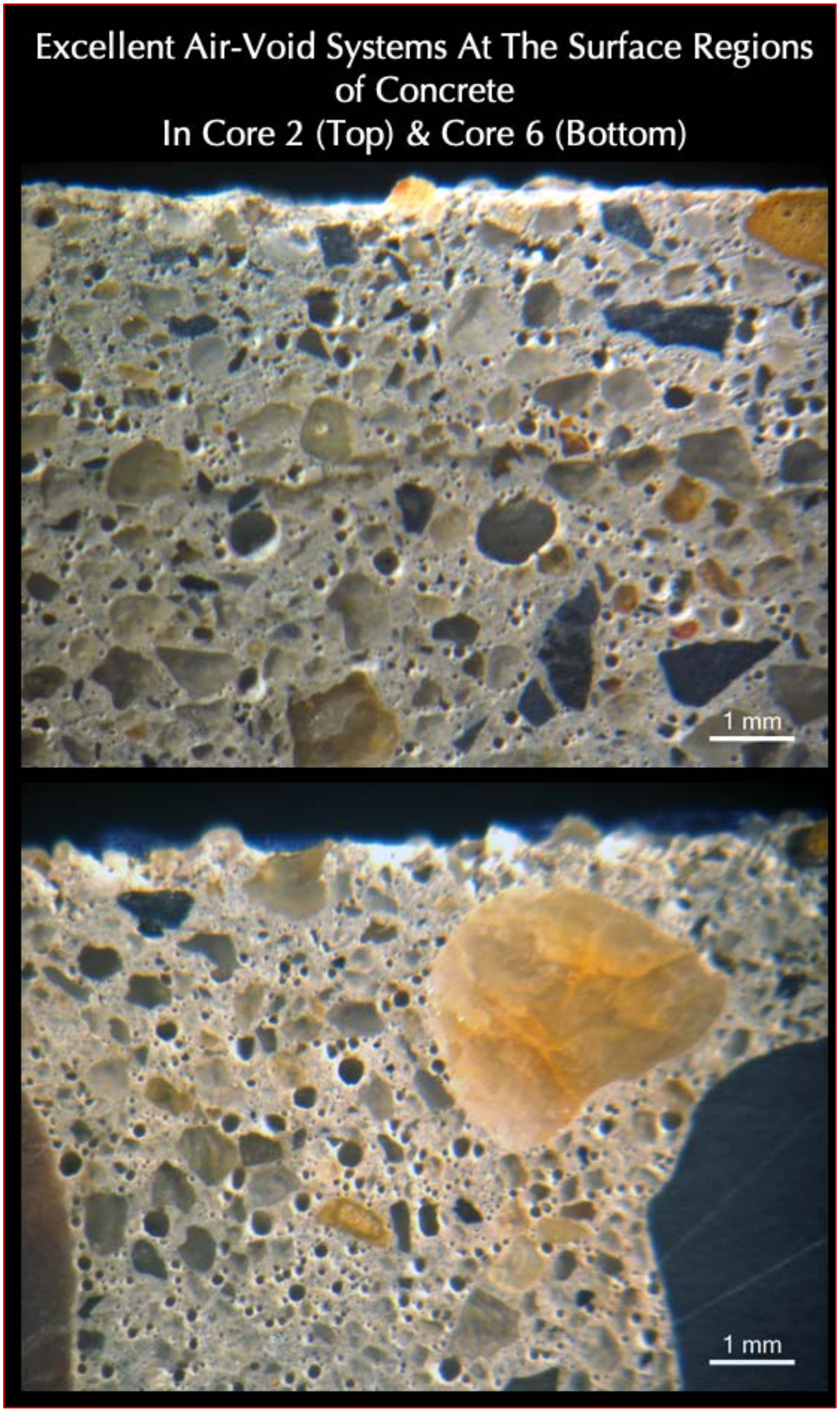

Figure 29: Micrographs of lapped cross sections of Cores 2 (top) and 6 (bottom) from the surface regions showing excellent air entrainment in concretes, consisting of numerous, fine, discrete, spherical and near-spherical entrained air voids. Air content is estimated to be 6 to 7 percent.

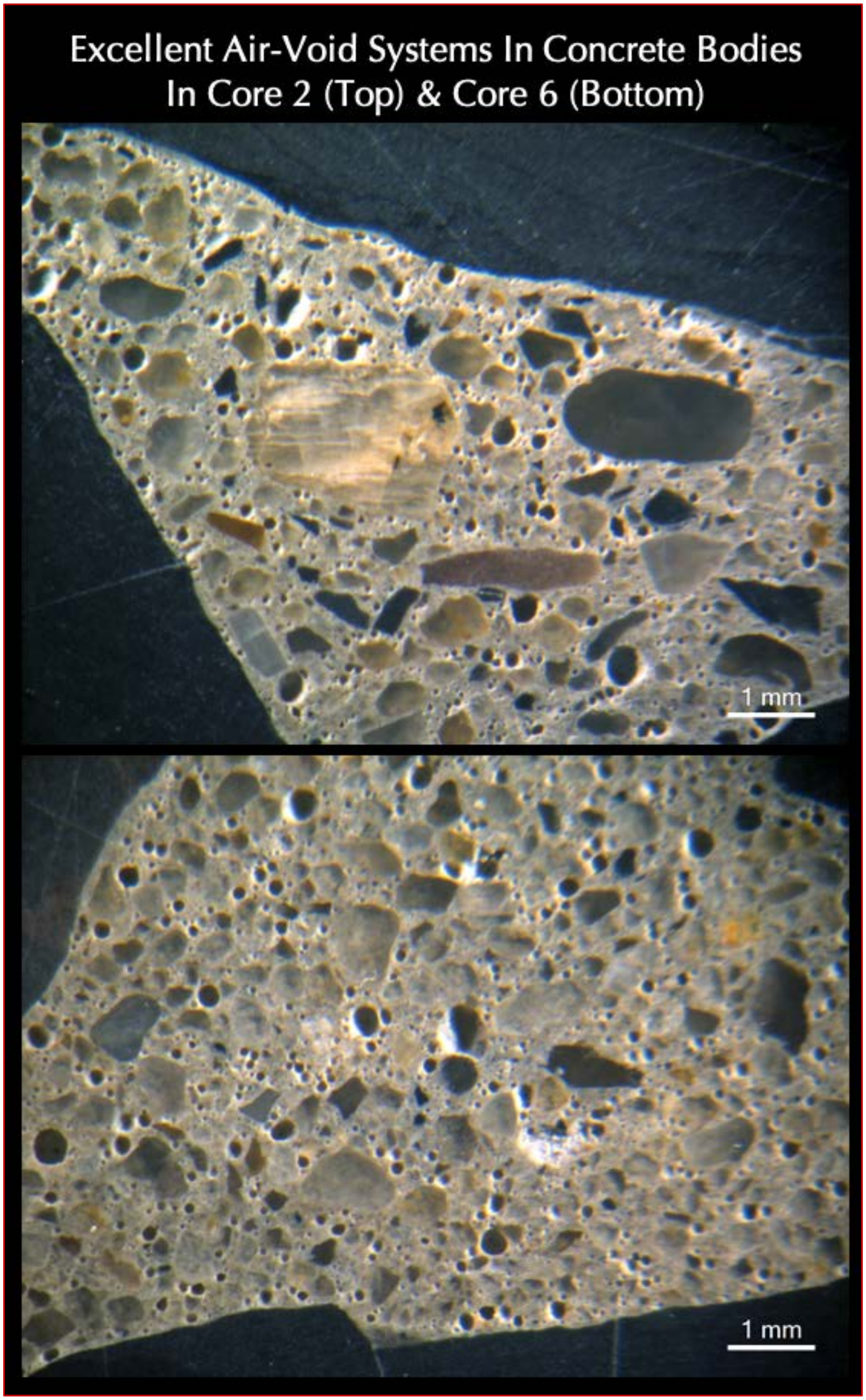

Figure 30: Micrographs of lapped cross sections of Core 2 (top) and 6 (bottom) from the interior bodies showing excellent air entrainment in concrete throughout the depths of the cores consisting of numerous, fine, discrete, spherical and near-spherical entrained air voids. Air content is estimated to be 6 to 7 percent.

BLUE DYE-MIXED EPOXY-IMPREGNATED THIN SECTIONS

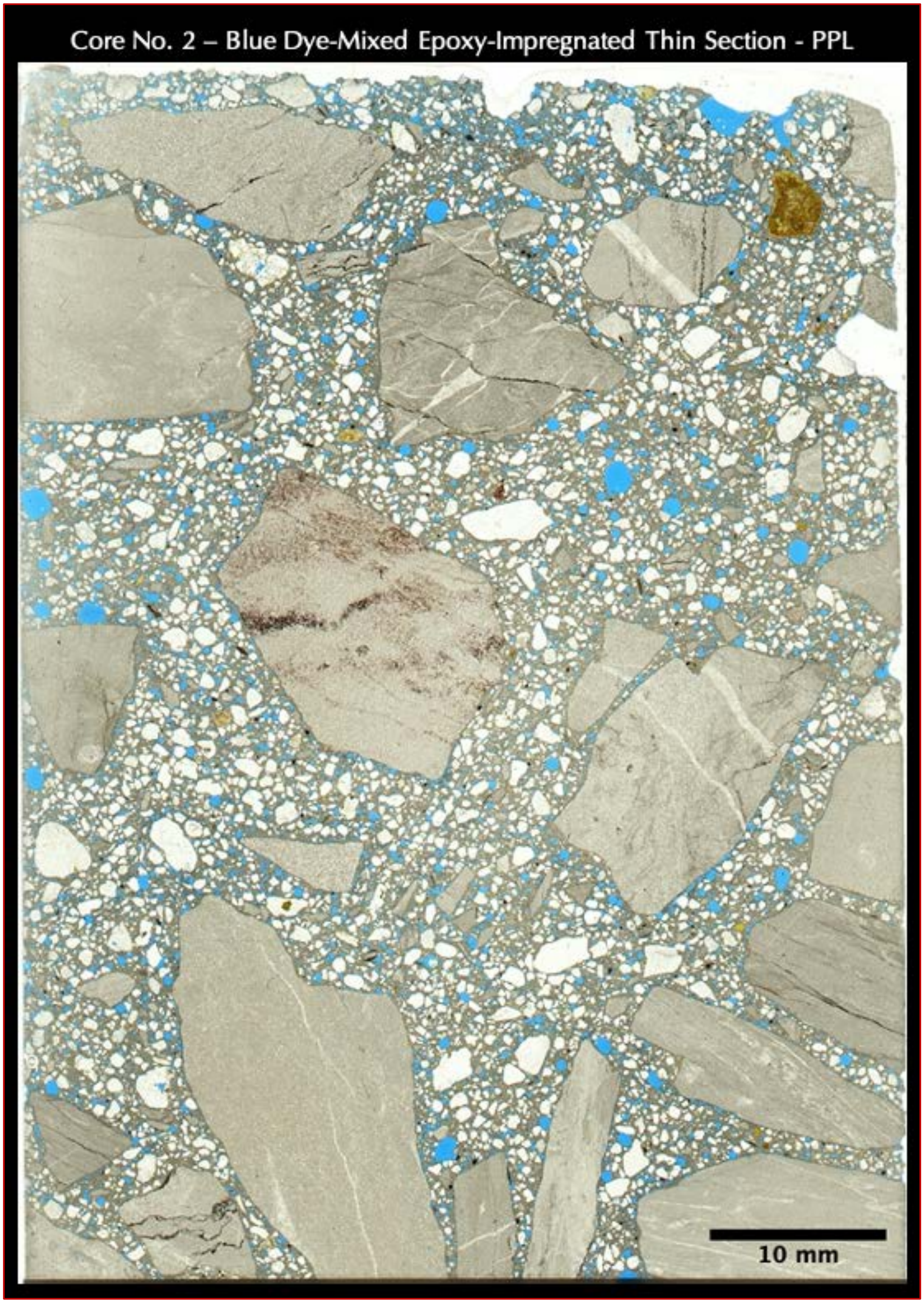

Figure 31: Blue dye-mixed epoxy-impregnated large-area (50 mm × 75 mm size) thin section of Core 2 shown in plane-polarized light mode to highlight the air voids and porous regions of paste by the blue epoxy that has been absorbed more in those areas compared to denser regions. The thin section was scanned on a film scanner with a polarizing filter.

Thin section shows: (a) air-entrained concrete where air voids are highlighted by blue epoxy, (b) crushed limestone coarse aggregate particles where many show dark argillaceous and carbonaceous veins; and (c) natural siliceous sand and finer sand-size fraction of crushed limestone.

Figure 32: Blue dye-mixed epoxy-impregnated large-area (50 mm × 75 mm size) thin section of Core 2 shown in crossed-polarized light mode to highlight the coarse and fine aggregates in concrete. The thin section was scanned on a film scanner with two perpendicular polarizing filters.

Thin section shows: (a) crushed limestone coarse aggregate particles where many show dark argillaceous and carbonaceous veins; and (b) natural siliceous sand and finer sand-sized fraction of crushed limestone.

Figure 33: Blue dye-mixed epoxy-impregnated large-area (50 mm × 75 mm size) thin section of Core 6 shown in plane-polarized light mode to highlight the air voids and porous regions of paste by the blue epoxy that has been absorbed more in those areas compared to denser regions. The thin section was scanned on a film scanner with a polarizing filter.

Thin section shows: (a) air-entrained concrete where air voids are highlighted by blue epoxy, (b) crushed limestone coarse aggregate particles where many show dark argillaceous and carbonaceous veins; and (c) natural siliceous sand and finer sand-sized fraction of crushed limestone.

Figure 34: Blue dye-mixed epoxy-impregnated large-area (50 mm × 75 mm size) thin section of Core 6 shown in crossed-polarized light mode to highlight the coarse and fine aggregates in concrete. The thin section was scanned on a film scanner with two perpendicular polarizing filters.

Thin section shows: (a) crushed limestone coarse aggregate particles where many show dark argillaceous and carbonaceous veins; and (b) natural siliceous sand and finer sand-sized fraction of crushed limestone.

MICROGRAPHS OF THIN SECTIONS

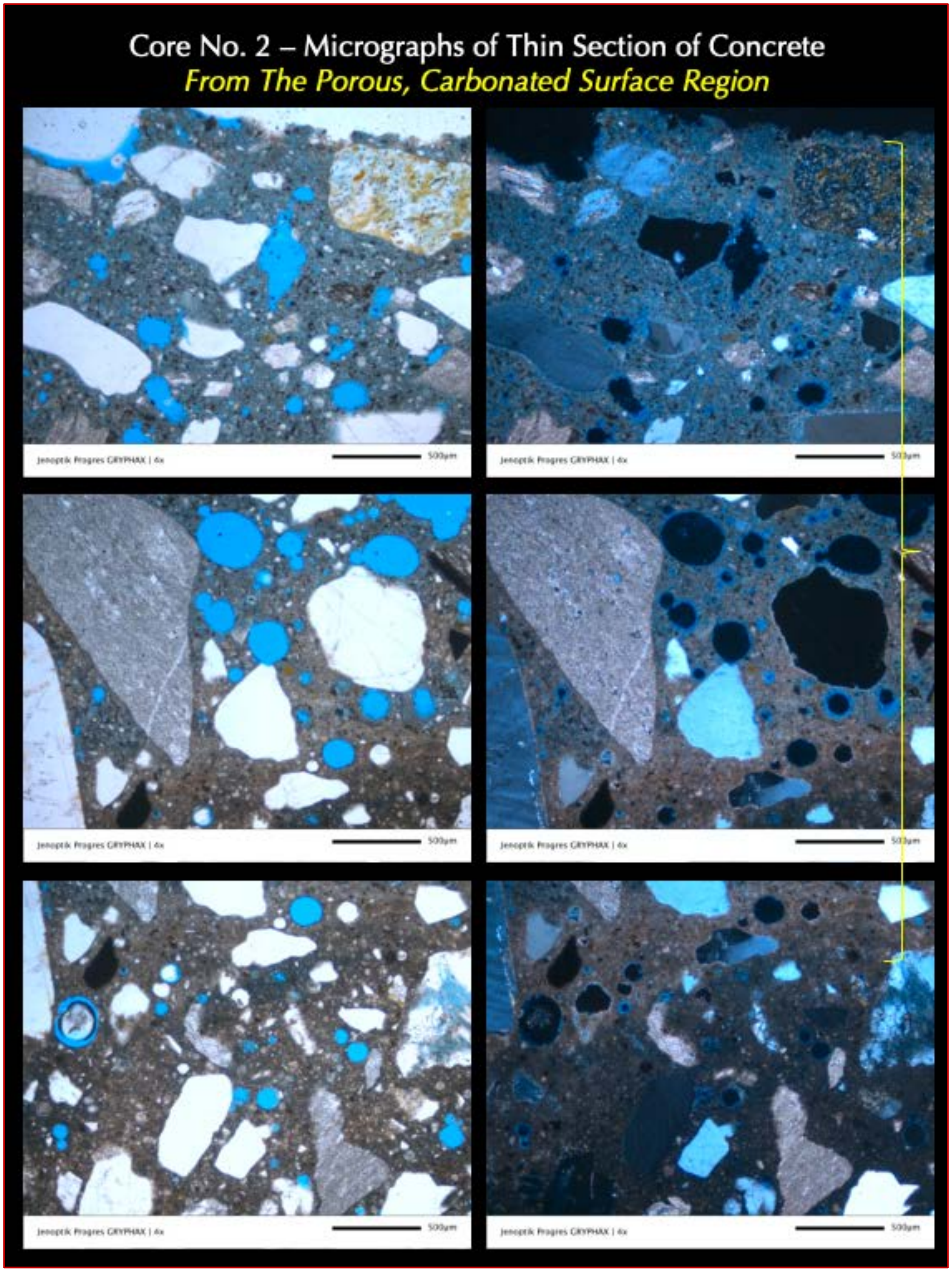

Figure 35: Micrographs of thin section of Core 2 from the exposed surface region showing the soft, porous, high *w/cm*, carbonated surface region to a depth of 5 to 6 mm from exposed surface. Notice the difference in density of paste from the soft, porous very top surface and the paste underneath that porous surface. Left and corresponding right column photos were taken with a petrographic microscope in plane and crossed-polarized light modes, respectively.

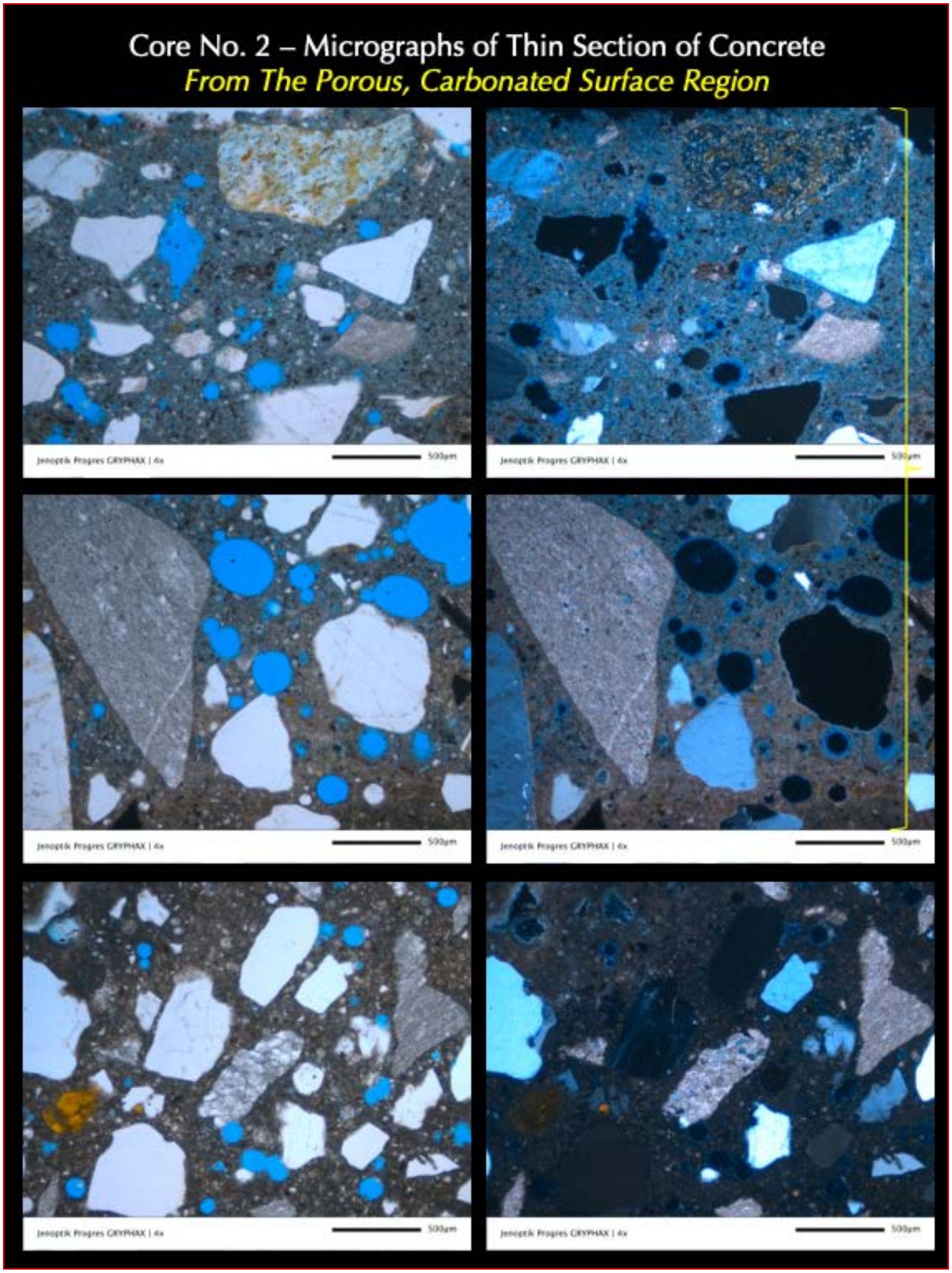

Figure 36: Micrographs of thin section of Core 2 from the exposed surface region showing the soft, porous, high *w/cm*, carbonated surface region to a depth of 5 to 6 mm from exposed surface. Notice the difference in density of paste from the soft, porous very top surface and the paste underneath that porous surface. Left and corresponding right column photos were taken with a petrographic microscope in plane and crossed-polarized light modes, respectively.

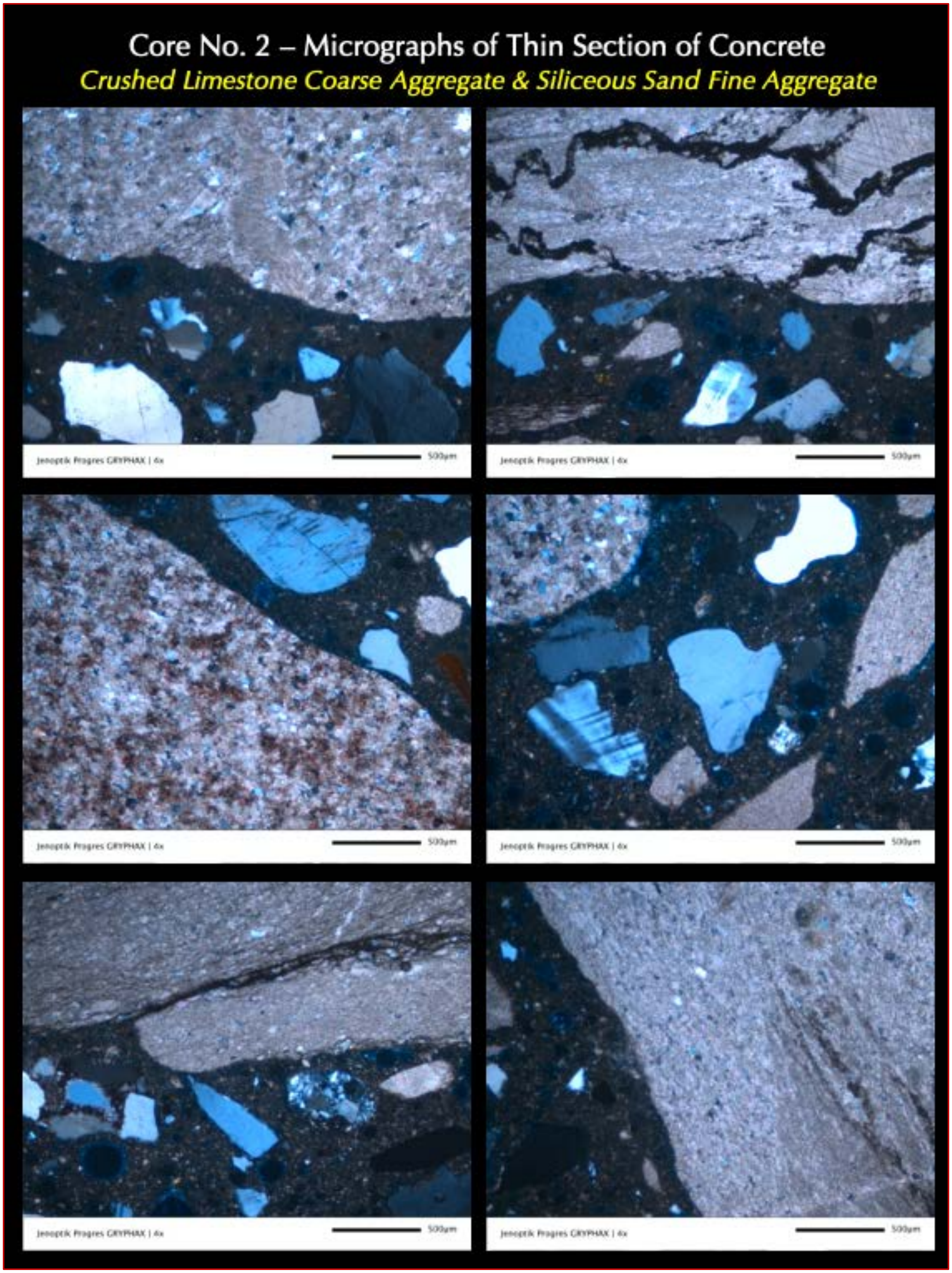

Figure 37: Micrographs of thin section of Core 2 showing the crushed limestone coarse aggregate particles and natural siliceous (quartz, quartzite, feldspar) sand and finer fraction of crushed limestone in the fine aggregate.

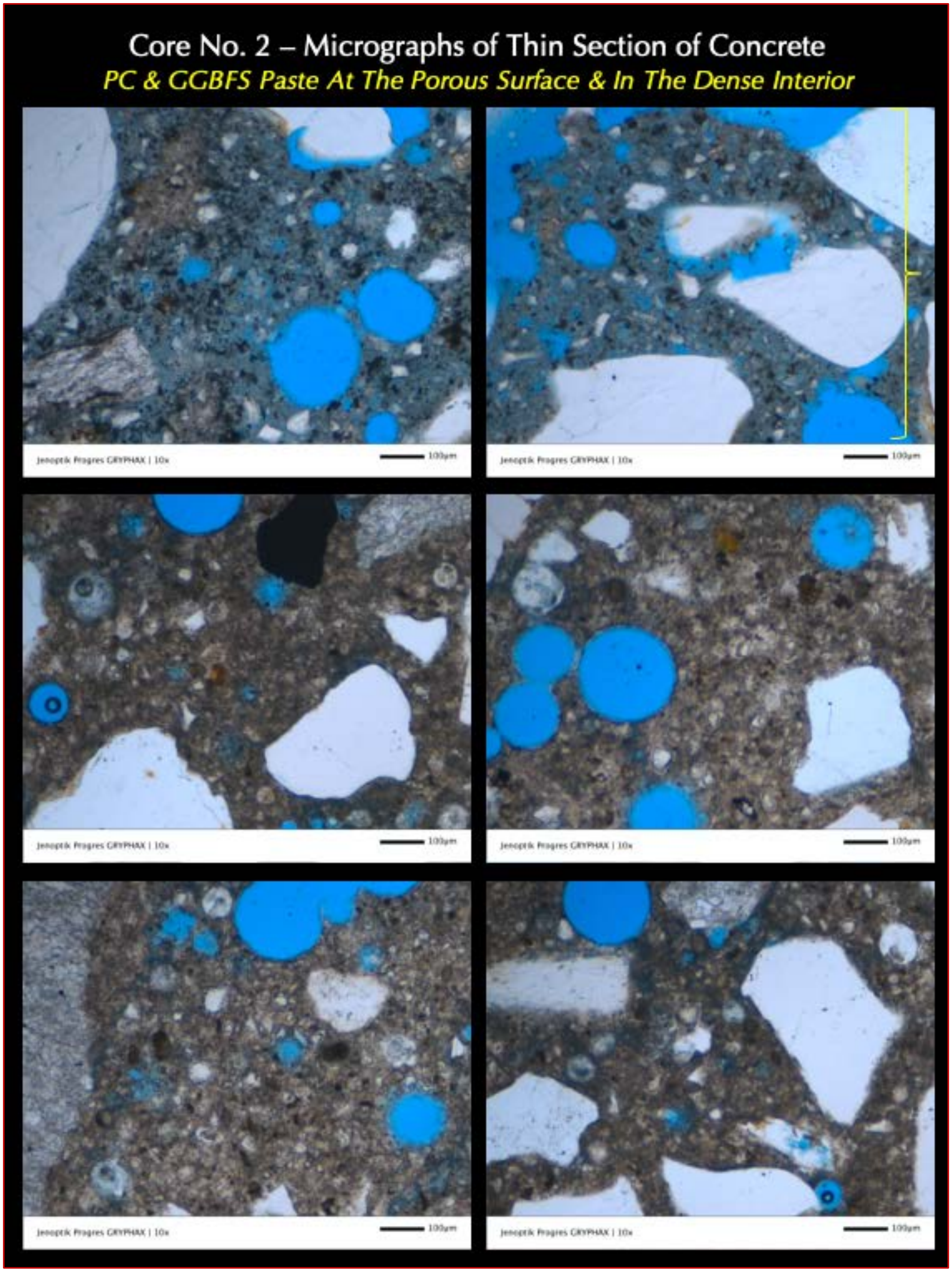

Figure 38: Micrographs of thin section of Core 2 showing soft, porous paste at the surface region in the top row and markedly denser paste in the interior in the middle and bottom rows. In all photos, angular, shard-like glassy particles of ground granulated blast furnace slag and residual Portland cement particles are scattered over cement and slag hydration products.

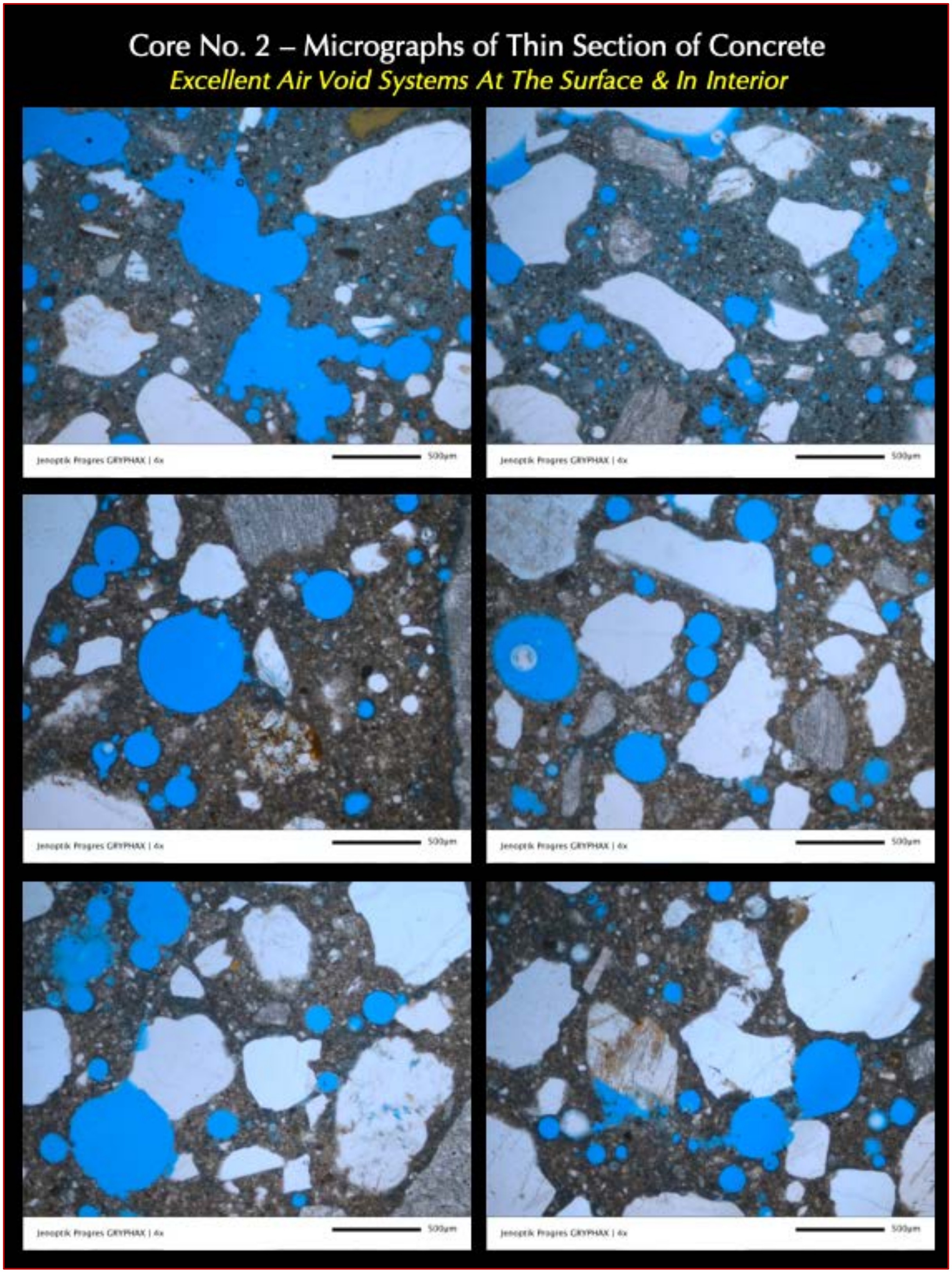

Figure 39: Micrographs of thin section of Core 2 showing air entrainment all throughout the depth from surface to interior and excellent air-void systems where air voids are highlighted by blue epoxy.

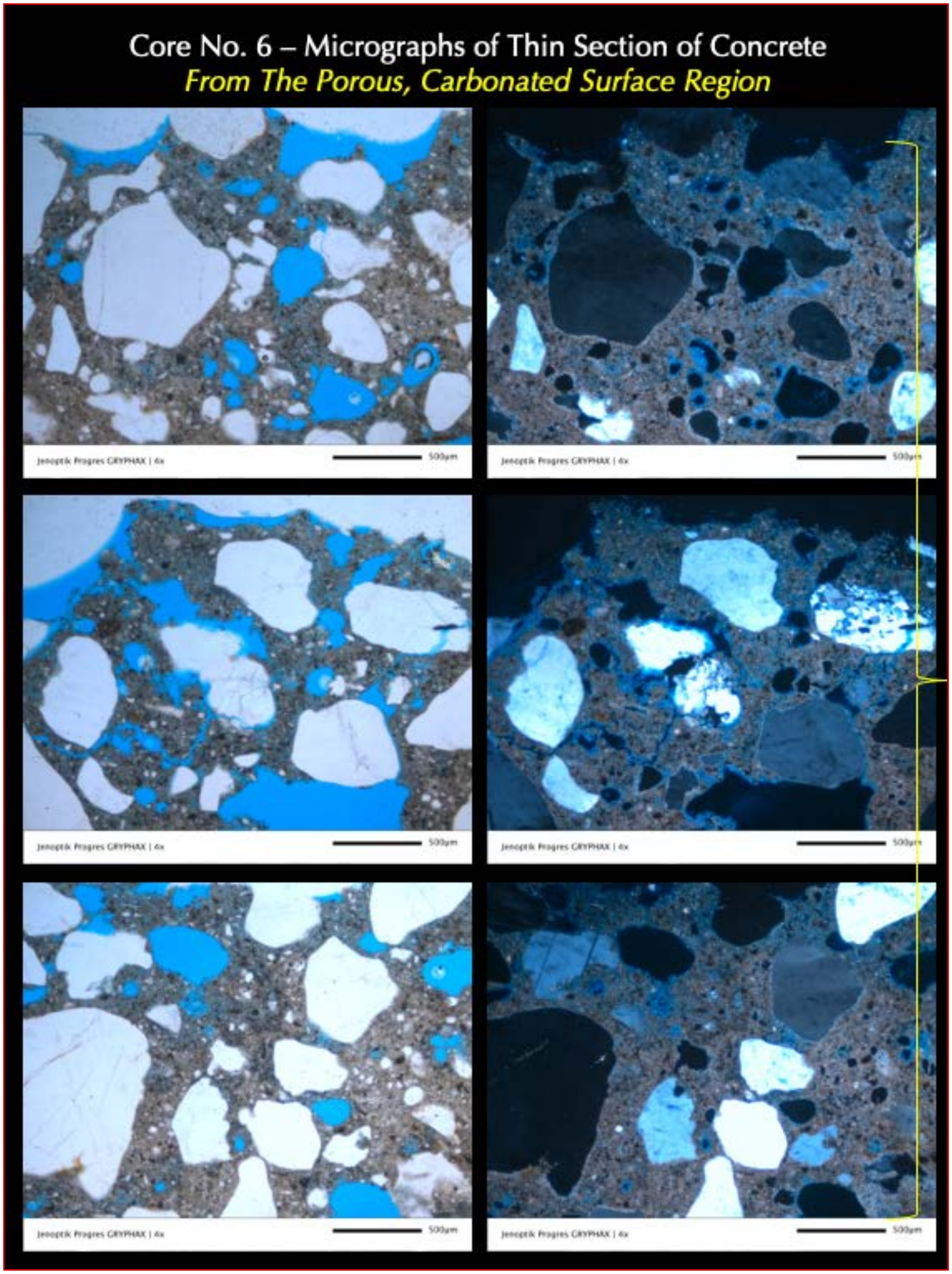

Figure 40: Micrographs of thin section of Core 6 from the exposed surface region showing the soft, porous, high *w/cm*, carbonated surface region to a depth of 5 to 6 mm from exposed surface. Notice the difference in density of paste from the soft, porous very top surface and the paste underneath that porous surface. Left and corresponding right column photos were taken with a petrographic microscope in plane and crossed-polarized light modes, respectively.

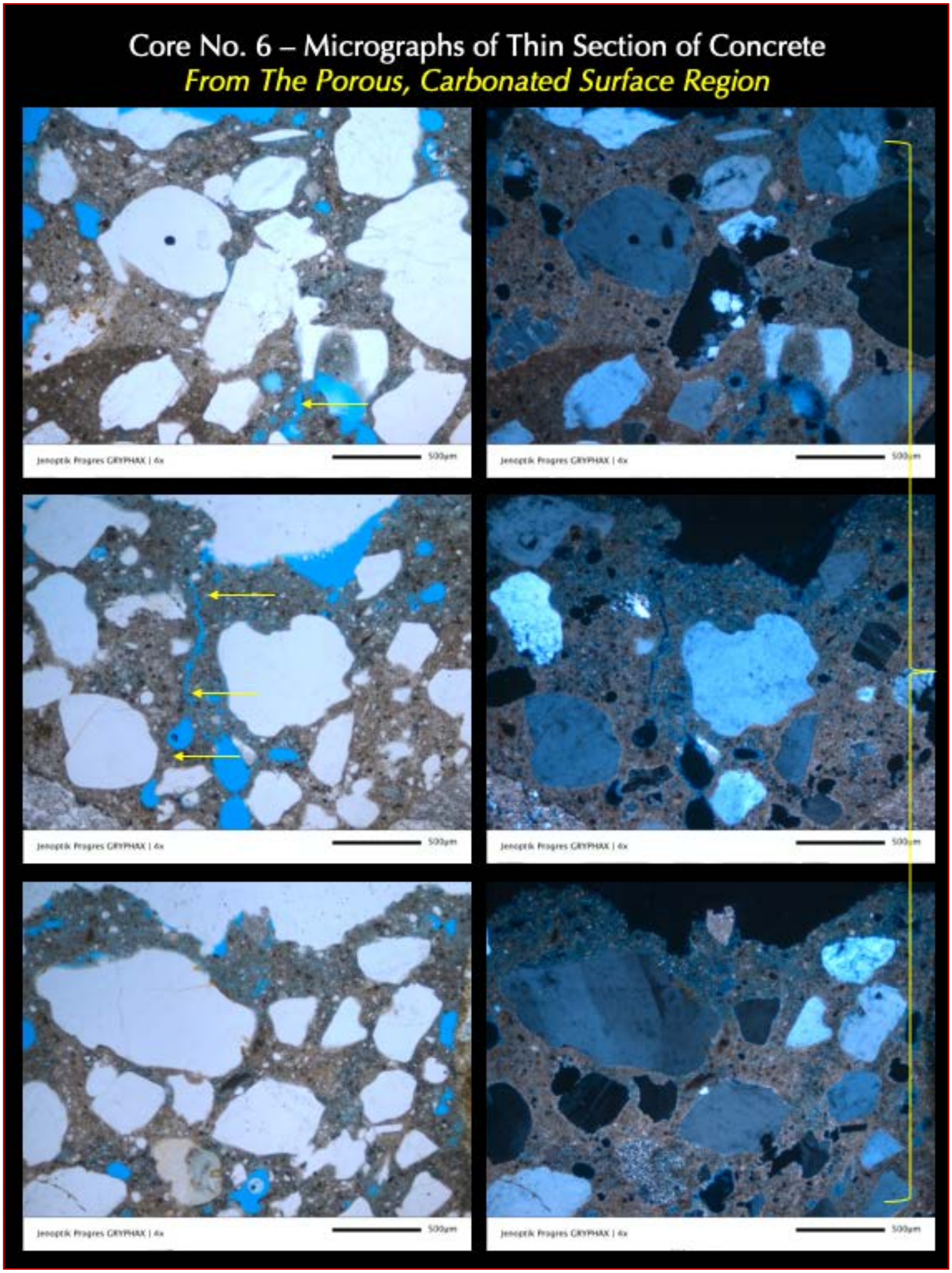

Figure 41: Micrographs of thin section of Core 6 from the exposed surface region showing the soft, porous, high *w/cm*, carbonated surface region to a depth of 5 to 6 mm from exposed surface. Notice the difference in density of paste from the soft, porous very top surface and the paste underneath that porous surface. Left and corresponding right column photos were taken with a petrographic microscope in plane and crossed-polarized light modes, respectively. The middle left photo shows a fine vertical shrinkage microcrack marked by arrows.

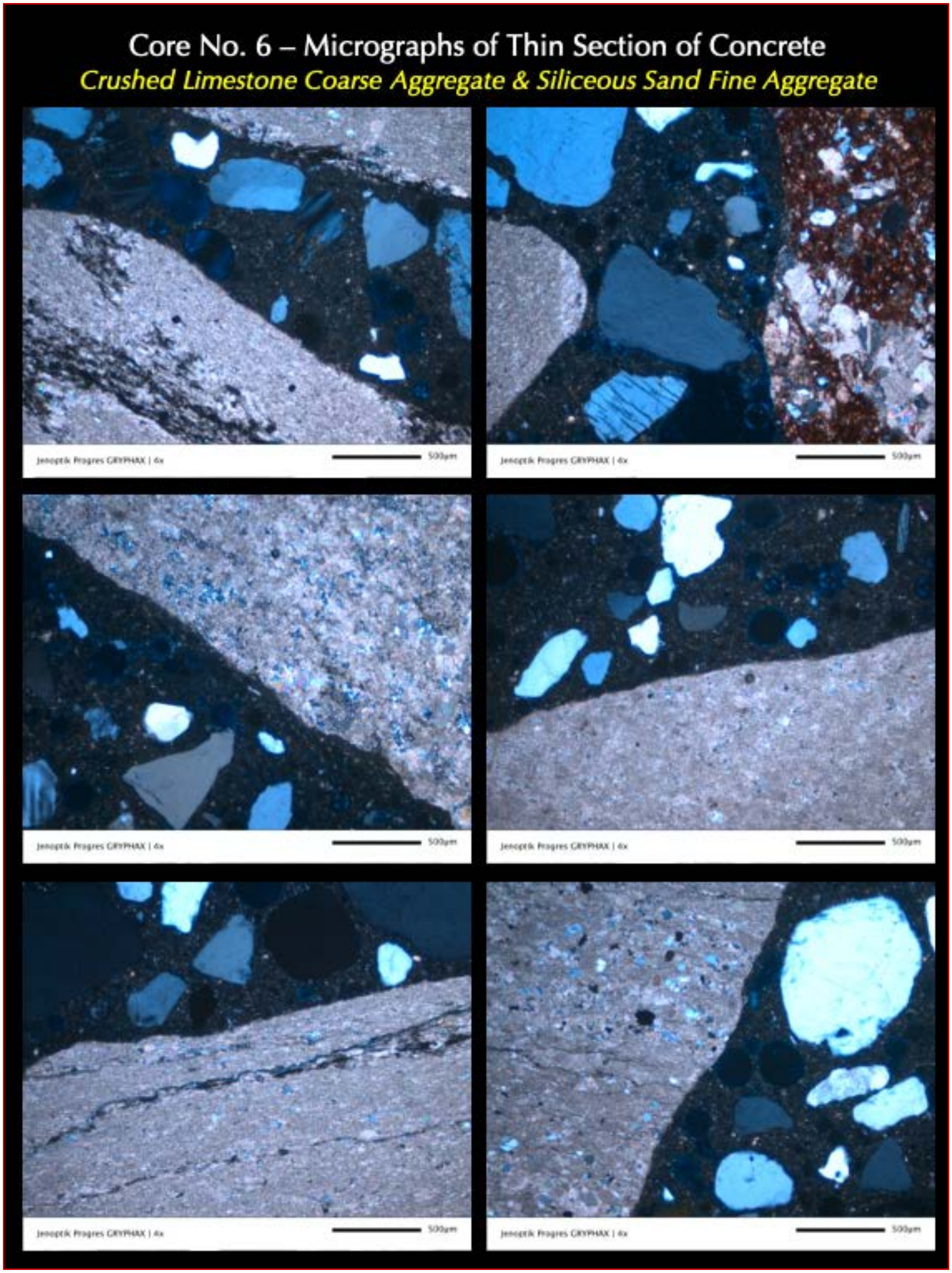

Figure 42: Micrographs of thin section of Core 6 showing the crushed limestone coarse aggregate particles and natural siliceous (quartz, quartzite, feldspar) sand and finer fraction of crushed limestone in the fine aggregate.

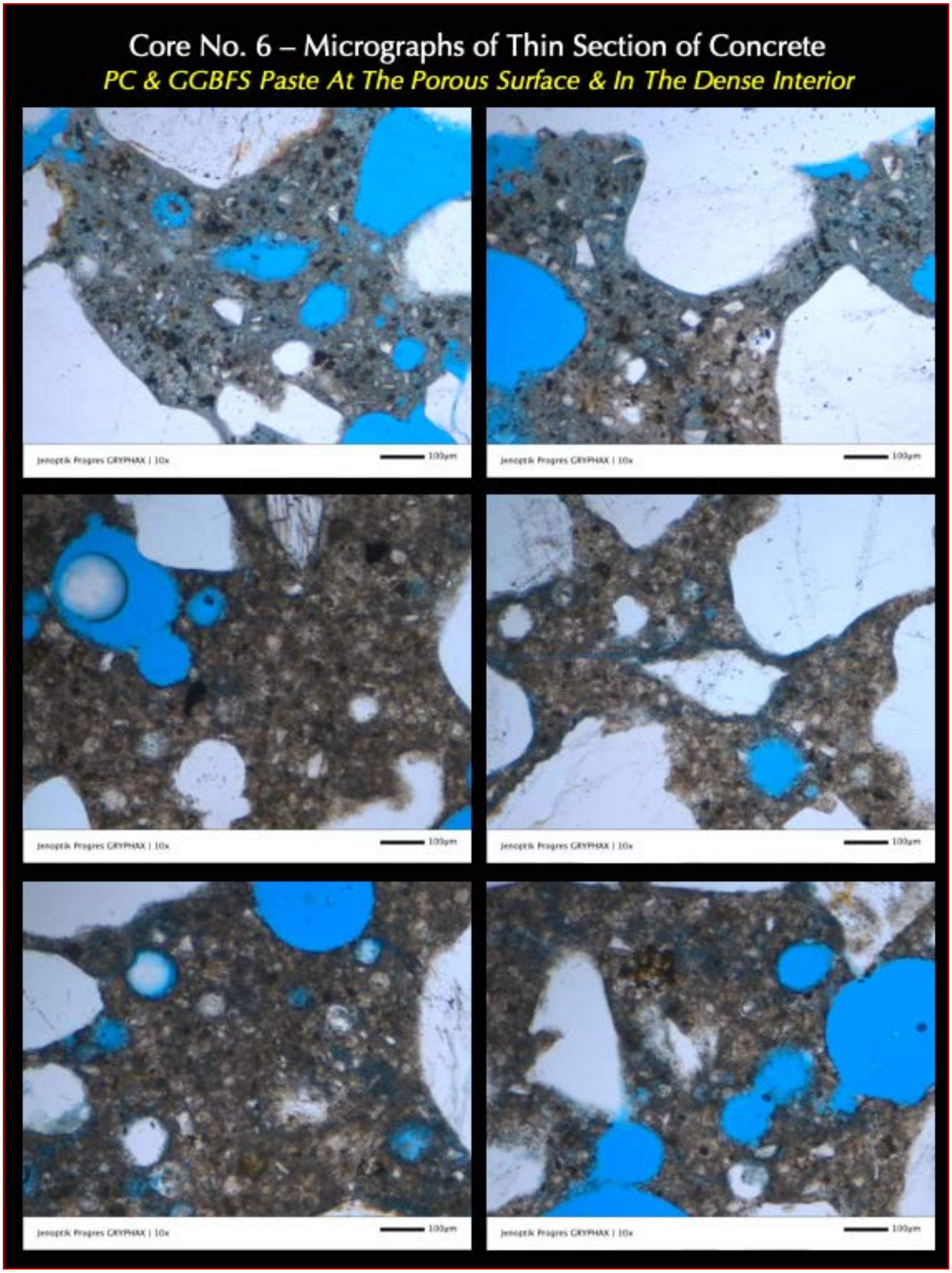

Figure 43: Micrographs of thin section of Core 6 showing soft, porous paste at the surface region in the top row and markedly denser paste in the interior in the middle and bottom rows. In all photos, angular, shard-like glassy particles of ground granulated blast furnace slag and residual Portland cement particles are scattered over cement and slag hydration products.

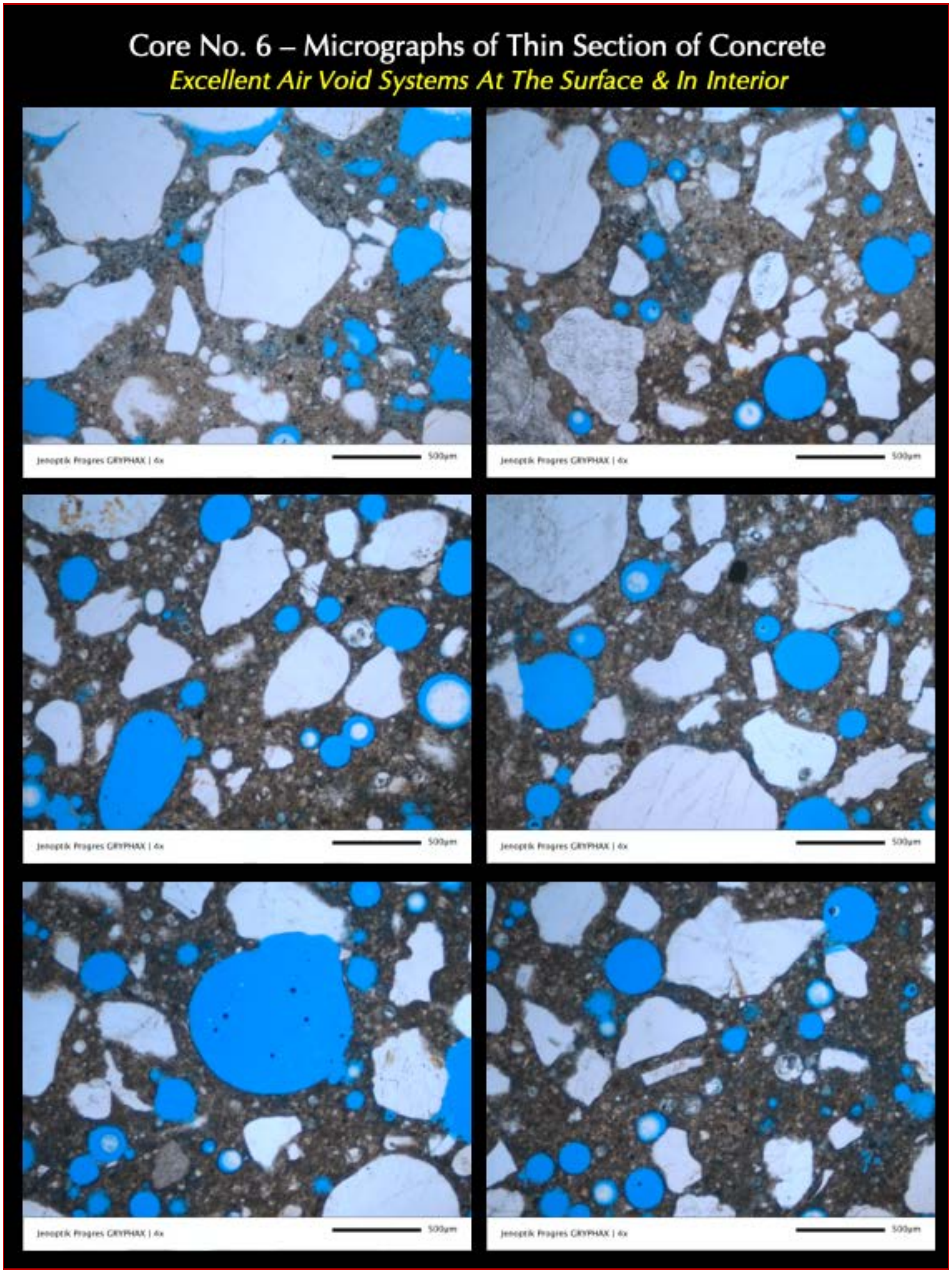

Figure 44: Micrographs of thin section of Core 6 showing air entrainment all throughout the depth from surface to interior and excellent air void systems where air voids are highlighted by blue epoxy.

COARSE AGGREGATES

Coarse aggregates are compositionally similar in both Cores 2 and 6, which are #57 crushed limestone. Limestone particles are angular, dense, hard, 3/4 in. (19 mm) in nominal size, often contains fine dark brown argillaceous veins. Particles are equidimensional to elongated, unaltered, uncoated, uncracked, well-graded, and well-distributed. There is no evidence of alkali-aggregate reactions or any other potentially deleterious reactions of coarse aggregates found in the concrete to cause the observed surface distress. Therefore, coarse aggregate particles have been sound during their service in the concrete and did not contribute to the distress. The argillaceous impurities detected in the limestone are judged inefficient to cause pop out or other distress in the near-surface particles.

FINE AGGREGATES

Fine aggregates are compositionally similar natural siliceous sands having nominal maximum sizes of 3/8 in. (9.5 mm) and made using major amount of quartz and subordinate amounts of quartzite, feldspar, siltstone, shale and other particles. Particles are variably colored, rounded to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and mostly 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 and did not contribute to the distress. The following Table summarizes properties of coarse and fine aggregates in the cores.

Properties and Compositions of Aggregates	No. 2	No. 6
Coarse Aggregates		
Types	Crushed Stone	Crushed Stone
Nominal maximum size (in.)	3/4 in. (19 mm)	3/4 in. (19 mm)
Rock Types	Limestone	Limestone
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dense, hard, often contains fine dark brown argillaceous veins	
Cracking, Alteration, Coating	Unaltered, Uncoated, and Uncracked	
Grading & Distribution	Well-graded and Well-distributed	
Soundness	Sound	Sound
Alkali-Aggregate Reactivity	None	None
Fine Aggregates		
Types	Natural siliceous sand	Natural siliceous sand
Nominal maximum size (in.)	3/8 in. (9.5 mm)	3/8 in. (9.5 mm)
Rock Types	Major amount of quartz and subordinate amounts of quartzite, feldspar, siltstone, shale, and other particles	
Cracking, Alteration, Coating	Variably colored, rounded to subangular, dense, hard, equidimensional to elongated	
Grading & Distribution	Well-graded and Well-distributed	

Properties and Compositions of Aggregates	No. 2	No. 6
Soundness	Sound	Sound
Alkali-Aggregate Reactivity	None	None

Table 3: Properties of coarse and fine aggregates of concrete in Cores 2 and 6.

PASTE

Properties and composition of hardened cement pastes are summarized in Table 2. Pastes are dense, hard, medium gray. Freshly fractured surfaces have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 10 to 12 percent of the paste volumes in the interior bodies. Distributed throughout the paste are angular, shard-like, glassy particles of ground granulated blast furnace slag (GGBFS) having the fineness of Portland cement. Hydration of Portland cement is normal.

Properties and Compositions of Paste	No. 2	No. 6
Color, Hardness, Porosity, Luster	Paste is dense, hard, medium gray. Freshly fractured surfaces have subvitreous lusters and subconchoidal textures	
Residual Portland Cement Particles	Normal, 10 to 12 percent of the paste volumes in the interior bodies	Normal, 10 to 12 percent of the paste volumes in the interior bodies
Calcium hydroxide from cement hydration	Normal, 10 to 14 percent by paste volume in the interior	Normal, 10 to 14 percent by paste volume in the interior
Pozzolans, Slag, etc.	Ground granulated slag	Ground granulated slag
Water-cementitious materials ratio (*w/cm*), estimated	0.40 to 0.44	0.40 to 0.44
Cement Content (bags per cubic yard)	7 to 7 $^{1}/_{2}$ of which 25 to 30 percent is estimated to be ground slag	7 to 7 $^{1}/_{2}$ of which 25 to 30 percent is estimated to be ground slag
Secondary Deposits	None	None
Depth of Carbonation, mm	5 to 6 mm from the surface region	5 to 6 mm from the surface region
Microcracking	None	None
Aggregate-paste Bond	Tight	Tight
Bleeding, Tempering	None	None
Chemical deterioration	None	None

Table 4: Proportions and composition of hardened cement pastes.

AIR

Concrete in both Cores 2 and 6 are air-entrained having air contents similar in both cores and through the depths and estimated to be 6 to 7 percent by volume. Air occurs as: (i) numerous very fine (< 100 micron) to fine (100 m micron to 1 mm) discrete, spherical and near-spherical voids having sizes of up to 1 mm, and (ii) a few coarse, near-spherical and irregularly shaped voids of sizes coarser than 1 mm. The former voids are characteristic of entrained air and the latter ones are characteristic of entrapped air.

Air-void systems of concrete in both cores are judged to be excellent for providing the necessary protection of concrete against distress due to cyclic freezing and thawing at critically saturated conditions, particularly in the presence of deicing chemicals. The observed surface distress of concrete is judged to be at least not due to the lack of entrained air, or inadequate entrained air in the concrete at least at the locations of Core Nos. 2 and 6 where the air-void systems were examined. Figures 25 to 28 show micrographs of lapped cross sections of cores where both cores show adequate entrained air and good air-void systems. Figures 29 and 30 compared air-void systems of cores at the exposed surface regions and in interiors where both the surface and interior showed adequate air and good air-void systems.

WATER-SOLUBLE CHLORIDE AND SULFATE CONTENTS

Table 5 and Figures 45 to 50 show results of water-soluble chloride and sulfate contents of concrete determined from ion chromatography (*a la* ASTM D 4327) on pulverized sections from the top exposed ends, and at mid-depth locations of Cores 1, 2, 5, 6, 7, and 8.

Core ID & Depth of Sample Section		Water-Soluble Chloride & Sulfate Contents from Ion Chromatography		
		% Chloride by mass of concrete	% Chloride by mass of cement (assuming 15% cement in normal-weight concrete)	Water-soluble Sulfate
Core 1 3606 Doc Berlin	0-10 mm	0.0931	0.62	0.1161
	75-85 mm	0.0037	0.02	0.0306
Core 2 3628 Doc Berlin	0-10 mm	0.1019	0.68	0.1530
	65-82 mm	0.0042	0.03	0.0379
Core 5 3624 Summer House	0-10 mm	0.0858	0.57	0.2421
	40-50 mm	0.0044	0.03	0.0715
Core 6 Corner of Maven Clara Downey	0-10 mm	0.0725	0.48	0.0522
	40-50 mm	0.0051	0.03	0.0267
Core 7 3710 Doc Berlin	0-10 mm	0.0504	0.33	0.0839
	75-85 mm	0.0042	0.03	0.0293
Core 8 3500 Doc Berlin	0-10 mm	0.0459	0.30	0.2336
	75-85 mm	0.0044	0.03	0.0356

Table 5: Water-soluble chloride and sulfate contents from the exposed, mid-depth, and bottom ends of cores. Values are all lower than common industry-recommended maximum threshold limit of 0.2 percent chloride by mass of cement to cause corrosion of steel in concrete in the presence of oxygen and moisture.

All cores show clear evidence of high chloride and sulfate at the exposed surfaces (shown in red) compared to interiors, indicating exposures to chloride and sulfate salts.

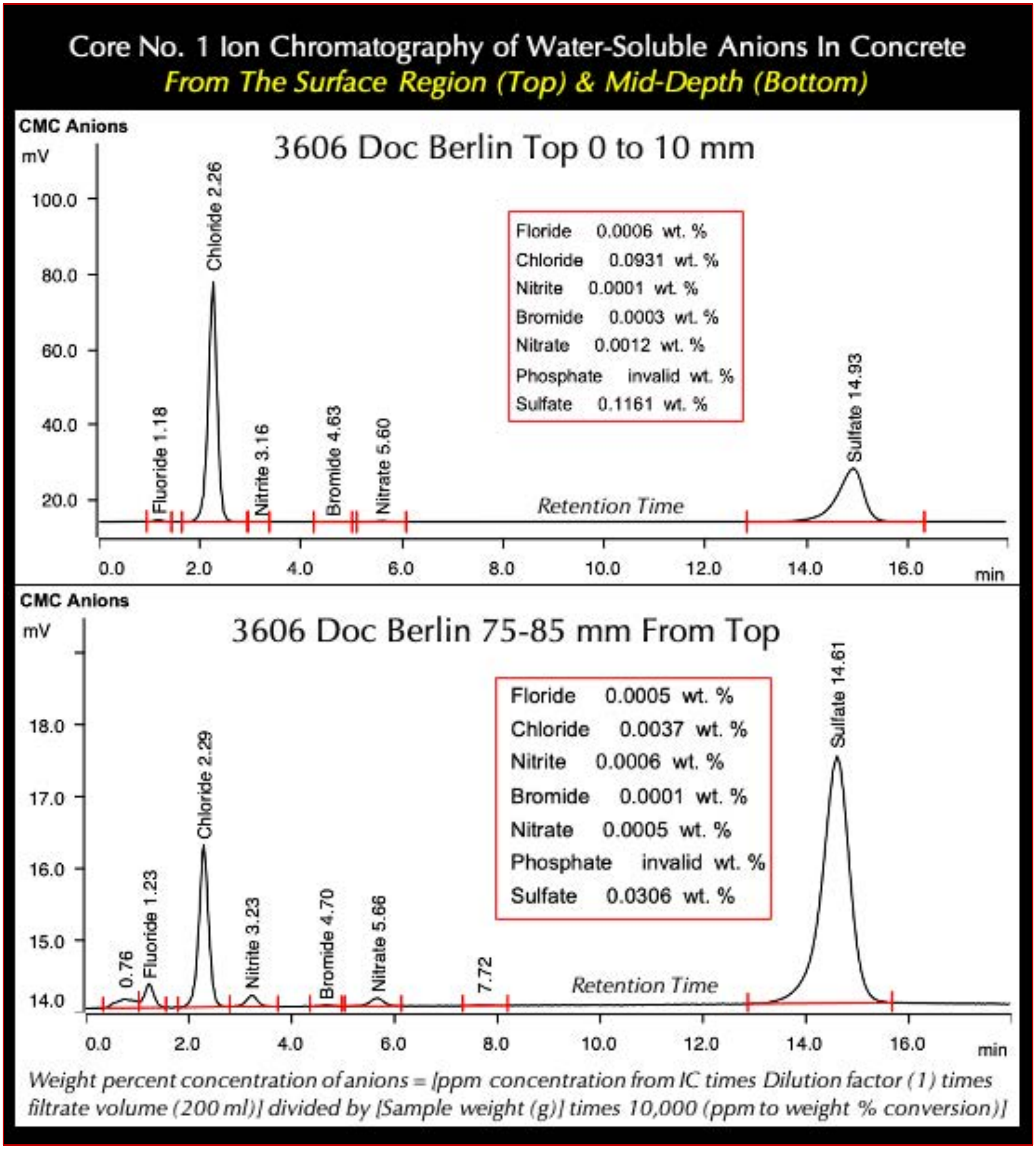

Figure 45: Ion chromatograms of water-soluble anions of filtrates from the exposed surface region and interior of Core 1 showing higher chloride and sulfate at the exposed surface region in the top chromatogram compared to the interior in the bottom chromatogram, indicating exposures to chloride and sulfate salts during service.

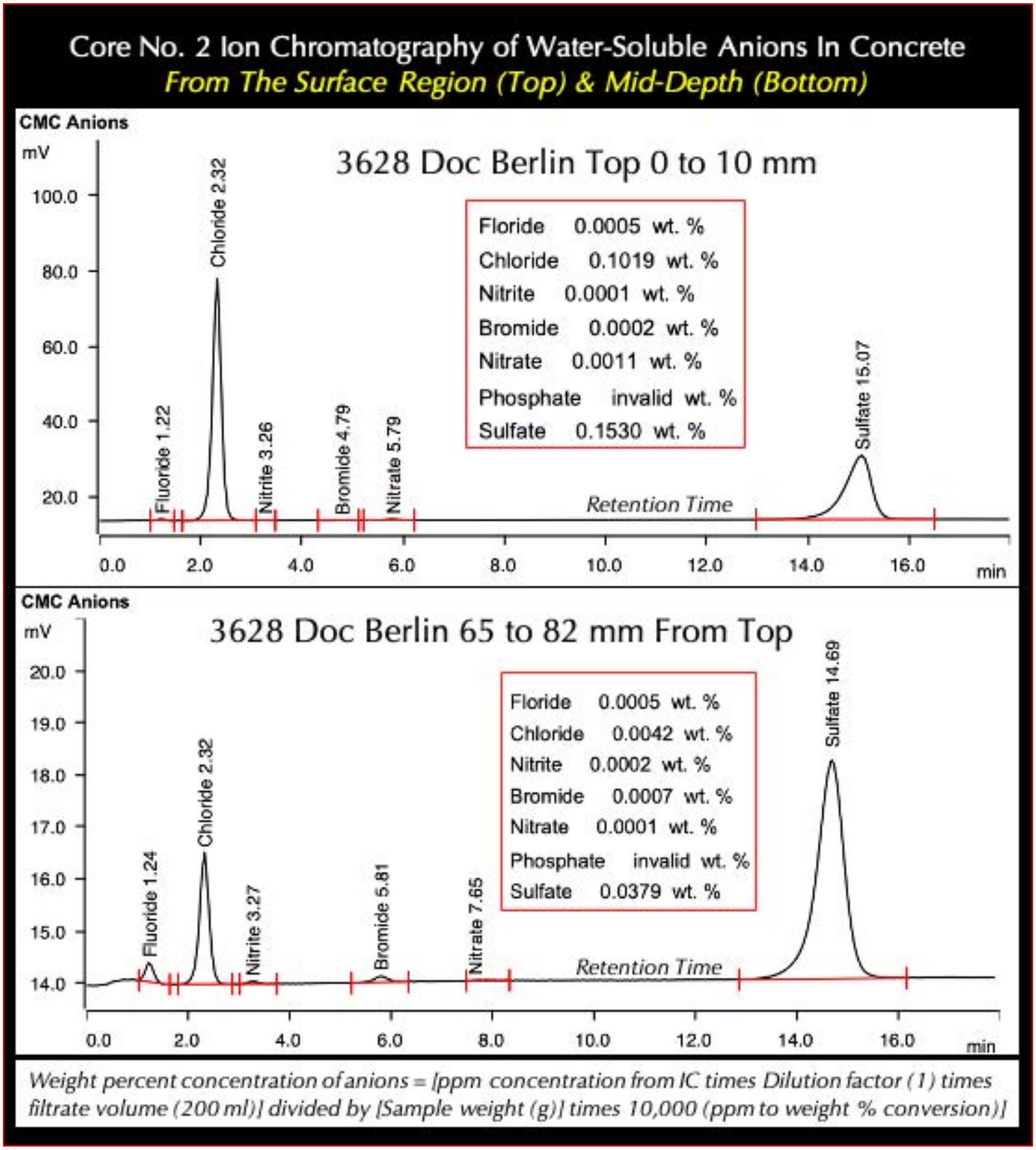

Figure 46: Ion chromatograms of water-soluble anions of filtrates from the exposed surface region and interior of Core 2 showing higher chloride and sulfate at the exposed surface region in the top chromatogram compared to the interior in the bottom chromatogram, indicating exposures to chloride and sulfate salts during service.

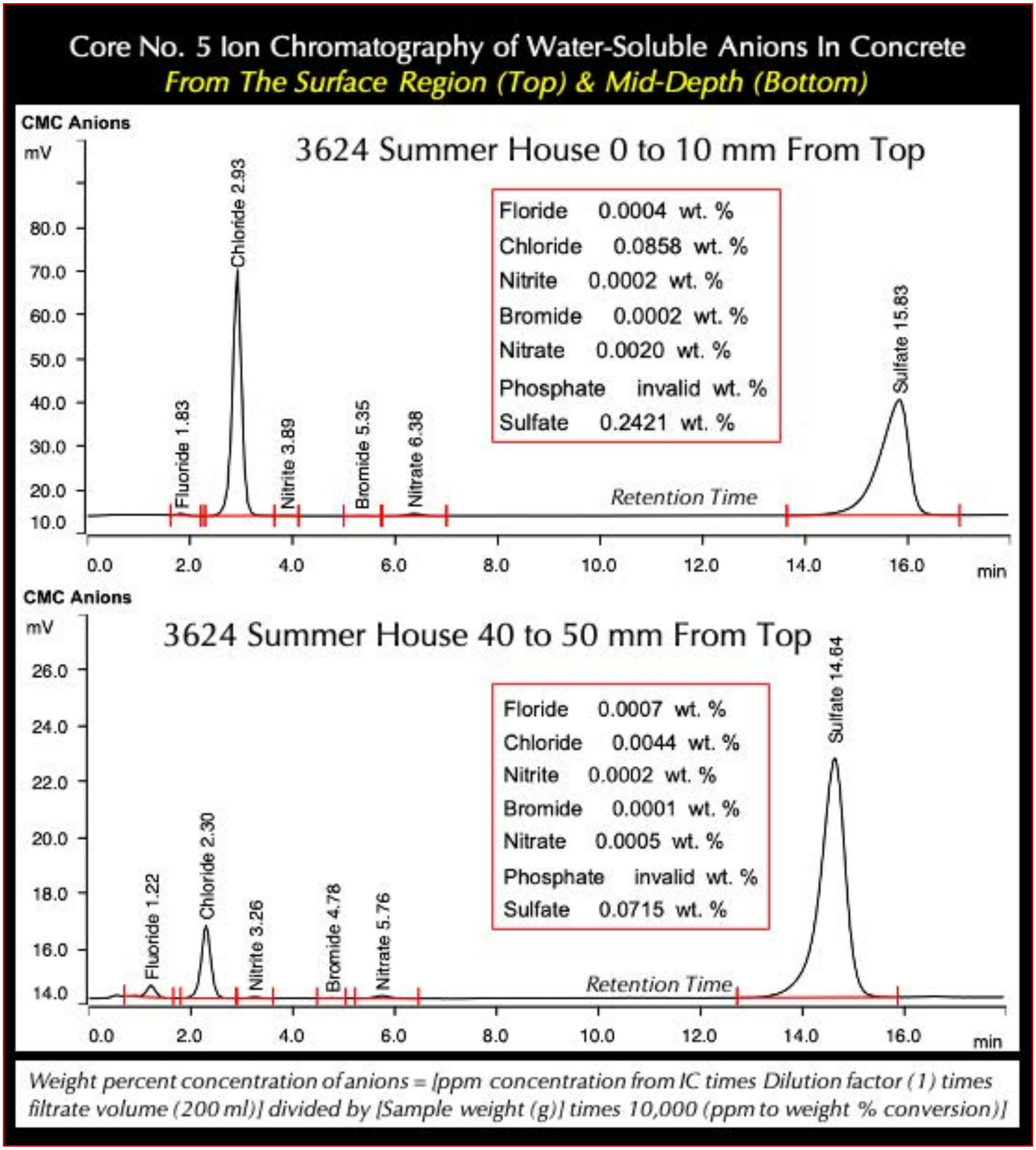

Figure 47: Ion chromatograms of water-soluble anions of filtrates from the exposed surface region and interior of Core 5 showing higher chloride and sulfate at the exposed surface region in the top chromatogram compared to the interior in the bottom chromatogram, indicating exposures to chloride and sulfate salts during service.

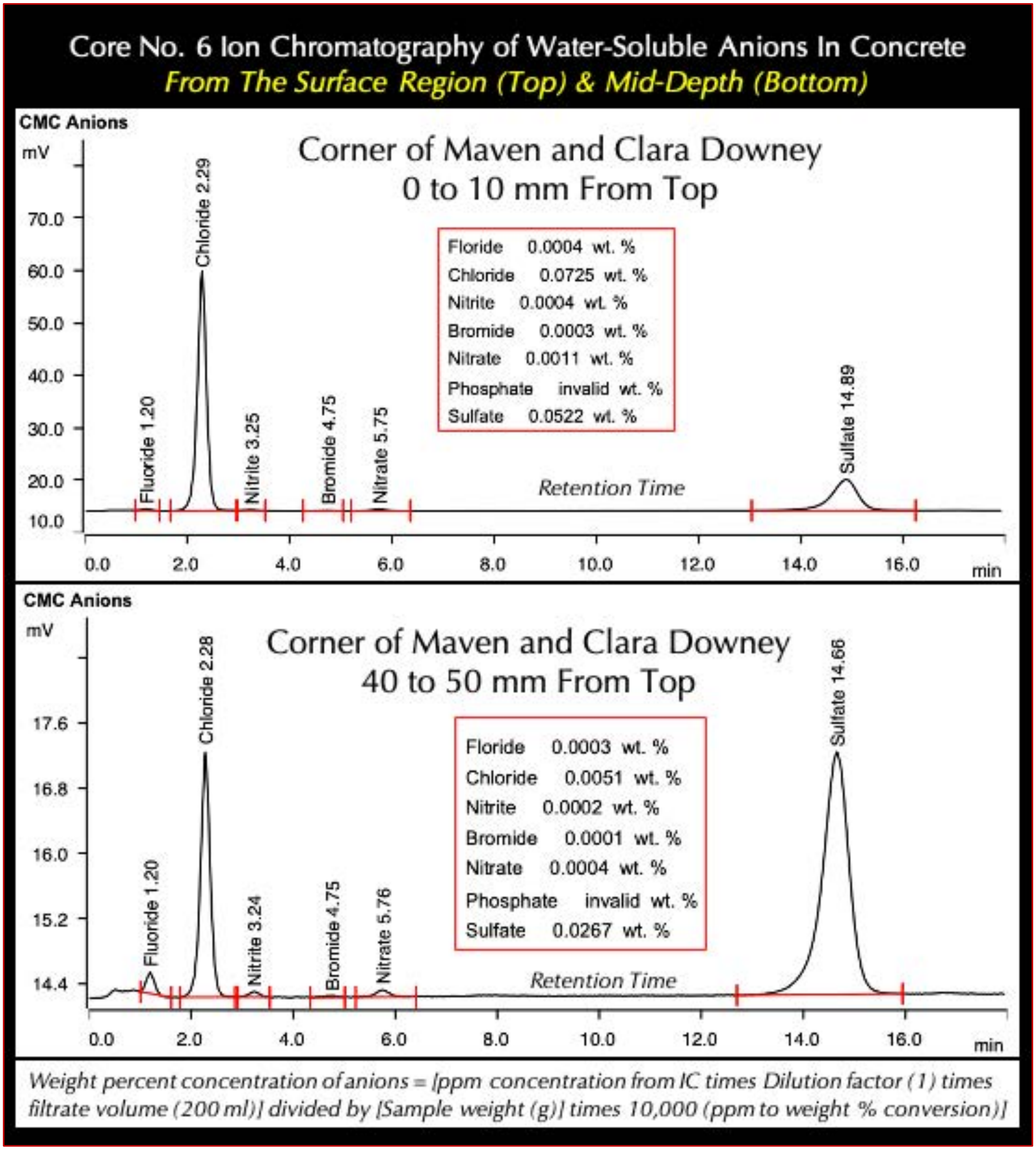

Figure 48: Ion chromatograms of water-soluble anions of filtrates from the exposed surface region and interior of Core 6 showing higher chloride and sulfate at the exposed surface region in the top chromatogram compared to the interior in the bottom chromatogram, indicating exposures to chloride and sulfate salts during service.

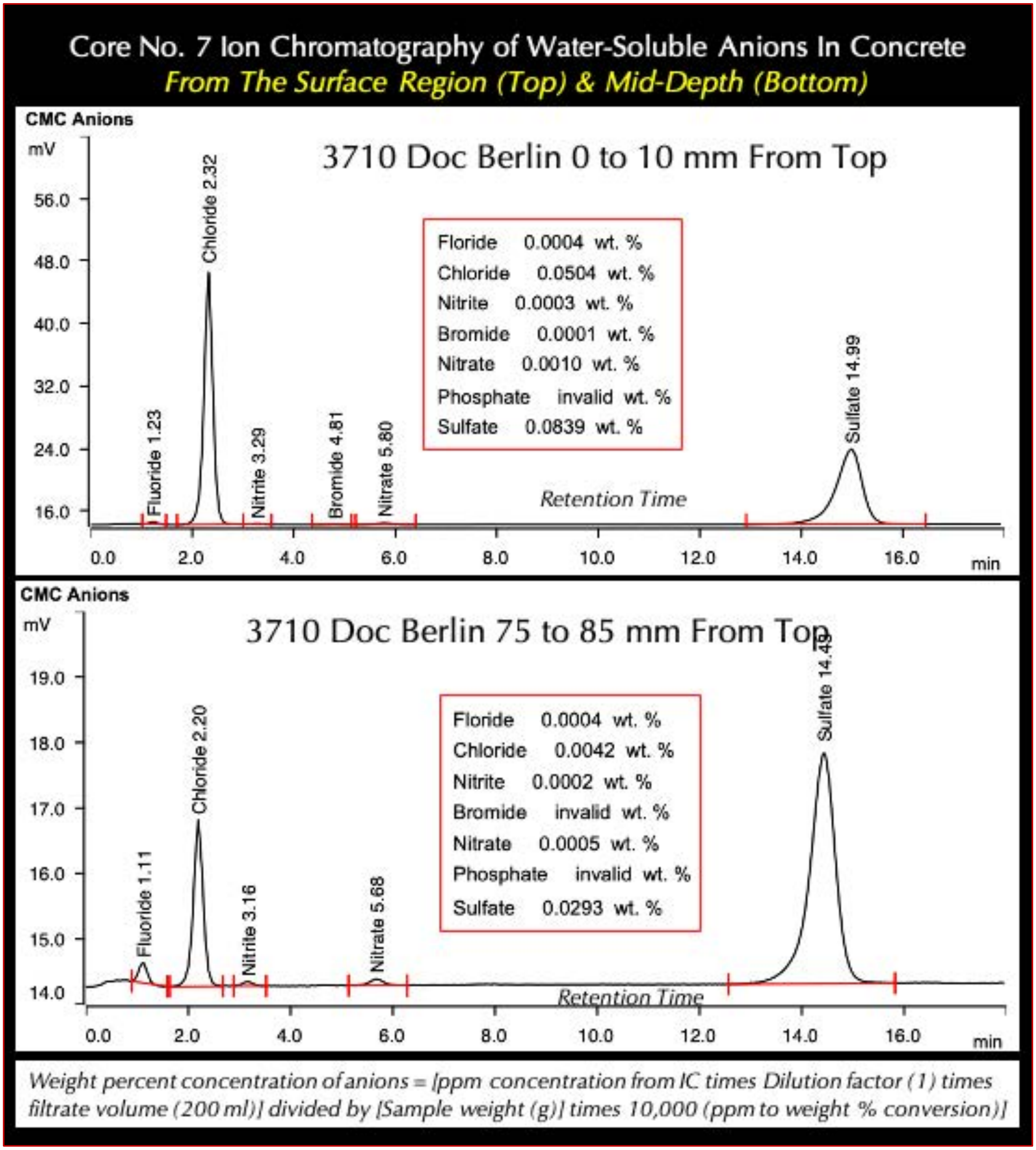

Figure 49: Ion chromatograms of water-soluble anions of filtrates from the exposed surface region and interior of Core 7 showing higher chloride and sulfate at the exposed surface region in the top chromatogram compared to the interior in the bottom chromatogram, indicating exposures to chloride and sulfate salts during service.

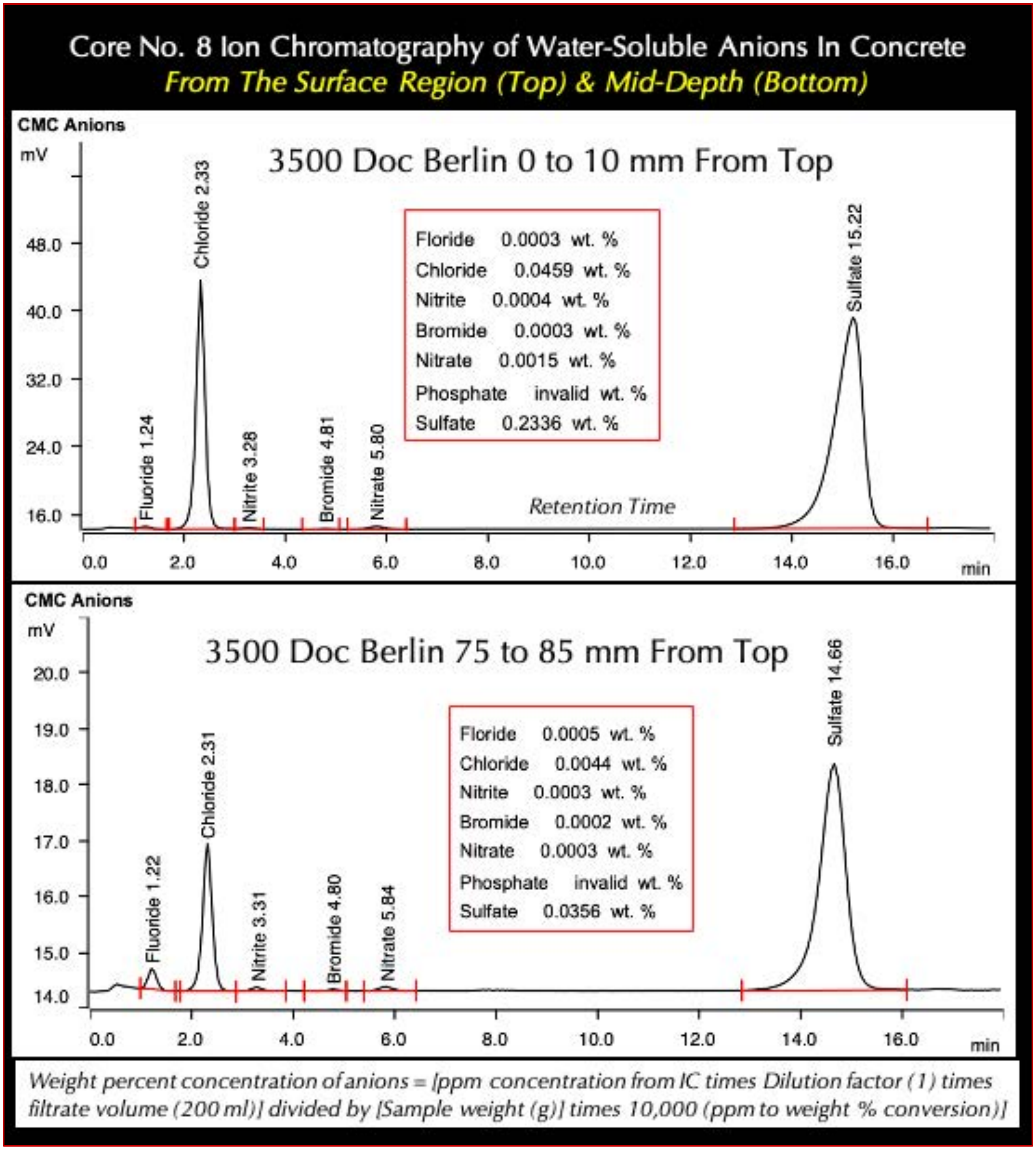

Figure 50: Ion chromatograms of water-soluble anions of filtrates from the exposed surface region and interior of Core 8 showing higher chloride and sulfate at the exposed surface region in the top chromatogram compared to the interior in the bottom chromatogram, indicating exposures to chloride and sulfate salts during service.

COMPRESSIVE STRENGTH

Core ID	Length (in.)	Diameter (in.)	Area (sq. in.)	Load (lbs.)	Corrected Strength (corrected psi)
No. 3	3.64	3.67	10.58	59675	4910

Table 6: Compressive strength results of Core No. 3 that was free of any visible cracks or reinforcement.

DISCUSSIONS

SURFACE DISTRESS

The following Table summarizes conditions of concrete surface at the locations of eight cores, as well as surface conditions of the cores when received.

Core ID	Core Location	Top Exposed Surface
1	3606 Doc Berlin	Broom-finished, sound
2	3628 Doc Berlin	Broom-finished, 3 mortar lift-offs, $^3/_8$ in. size
3	Mailbox near 15711 Murpheys Tin	Finished, 1 small pop-out ($^1/_8$ in. size) otherwise sound
4	Near dog waste station at Doc Berlin tot lot	Sheet scaling with fine aggregate exposure, 1 mm thin sheet of original finished surface loosely adhered to the main body
5	3624 Summer House	Broom-finished, sound
6	Corner of Maven and Clara Downey	Broom-finished, sound, with beige discoloration of paste at top 2 mm
7	3710 Doc Berlin	Finished with 2 pop outs, $^3/_8$ in. size
8	3500 Doc Berlin	Partially scaled (10%), Fine broom-finish

Table 7: Conditions of wearing surfaces in eight cores.

AIR CONTENTS AND AIR-VOID SYSTEMS

Concrete in Cores 2 and 6 are air-entrained having an excellent air-void system in both cores, both at their wearing surface region as well as in the interiors. Air contents are estimated from petrographic examinations to be 6 to 7 percent by volume. Air occurs as: (i) numerous very fine (< 100 micron) to fine (100 m micron to 1 mm) discrete, spherical and near-spherical voids having sizes of up to 1 mm, and (ii) a few coarse, near-spherical and irregularly shaped voids of sizes coarser than 1 mm. The former voids are characteristic of entrained air and the latter ones are characteristic of entrapped air.

Air-void parameters are judged to be in conformance to the common industry requirements for concretes from an outdoor environment exposed to freezing, thawing, and deicing chemicals in a moist environment, where the concrete should have a total air content in the range of 4.5 to maximum 7.5 percent.

The other air-void parameters that are more crucial for freeze-thaw durability of concrete than the total air are the air-void specific surface, which measures the 'fineness' of air-voids, and, air-void spacing factor, which measures the 'closeness' of voids. Both these parameters are judged to be satisfactory and in conformance to common industry recommendations.

Entrained air-voids are necessary for the protection of a concrete in a moist outdoor environment against distress due to cyclic freezing and thawing at critically saturated conditions, especially in the presence of deicing salts (Jana 1997, 2004, 2007, Jana and Cole 1997, Jana and Erlin 2001). Entrained air provides the necessary room for the water to escape during freezing, thus relieving the freezing-related stresses to not exceed the tensile strength of concrete for it not to crack or spall. Having a very fine network of numerous discrete spherical air bubbles at a very close-spaced distance for ready escape of water (i.e. fulfilling the specific surface and void-spacing factor requirements) are far more important for an outdoor concrete in a moist environment than having a lot of air-voids but not fine enough and close enough for water to escape. The absolute total air content of concrete, therefore, has little significance on freeze-thaw durability (Jana et al. 2005, except possible strength loss from high air) than the fineness of air-void system (i.e. the specific surface) and its closeness (i.e. the void-spacing factor).

AGGREGATES

The crushed limestone coarse aggregate and natural siliceous (quartz-quartzite) sand fine aggregate particles in Cores 2 and 6 are present in sound conditions and did not contribute to the observed distress. These coarse and fine aggregate should not cause any pop out from unsoundness. Therefore, any distress that resembles pop outs i.e. having fractured remains of underlying near-surface aggregate could possibly be mortar lift-off than a pop out, where the original finished surface was lifted off from the flat topside of underlying aggregate due to the weak bond between the finished surface and the underlying aggregate than any expansion or unsoundness of the aggregate itself. Aggregates, therefore, are not responsible for the distress.

PLACEMENT, FINISHING, AND CURING

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 Cores 2 and 6.

Petrographic examinations of Cores 2 and 6, however, found evidence of higher water-cementitious materials ratio at the very top 5 to 6 mm resulting in lighter toned paste from the interior which could have formed from addition of water during finishing and/or finishing in the presence of bleed water at the surface. Such practices can reduce the overall freeze-thaw durability and wearing resistance of surface despite having a good air entrainment.

Additionally, there is evidence of premature finishing, i.e. finishing prior to the cessation of bleeding as sheet-scaling, which forms due to accumulation of bleed water beneath the finished surface eventually causing separation of the top thin sheet of finished surface from the main body of concrete.

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. Cores 2 and 6 showed 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 scaling.

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.

The 4910-psi compressive strength of Core 3 is adequate for attainment of maturity as long as the concrete received at least 4000 psi strength within the first month of placement and a period of air drying prior to the first exposure of winter, salt, and snow.

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).

Due to the higher *w/cm* of paste at the top than the interior, exposures to common sodium or calcium chloride-based deicing salts could have aggravated surface scaling. Due to the hygroscopic character of common road salts, having adequate entrained air-voids is essential for resistance to salt-related scaling. Exposures to corrosive salts, such as magnesium-based salts, however, could cause scaling even in a good concrete by chemical decomposition of calcium silicate hydrate, the main component of paste that is responsible for development of strength in a concrete to magnesium silicate hydrate that has no cementitious property.

Results of water-soluble chloride and sulfate profile analyses from the top wearing surface regions and the interior bodies of Cores 1, 2, 5, 6, 7, and 8 show higher chloride and sulfate at the surfaces compared to bodies thus indicating exposures to chloride and sulfate salts at the surface during service, indicating potential distress of wearing surface from such exposures.

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 of evidence of premature finishing or finishing with bleed water at the surface. 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 for providing the firsthand 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.

CONCLUSIONS

Based on detailed laboratory investigations, the observed and reported surface distress of concrete slab are judged to be due to one or a combination of the following factors:

a. Improper finishing practices leading to less durable wearing surface compared to interiors in having higher *w/cm* pastes at the exposed surfaces compared to interiors, at least at the locations of Cores 2 and 6;

b. Premature finishing prior to the cessation of bleeding causing accumulation of bleed water beneath the finished surface, at least at the location of Core 4;

c. Inadequate embedding of the near-surface coarse aggregate particles causing exposures of flat topsides of near-surface crushed limestone particles due to the presence of weak bonds between the flat topsides of near-surface coarse aggregate and the thin sheet of finished surface above those particles to cause mortar lift-offs, at least at the locations of Cores 2, 3, 5, 7, and 8;

d. Pop outs due to moisture-induced expansions of near-surface argillaceous limestone coarse aggregate particles can also occur, which, however, is not found in the cores examined here; and,

e. Exposures to potentially deleterious chloride and sulfate-based salts during service, which can cause and/or aggravate the surface conditions especially during cyclic freezing and thawing.

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✪ ✪ ✪ END OF TEXT ✪ ✪ ✪

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.

Concrete, Construction, or Salt—Which Causes Scaling?

Part 2: Importance of finishing practices

BY DIPAYAN JANA

Scaling of concrete surfaces is a common problem in many outdoor slabs exposed to deicing salts and cyclic freezing and thawing. Despite occurrences of adjacent panels—one perfectly sound while the other severely scaled—exposed to the same deicing conditions, salt is, allegedly, the most common culprit of scaling. The first part of this two-part article described how a poor air-void system can cause surface scaling in concrete. In all case studies described, concrete scaling was *initiated* due to the poor air-void system and was *aggravated* by the presence of deicing salts. Concrete with a good air-void system showed much better resistance to freezing and salt than that with a poor air-void system.

This second part describes three additional case studies where, despite having good air-void systems, the concrete scaled due to improper finishing practices such as: a) initiation of finishing prior to the cessation of bleeding (entrapping bleed water under the finished surface); b) finishing in the presence of excess water at the surface, which reduces the scaling and abrasion resistance of the surface; and c) prolonged finishing, which severely reduces the air content at the surface and increases the concrete's potential to scale.

IMPORTANCE OF FINISHING

Case study I: Premature finishing

This particular case study is of a concrete sidewalk that developed severe scaling in some panels within 2 years of placement. The scaled panels, however, were adjacent to sound, broom-finished panels. Within the scaled panels, isolated areas lay where the original broom-finished surface was found loosely adhered to the main body of the slab with a distinct gap (Fig. 1). This gap between the loosely attached, finished surface (having a nominal thickness of 1/8 in. [3.2 mm]) and the main slab is usually less than 1/8 in. (3.2 mm) in width.

The sheet-like masses of loosely adhered finished surfaces are incipient scales, ready to be scaled off by cyclic freezing and thawing and/or by traffic loading. Unlike the lenticular configuration of scales formed by cyclic freezing and thawing of poorly air-entrained concrete, these sheet-like scales have an almost uniform thickness. Areas surrounding the incipient scales are severely scaled where the finished surface is missing, and coarse and fine aggregate particles are exposed; therefore, it is unlikely that this difference in surface conditions of adjacent panels is due to the application of deicing salts.

Detailed petrographic examinations of core samples taken from the sound and scaled panels showed textural and microstructural evidence indicative of premature finishing (that is, finishing prior to the cessation of bleeding, which entraps bleed water underneath the finished surface and causes scaling and incipient scales). Some of this textural and microstructural evidence includes bleed water channels, soft paste at the surface, and coarse aggregate sockets on the scaled surface and on the undersides of scales (Table 1 and Fig. 1).

The optimum time to finish a concrete surface has proven to be between the initial and final sets. Conditions that slow and/or prolong bleeding and/or increase the rate of evaporation of water at the surface alter the optimum finishing time and increase the potential for premature finishing. In the petrographic analysis, the air-void systems of both scaled and sound cores were similarly good in the slab and at the surface, thus they were not responsible for scaling. Because deicing salts increase the degree of saturation of concrete, the gap underneath the incipient scales saturates more easily in the presence of salts, which increases the aggressiveness of scaling.

Case study II: Excess surface water

Figure 2 shows a core taken from a contraction joint in a sidewalk having adjacent sound and scaled panels.

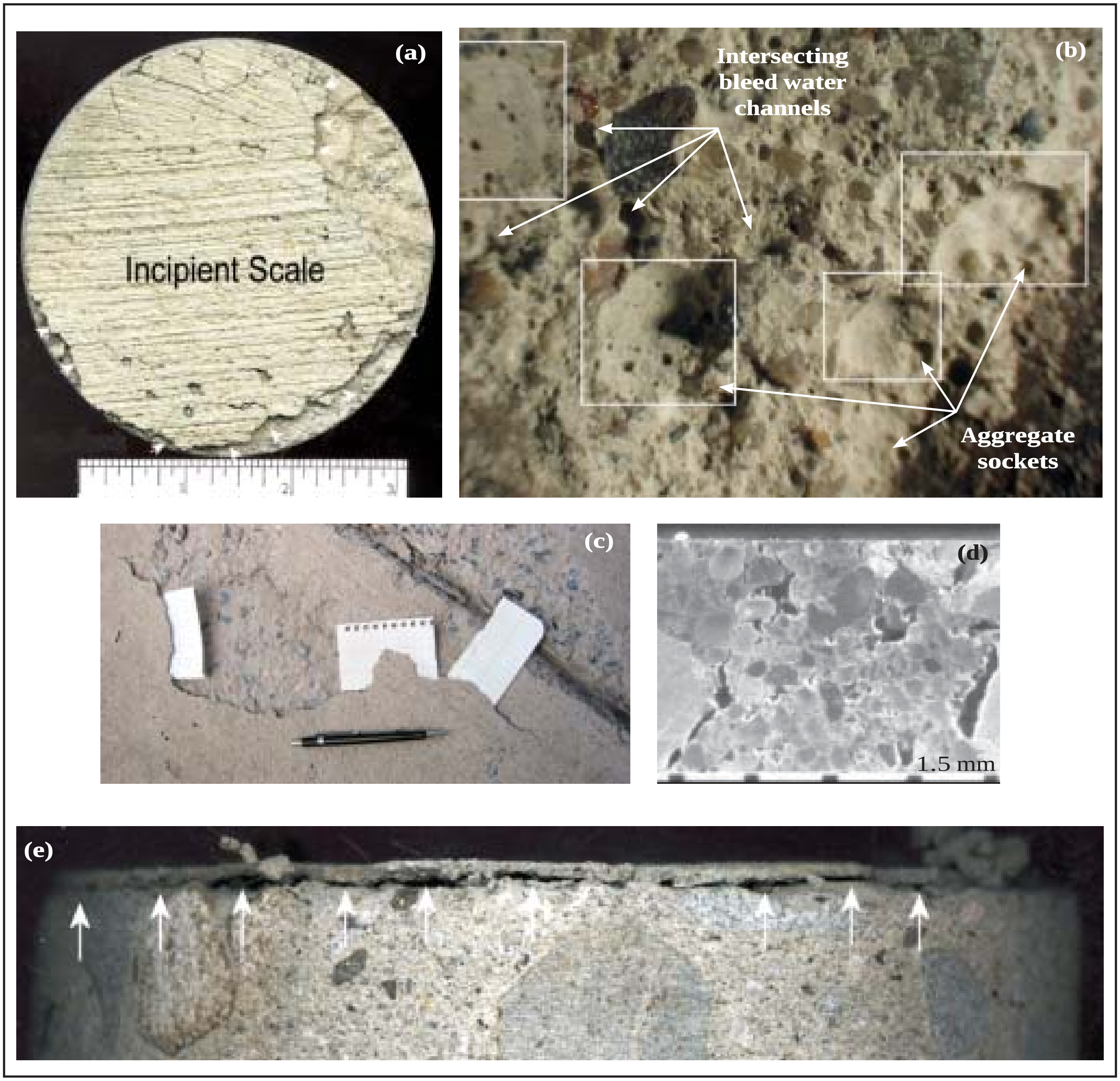


Fig. 1: Case study I (Scaling due to premature finishing)—Shown are: (a) a core from an incipient scale showing a broom-finished surface loosely adhered to the body of the core; (b) abundant coarse aggregate sockets, intersecting bleed water channels, and voids on the scaled surface; (c) insertion of paper into the “gaps” between the finished surface and the body; (d) bleed water channels underneath the finished surface; and (e) the incipient scaling of the finished surface in the side view of the core shown in (a)

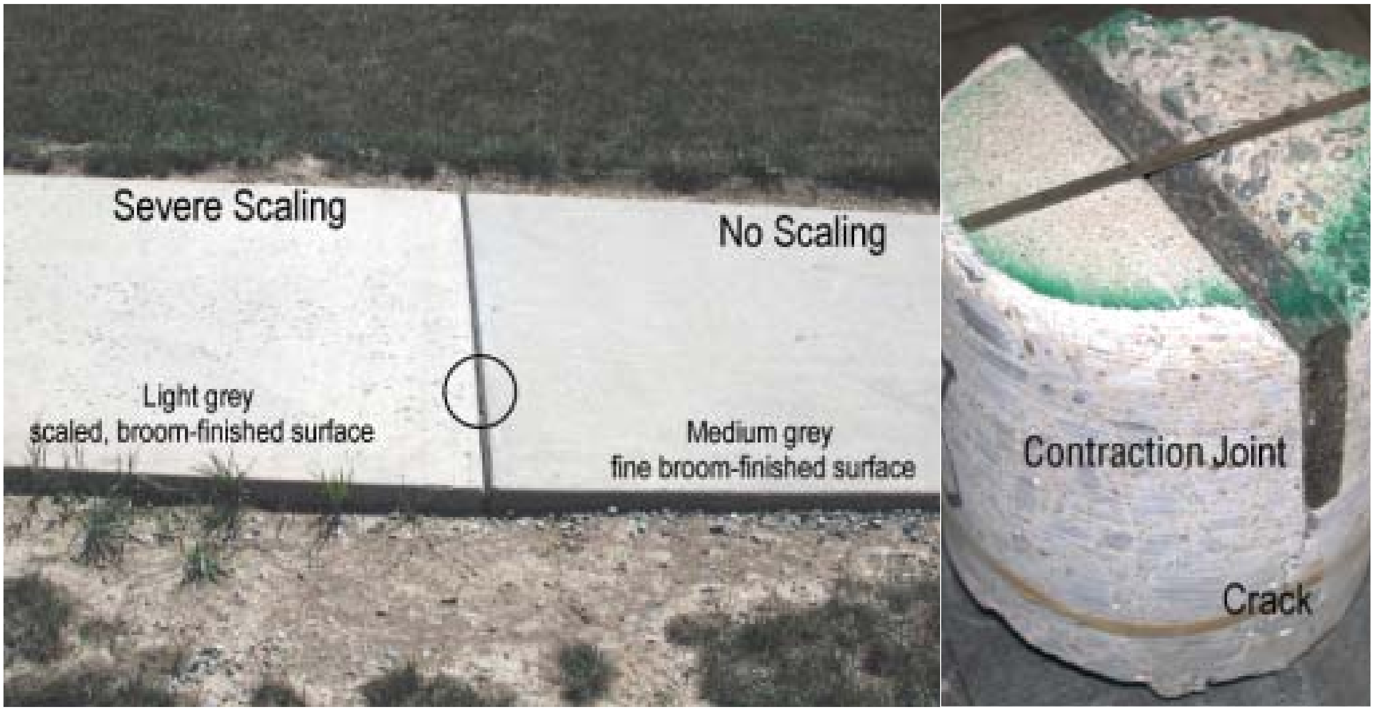


Fig. 2: Case study II (Scaling due to finishing in the presence of excess water at the surface)—Concrete core from a contraction joint showing adjacent sound and scaled surfaces

TABLE 1:
Some petrographic observations in the three case studies of scaling described in this article

Case studies of scaling	Petrographic observations
I: Scaling due to cyclic freezing and thawing of concrete that has been finished prematurely prior to the cessation of bleeding	1) A distinct, narrow separation (not a crack) between the loosely adhered finished surface (the incipient scale) and the body of the concrete. 2) Uniform thickness of loose scales. 3) Texture of the underside of the incipient scale shows irregularly shaped water voids that are indicative of bleed water entrapment. 4) Narrow, vertical, stringy voids or bleed water channels in the body, some of which may be intersected by the scaled surface. 5) Evidence of excessive bleeding in the concrete such as progressively increasing *w/cm* toward the top and laitance. 6) Texture of the freshly scaled surface under the loosely adhered, incipient scale shows soft, high *w/cm* paste relative to the *w/cm* in the main slab. 7) The scaled surface (and the underside of incipient scale) contains abundant coarse aggregate sockets that are indicative of a weak aggregate-paste bond due to the presence of excess water during finishing.
II: Scaling (abrasion) due to finishing in the presence of excess water at the surface	1) Soft, porous, fragile, high *w/cm*, light gray paste on the scaled surface and to a depth of 1/8 to 1/2 in. (3 to 13 mm). 2) Distinct variations of these surface properties from the paste in the interior of the slab. 3) High depth of carbonation. 4) The abundance of residual portland cement particles is significantly less at the surface than in the interior; the degree of hydration of cement particles is adequate at the surface.
III: Scaling (delamination) due to prolonged finishing and lack of air voids at the surface	1) Severe loss of air at the surface and in the near-surface region of air-entrained concrete (usually to a depth of 1 in. [25 mm]). 2) A dense, hard, dark gray, low (or no) air-near-surface zone rich in the mortar fraction of the concrete.

Both panels were made using the same concrete and were sealed after finishing with a cure-seal compound. Cores taken from both panels have good air-void systems and similar chloride contents (Table 2); but the top 1/2 to 3/4 in. (13 to 19 mm) in the scaled panel was found to have soft, porous, fragile paste compared to the interior of the slab or to the concrete in the sound panel.

The soft paste of the scaled surface was due to a higher water-cementitious materials ratio (*w/cm*) in the surface paste relative to that in the rest of the slab or in the sound panel. As a result, there were fewer residual portland cement particles at the panel surface and a greater depth of carbonation compared with the sound panel (Table 1). Soft, high *w/cm* paste at the scaled surface typically occurs when finishing is performed in the presence of excess water at the surface (from bleed water and/or from water added during finishing). This soft paste not only reduces the abrasion resistance of the surface, but also increases its vulnerability to scaling due to cyclic freezing at critically saturated

TABLE 2:
Air-void parameter, *w/cm*, and chloride content of sound and scaled concrete cores in the three case studies described

Three case studies of scaling	Surface conditions of samples	Locations where various parameters were measured	Total air content, %	Entrained air content, %	Specific surface, in^2/in^3	Void-spacing factor, in.	Estimated *w/cm*	Chloride content, % by mass of concrete
Industry recommended parameters*	—	—	6 to 7† 1.5‡	—	≥600	≤0.008	≤0.45	—
Scaling due to improper finishing practices								
I: Scaling due to premature finishing prior to the cessation of bleeding	Sound	Top 1/8 to 1/4 in.	4.6	3.0	660	0.007	0.50	0.178
		Interior	5.2	4.2	610	0.007	0.45	0.012
	Scaled	Top 1/8 to 1/4 in.	4.4	3.0	675	0.008	0.45	0.156
		Interior	5.5	4.4	640	0.008	0.40	0.008
II: Scaling due to finishing in the presence of water at the surface	Sound	Top 1/8 to 1/4 in.	3.5	3.0	670	0.007	0.45	0.255
		Interior	4.6	3.8	650	0.007	0.40	0.023
	Scaled	Top 1/8 to 1/4 in.	3.4	3.0	620	0.012	0.60	0.252
		Interior	4.4	3.6	600	0.008	0.44	0.020
III: Scaling (delamination) due to prolonged finishing and lack of entrained air at the surface	Sound†	Top 1/8 to 1/4 in.	4.6	3.6	720	0.007	0.40	0.008
		Interior	5.2	4.0	645	0.008	0.45	0.008
	Scaled†	Top 1/8 to 1/4 in.	0.0	0.0	—	—	0.30	0.006
		Interior	4.5	4.0	620	0.008	0.45	0.004

Note: The most important parameter responsible for scaling is highlighted in orange. In all cases, the scaled and sound cores came from adjacent panels or sidewalks and were exposed to similar environmental and deicing conditions (except the last case).
1 in. = 25.4 mm; 1 mm^2/mm^3 = 25.4 $in.^2/in.^3$

*ACI 201.2R-01, "Guide to Durable Concrete;" ACI 212.3R-91, "Chemical Admixtures for Concrete;" ACI 318-02/318R02, "Building Code Requirements for Structural Concrete and Commentary;" ASTM C 457.

†The scaled core is from a trowel-finished surface inside a warehouse floor and the sound core is from a broom-finished surface on the loading dock of the warehouse—both cores are air-entrained and made using the same concrete.

‡The industry recommended air content is for concrete containing 1/2 to 1 in. (13 to 25 mm) size aggregates and exposed to severe weather conditions.

conditions, especially in the presence of deicing salts. Due to the absence of scaling in the adjacent sound panel, salt was not the primary cause of scaling.

Case study III: Finishing-induced loss of air

In the first part of this article, it was mentioned that finishing practices can reduce the air content at the surface relative to that in the body of the slab. As long as finishing-induced air loss is due to a reduction of large voids (where large voids are replaced with many fine, close-space entrained air voids) and the surface still contains the industry recommended specific surface and void spacing factor (and has been placed, cured, and matured properly—see Part I), the surface will still resist scaling. If finishing is prolonged and extended beyond the final set of concrete, however, or if the finishing pressure is high due to excessive steel troweling or machine troweling, the air content at the surface can be reduced significantly. When exposed to the outdoors, such severe loss of air by prolonged finishing increases the potential for scaling at saturated conditions, especially in the presence of salt. Even good, air-entrained concrete can lose most of its air at the surface by prolonged finishing.

Usually such finishing-induced loss of air occurs in the top 1/4 to 1 in. (6 to 25 mm) of the slab, depending on the duration and the pressure applied during finishing. Cases have been observed where a severe air loss has caused scaling in outdoor slabs and delamination in machine-troweled indoor slabs. Figure 3 shows an example of finishing-induced loss of air at the surface of a warehouse slab where delamination developed due to finishing prior to the cessation of bleeding, accumulation of bleed water and air underneath the dense machine-troweled surface, and development of a "plane" of delamination. Air entrainment was included due to the anticipated exposure of the concrete to freezing during construction, but the slab was subsequently delaminated due to the machine troweling of the air-entrained slab.

LESSONS LEARNED

1. A good, air-entrained concrete that is finished prematurely (prior to the cessation of bleeding) can scale because bleed water is entrapped beneath the finished surface;
2. Air-entrained concrete can lose air near its surface by prolonged finishing. Unless the surface is adequately dense and impermeable to moisture or has adequate fine, closely spaced voids, it can have a high risk of scaling (due to low or no air) and delamination (if machine troweled);
3. Trowel-finishing an air-entrained concrete increases its potential for delamination;
4. Concrete's scaling and abrasion resistance decreases if water is added during finishing or if it is finished in the presence of bleed water. In the latter case, concrete may scale even in the presence of adequate air;

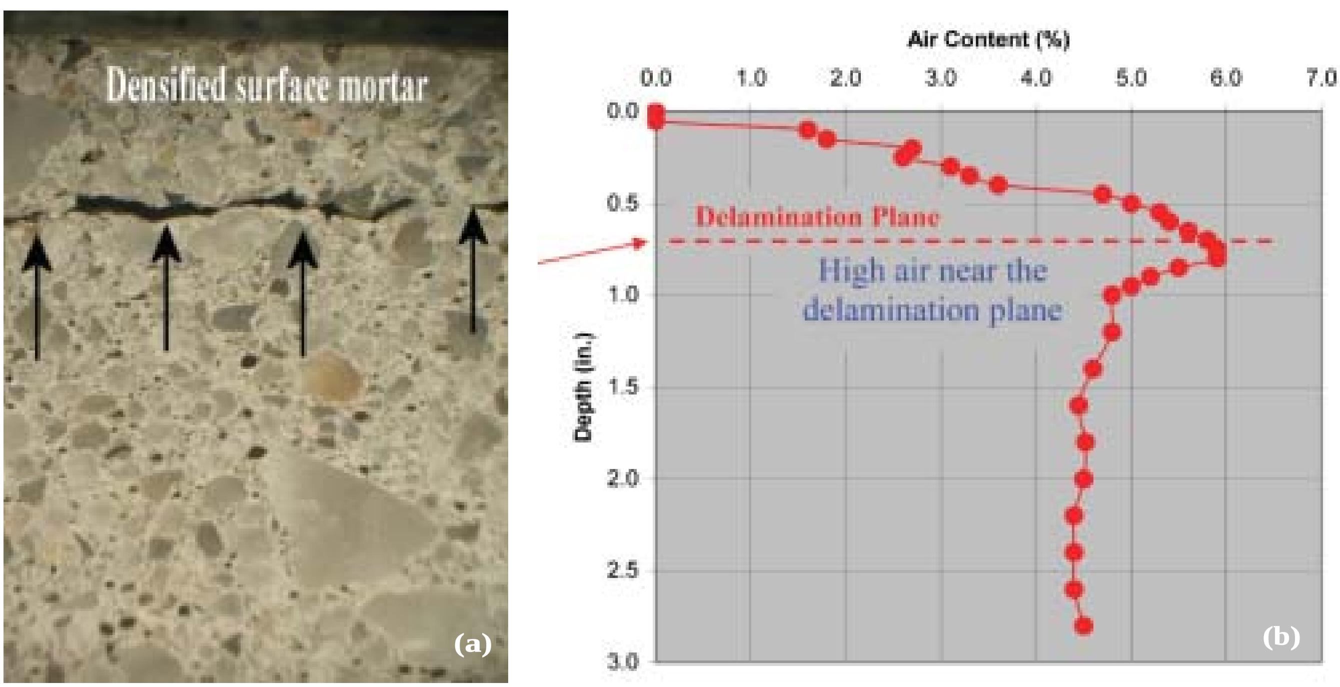


Fig. 3: Case study III (Delamination due to prolonged finishing and entrapment of bleed water and air beneath the finished surface)—(a) cross section of a concrete core, and (b) air profile showing the dense, air-free, near-surface mortar, the plane of delamination, and the air-entrained concrete in the slab. Note: 1 in. = 25.4 mm

5. Inadequately air-entrained or nonair-entrained concrete is very susceptible to scaling when saturated with water (especially in the presence of deicing salts) even if the concrete is placed, finished, cured, and matured properly. Horizontal structural elements (slabs and beams) are more susceptible to scaling than vertical elements (columns and walls);

6. An improperly air-entrained concrete having adequate total air but a coarse air-void system, has a marginal chance of avoiding scaling or delamination, especially in the presence of deicing salts; and

7. Meeting industry recommendations for strength, *w/cm*, and "total air" content will not necessarily guarantee a scale-resistant slab. The concrete must also have a good air-void system and have been placed, finished, cured, and matured properly.

ACHIEVING GOOD QUALITY CONCRETE
Other factors to remember

- Because the surface of concrete is exposed to freezing-and-thawing cycles and deicing salts, it's essential that the surface is adequately cured to have a dense, near-impermeable paste and a good air-void system;
- Aggregates should be well graded and frost resistant;
- Aggregates with a low modulus of elasticity (argillaceous rocks such as shale, slate, greywacke), porous limestone, dolomite, and alkali-silica reactive particles (chert, chalcedony, volcanic rocks) can cause expansion and aggregate popouts at the surface. Lift-off of a thin layer of surface mortar above flat, near-surface coarse aggregates can occur due to finishing improprieties and/or inadequate curing;
- Factors that slow or prolong bleeding (air, fine particles, thickness of the slab, or set-retarding chemicals) can increase the potential for scaling because finishing may begin prior to the cessation of bleeding;
- Crusting of the surface due to rapid evaporation of surface water on a hot, sunny, windy, or dry day can also trap bleed water and cause scaling;
- Working excess bleed water at the surface during finishing or sprinkling dry cement to remove excess bleed water are bad practices, which can cause dusting, softening of the surface mortar, and scaling;
- Inadequate curing creates a soft, friable paste with a low degree of cement hydration. This soft paste will be susceptible to abrasion by freezing and thawing and/or traffic loading;
- Slabs placed during late fall or winter may not attain maturity prior to freezing—in that case, it may be beneficial to avoid salting during the first season, and preferably protect the concrete by a film-forming or penetrating type surface sealer; and
- Inadequate drainage and water ponding will keep concrete saturated during freezing and increase its potential for scaling, especially if the concrete is poorly air-entrained.

MORE THAN AIR, W/CM, AND STRENGTH

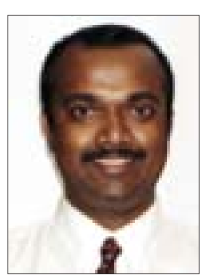
Occurrences of concrete surface scaling are increasing at an alarming rate. Common industry recommendations for freezing-and-thawing resistance of concrete are: a) a total air content of 6 to 7% (±1½%) (for concrete containing 1/2 to 1 in. [13 to 25 mm] nominal maximum size aggregate and exposed to severe weather conditions); b) a minimum compressive strength of 4500 psi (32 MPa); and c) a maximum *w/cm* of 0.45. Fulfilling these three parameters is certainly not sufficient for scaling-resistance unless the concrete has a good air-void system and has been placed, consolidated, finished, cured, and matured properly.

Many mixture proportions requiring "total air" do not account for the amount of the entrained air, or the size, distribution, and spacing of the bubbles, which are more important for scaling-resistance than the mere volume of the total air. Attention to the concrete quality, construction procedures, and design details are all needed to improve concrete's salt and scaling resistance. Concrete, construction, and salt all cause scaling, but the first two are commonly more responsible than the last. The presence of salt surely makes good concrete and proper construction practices even more critical.

Acknowledgments

Sincere thanks to Bernard Erlin for providing help, guidance, and many suggestions during various projects on scaling and to four anonymous reviewers for their suggestions.

Received and reviewed under Institute publication policies.



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Concrete, Construction, or Salt—Which Causes Scaling?

Part I: Importance of air-void system in concrete

BY DIPAYAN JANA

Scaling of concrete pavements, sidewalks, driveways, decks, and other slabs is a common problem in outdoor construction exposed to severe winter weather and deicing salts. Very often, the blame circulates around the quality of the concrete supplied (to the supplier), the methods of construction used (to the contractor), or the salt applied for snow removal (to the owner). Among these three, the most common culprit is *assumed* to be the deicing salt. The dispute is usually settled by field investigation, detailed petrographic examinations, air-void analysis, chloride analysis of concrete cores or saw-cut sections from the scaled and sound areas of a slab, and investigation of the various factors responsible for scaling.

Part I of this article provides three case studies that demonstrate the roles of lack of air entrainment, improper air entrainment (coarse air-void system), and inadequate air entrainment (low entrained air content) in scaling. Part II will provide three case studies to show scaling due to the initiation of finishing prior to the cessation of bleeding, finishing in the presence of excess water at the surface, and prolonged finishing practices. A poor air-void system causes scaling of the concrete surface at saturated conditions during cyclic freezing and thawing. Finishing improprieties, on the other hand, can cause scaling, abrasion, or delamination even in the absence of cyclic freezing and thawing.

According to the ACI Committee 116 report on "Cement and Concrete Terminology," scaling is defined as "local flaking or peeling away of the near-surface portion of hardened concrete or mortar" and is rated as "light," "medium," "severe," and "very severe" depending on the loss of surface mortar down to depths of less than 5 mm (0.2 in.); 5 to 10 mm (0.2 to 0.4 in.) and exposure of coarse aggregate; 5 to 10 mm (0.2 to 0.4 in.) "with some loss of surface mortar surrounding aggregate particles 10 to 20 mm in depth"; and greater than 20 mm (0.8 in.), respectively.

For resistance to scaling in severe weather, concrete should be:

(a) "Adequately" air-entrained and made using well-graded, frost-resistant aggregates: the concrete should have an air content of 6 to 7% (±1.5%) (for normalweight or lightweight concrete having 1/2 to 1 in. [13 to 25 mm] nominal maximum-size aggregate and exposed to severe weather), a specific surface of at least 600 in.$^{-1}$ (24 mm^{-1}), and a maximum void-spacing factor of 0.008 in. (0.2 mm);

(b) Properly placed, finished, and cured: the concrete should be well consolidated; it should be finished properly without any entrapment of bleed water beneath the finished surface; it should not be over-finished or finished in the presence of excess water at the surface; and it should be well-cured to provide adequate cement hydration and necessary development of strength at the surface to create a dense, near-impermeable, moisture-tight concrete; and

(c) Mature: that is, the concrete should undergo a period of air drying and should attain a compressive strength of at least 28 MPa (4000 psi) prior to the first exposure to freezing and deicing salts. Air drying is necessary to minimize the amount of freezable

TABLE 1:
Factors that can cause scaling—a holistic approach. Shown are the 10 common factors (categorized into Concrete, Construction, and Design/maintenance) to consider for resistance to scaling

Three main pillars	Ten factors	Details	Requirement
Design/maintenance	10. Deicing salt	Causes scaling only in poor-quality or poorly constructed concrete unless salt is applied at an early stage before the attainment of maturity	Third
	9. Drainage	Poor drainage and water ponding increases the degree of saturation	
	8. Maturity	A compressive strength of at least 4000 psi (28 MPa) and at least a period of air drying before the first exposure to freezing and deicing salt	
Construction procedures	7. Curing	Inadequate curing? Curing procedure	Second
	6. Finishing	Premature finishing? Over-finishing? Finishing in the presence of excess water on surface?	
	5. Consolidation	Degree of consolidation (amount of entrapped air)	
	4. Placement	Method of placement	
Concrete quality	3. Strength and *w/c*	How dense and moisture-tight is the concrete?	First
	2. Aggregates	Size, grading, modulus of elasticity, and frost resistance	
	1. Air-void system	Air void distribution from the surface downward. Specific surface (How fine are the voids?); void-spacing factor (How close are the voids?); and air content (How much air? Does the concrete have enough air to provide 9 ± 1% air in its mortar fraction?)	

water in the concrete, and a strength requirement is needed to resist the freezing-related tensile stresses in concrete.

Concrete that fulfills *all three conditions* should be durable in winter even in the presence of salt. Concrete that lacks any one of these conditions is susceptible to scaling and even more so in the presence of salt.

CASE STUDIES

Table 1 provides a holistic approach of ten different factors categorized into: Concrete Quality, Construction, and Design and Maintenance that can cause scaling. Out of hundreds of case studies on scaling that I have investigated, poor air-void systems and/or finishing improprieties are found to be the two most common causes of scaling. Therefore, I have screened six classic case studies where: a) scaling was found to be due to either poor air-void systems in the concrete (Part I), or improper finishing practices (Part II); b) 3- to 4-in.-diameter (75 to 100 mm), through-depth core samples were collected from the scaled and sound areas, which were either from the adjacent panels of a sidewalk, a driveway slab, or from adjacent slabs exposed to similar environmental and deicing conditions; c) except for air and finishing, the other factors listed in Table 1 were not found to be responsible for scaling (for example, in all cases the concrete was made using frost-resistant aggregates, well cured, and mature prior to freezing); and d) detailed field investigations, petrographic examinations, air-void analyses, and chloride analyses were done; all background information of the projects, concrete mixture proportions, construction practices followed, and weather conditions during construction were documented for comprehensive study.

In all the case studies, the concrete slab was exposed to sodium- or calcium chloride-based deicing salts. Prior to the investigation, salt was alleged to be the cause of scaling. In all the cases, however, both the sound and scaled panels have similar chloride concentrations due to their presence in the same deicing conditions. Salt was found to have played only a secondary role in scaling. Poorly air-entrained concrete was selectively scaled in the presence of salt, whereas good quality, properly constructed, and matured concrete remained sound.

Concrete causing scaling—importance of air-void system

Table 2 provides the air-void parameters, water-cementitious material ratios (*w/cm*), and chloride contents of the scaled and sound cores of the following case studies. Air-void analysis was done using the modified point-count method of ASTM C 457 "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." The profiles of air-void parameters were determined by using the procedures of ASTM C 457 along a series of parallel traverse lines on a vertical cross section of a core, as well as on a series of parallel, circular cross sections at various depths of a core. The *w/cm* was estimated by using various physical, textural, compositional, and mineralogical properties of paste in the unknown concrete and by comparing these properties with the standard concretes of known *w/cm*. Detailed petrographic examinations were done all on samples according to ASTM C 856 "Standard Practice

TABLE 2:
SOME PETROGRAPHIC OBSERVATIONS OF THE CASE STUDIES DESCRIBED IN THIS ARTICLE

Case studies of scaling	Petrographic observations
Scaling due to cyclic freezing and thawing of nonair-entrained concrete in the presence of salts	Concrete does not have "entrained" air, which is the intentionally introduced fine, discrete, spherical or near-spherical air voids having sizes of 1 mm (0.04 in.) or less. It is not uncommon for a nonair-entrained concrete to "generate" a couple of such air voids, but their amount and frequency are low enough to distinguish them from those intentionally introduced. The scales have lenticular configurations with tapered edges. Scaling occurs by surface-parallel cracks that transect and circumscribe the aggregate particles.
Scaling due to cyclic freezing and thawing of inadequately air-entrained concrete in the presence of salts	Concrete has "entrained" air, but the total air content is less than the industry-recommended amount, and the entrained air content is low.
Scaling due to cyclic freezing and thawing of improperly air-entrained concrete in the presence of salts	Concrete has entrained air, and the total air content may fulfill the industry requirements, but the voids are coarse and wide-spaced—that is, the specific surface (< 600 in.$^{-1}$ or < 24 mm^{-1}) and void spacing factor (> 0.008 in. or > 0.2 mm) are outside the industry recommendations.

for Petrographic Examination of Hardened Concrete." Chloride content analysis was done by using the methods of ASTM C 1152/C 1152M "Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete."

Case study I: nonair-entrained concrete

A nonair-entrained concrete that is critically water-saturated and exposed to cyclic freezing and thawing is very susceptible to scaling. Because deicing salt increases the degree of saturation of concrete, the detrimental effect of salt is most severe in a nonair-entrained concrete. In some cases, severe scaling of a panel adjacent to a perfectly sound and air-entrained concrete panel was found to be due to the accidental lack of dosage of the air-entraining admixture in the scaled concrete batch (this usually occurs where a scaled panel is separated from a sound panel by a construction joint indicating delivery of a new batch of concrete after a pause). A frequent measurement of air during placement of each batch is thus essential to ensure the uniformity of the concrete quality. The first example in Table 2 shows such a case study where scaling was due to the absence of entrained air in the scaled core from a sidewalk. Figure 1 shows a cross section of nonair-entrained concrete that has scaled and the adjacent air-entrained concrete that was sound.

If the concrete is air-entrained, scaling can still occur if: a) the concrete has a coarse air-void system with a low specific surface (<600 in.$^{-1}$ or <24 mm^{-1}) and a large void-spacing factor (>0.008 in. or >0.2 mm)—the air content may or may not satisfy the industry requirements (6 to 7 ± 1.5%); and/or b) the useful "entrained" air content of the concrete is low (irrespective of the total air content), which usually reduces the specific surface and increases the void-spacing factor of the air-void system. I have encountered both situations frequently—in many cases, the total air content did conform to the so-called designed "total air" requirement, and yet the concrete had a poor air-void system. It became obvious that it is the number of the tiny entrained air bubbles and their void-spacing factor, which are much more important for scaling resistance of concrete than the volume of total air.

Case study II: air-entrained concrete with an improper air-void system

The second example in Table 2 shows a case study of scaling in a downtown concrete sidewalk exposed to severe winter weather and the heavy application of salt. The core from a sound panel has an excellent air-void system—the air content, specific surface, and void spacing factor all conform to the industry recommendations. The core from a severely scaled panel, though air entrained, has a low air content and a coarse air-void system with a low specific surface and a high void-spacing factor (Fig. 2). A coarse air-void system can occur due to a low dosage of air-entraining admixture, excessive mixing of the concrete, or retempering or excessive addition of water (the other causes of a coarse air-void system—for example, the presence of high-range water-reducing admixtures or cement-admixture incompatibility—were not present). In spite of deicing salt being the alleged factor for scaling, the chloride content was found to be similar in both scaled and sound cores (due to their similar salt exposures) and, in fact, was higher in the sound core. Scaling was initiated in the panels having improper air-void systems and became aggravated in the presence of salt. Although both sound and scaled panels

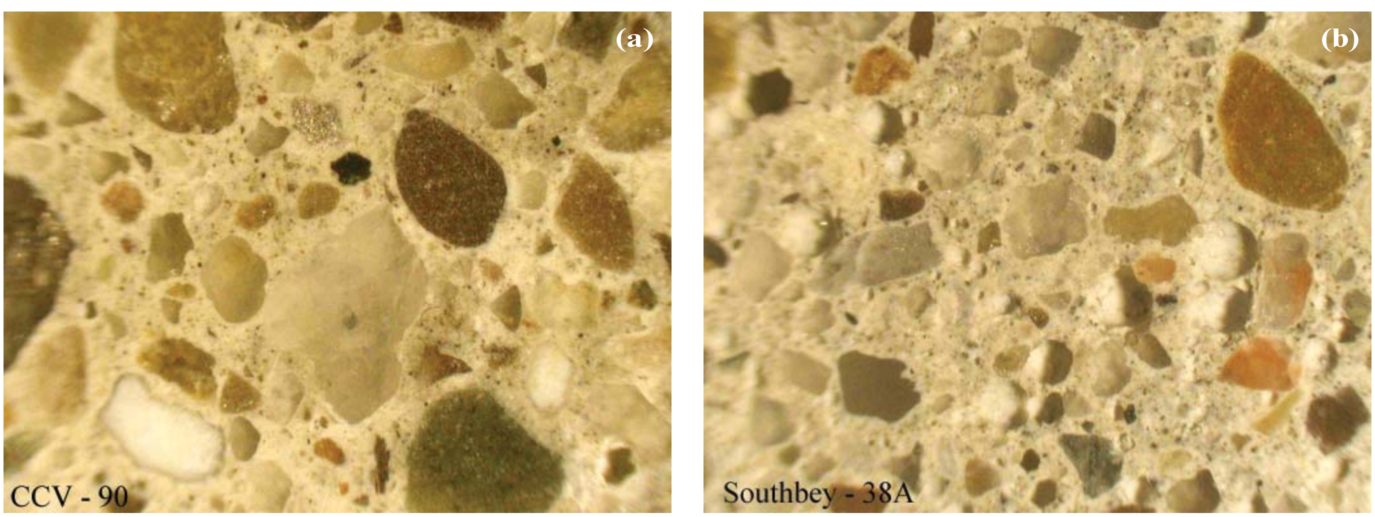


Fig. 1: Case study I: Air-void systems of nonair-entrained (a) and air-entrained (b) concretes from adjacent driveways. Scaling was due to the accidental escape of the air-entraining admixture in the concrete. The air-entrained concrete in the sound panel is prepared according to the mixture proportions and has performed satisfactorily

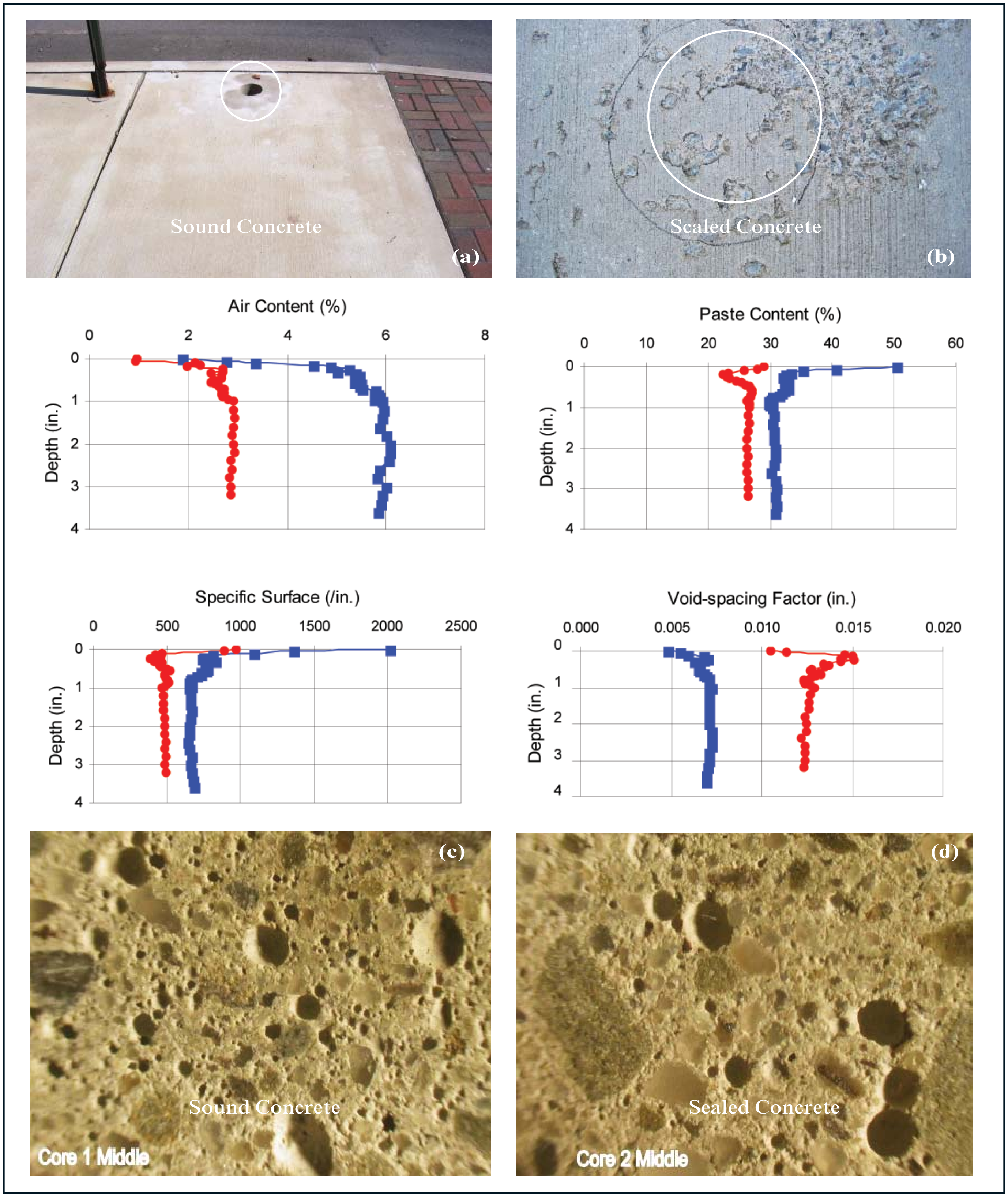


Fig. 2: Case study II: Scaling due to improper air entrainment (coarse air-void system with low air content and wide void spacing). Photos (a) and (b) show the surface conditions of panels where cores were taken; the graphs show profiles of air-void parameters in scaled (in red) and sound (in blue) concretes; and photos (c) and (d) show air-void systems in cross sections of sound and scaled cores. Note: 1 in. = 25.4 mm

experienced some finishing-induced loss of air at the surface, the air bubbles at the surface of the sound panel were still close enough to each other to provide the necessary protection of paste against distress due to cyclic freezing and thawing. This indicates that for scaling resistance, the air-void-spacing factor is more important than the air content. Figure 3 shows another very similar case where the "total air" content of the scaled core fulfilled the design air requirement, but the concrete still scaled due to such a coarse air-void system having widely-spaced bubbles.

Case study III: air-entrained concrete with inadequate entrained air

The third example in Table 2 and in Fig. 4 shows a case where a stamped concrete sidewalk has inadequate consolidation and, as a result, has more than the usual amount of entrapped air. The total air content again conformed to the design air, but the scaled panel had too little entrained air (<1%) to provide protection. The adjacent sound panel had 3% entrained air and 8.5% total air, which reduced down to 1.5 and 3.7% at the surface, respectively. Although the air-void system is coarse in the body, the surface has close-spaced bubbles to provide the necessary protection of the paste.

In all three cases: a) the sound cores have consistently slightly higher chloride contents than the scaled cores; and b) the chloride contents are significantly higher at the surface than in the body, which is consistent with the application of deicing salts. Concretes having poor air-void systems scaled, whereas those with good air-void systems were sound. Concretes in the panels having

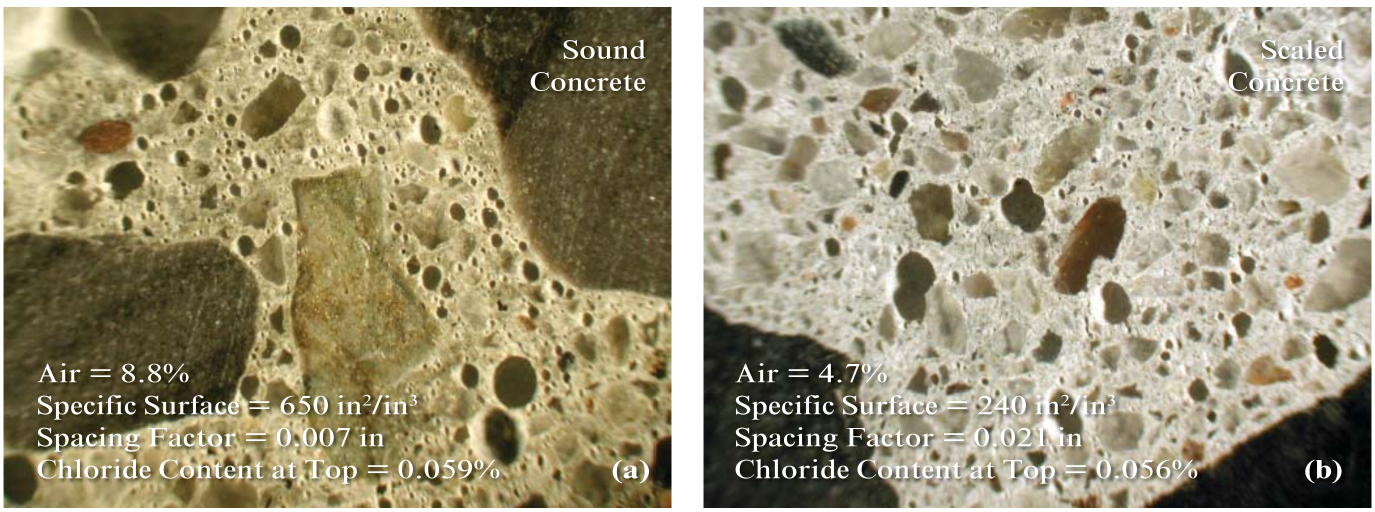


Fig. 3: Case study II: Scaling due to improper air entrainment (coarse air-void system with low air content and wide void spacing). Shown are air-void systems of sound (a) and scaled cores (b) and associated air-void parameters and chloride contents at the top 1/2 in. (13 mm)

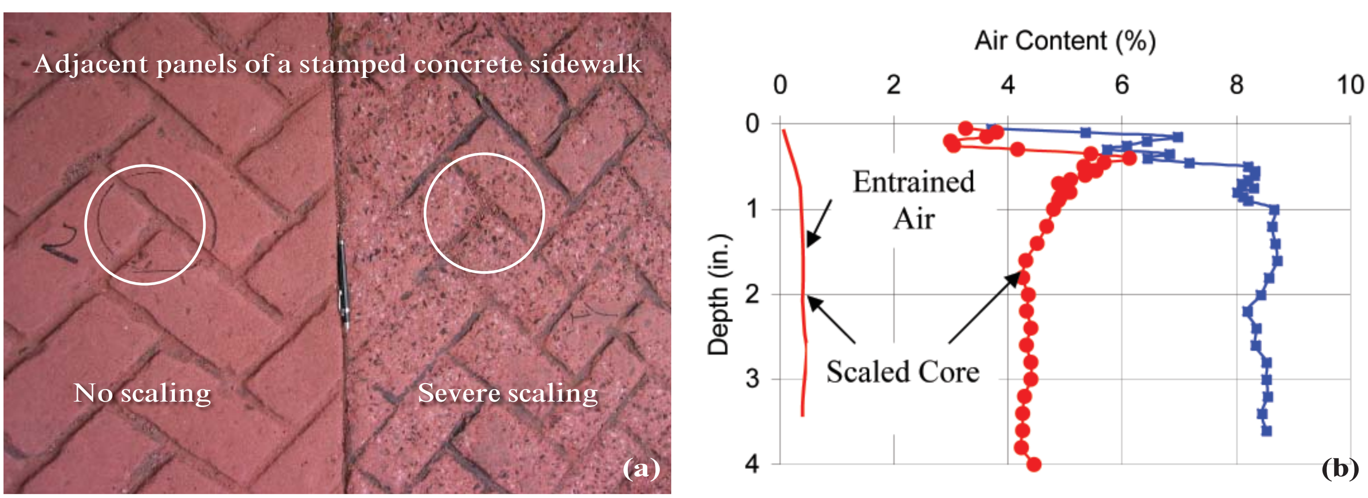


Fig. 4: Case study III: Scaling due to low entrained air. Two cores (a) taken from adjacent sound and scaled panels of a stamped concrete sidewalk showed very different air contents, loss of air at the surface, and most importantly, very low amounts of entrained air in the scaled panel (in red in (b)). Note: 1 in. = 25.4 mm

low air contents should have been rejected during placement—this indicates the importance of frequent air measurements during concrete placement. Even the ones having total air within the design requirements scaled due to their poor air-void systems—this indicates that fulfilling the design total air requirement does not necessarily guarantee frost resistance unless the concrete has a good air-void system. This indicates the importance of measuring not only the "total air" by conventional methods but also the air-void system (void amount, size, distribution, and spacing) during concrete placement. A recently developed instrument called "air-void

TABLE 3:
Air-void parameter, *w/cm*, and chloride content of sound and scaled concrete cores in the three case studies described in the article. Parameters responsible for scaling are highlighted in red. In all cases, the scaled and sound cores came from adjacent panels or sidewalks and were exposed to similar environmental and deicing conditions

Case studies of scaling	Surface conditions of samples	Locations where various parameters were measured	Total air content , %	Entrained air content, %	Specific surface, in.^{2}/in.^{3}	Void-spacing factor, in.	Estimated *w/cm*	Chloride content, % by mass of concrete
Industry* recommended parameters	—	—	6 to 7 ± (1.5)†	—	≥ 600	≤0.008	≤0.45	—
Scaling due to poor air-void system of concrete								
I: Scaling due to nonair-entrainment	Sound	Top 1/8 to 1/4 in.	4.4	3.0	920	0.007	0.50	0.212
		Interior	4.8	4.0	635	0.007	0.48	0.024
	Scaled	Top 1/8 to 1/4 in.	1.3	0.0	180	0.094	0.50	0.200
		Interior	2.0	0.0	155	0.280	0.46	0.014
II: Scaling due to improper air entrainment (coarse air-void system, large void spacing factor)	Sound	Top 1/8 to 1/4 in.	1.8	1.6	975	0.005	0.50	0.087
		Interior	5.8	4.8	685	0.007	0.45	0.004
	Scaled	Top 1/8 to 1/4 in.	0.9	0.5	350	0.025	0.50	0.076
		Interior	2.8	1.7	500	0.012	0.45	0.008
III: Scaling due to inadequate air entrainment (low amount of entrained air)	Sound	Top 1/8 to 1/4 in.	3.7	1.5	615	0.010	0.45	0.139
		Interior	8.5	3.0	350	0.009	0.40	0.023
	Scaled	Top 1/8 to 1/4 in.	3.2	0.3	270	0.024	0.45	0.111
		Interior	4.5	0.5	170	0.033	0.40	0.012

*ACI 201.2R-01, "Durability of Concrete"; ACI 212.3R-91, "Chemical Admixtures for Concrete"; ACI 318-02/318R-02, "Building Code Requirements for Structural Concrete and Commentary"; ASTM C 457, and the like.

† The industry-recommended air content is for concrete containing 1/2 to 1 in. (13 to 25 mm) size aggregates and exposed to severe weather condition.

Note: 1 in. = 25.4 mm; 1 mm^2/mm^3 = 25.4 in.^{2}/in.^{3}

analyzer" has the potential to measure void size and spacing in fresh concrete. Widespread applications of such instruments are essential for assuring a good air-void system in fresh concrete.

SALT CAUSING SCALING

Due to the lower vapor pressure of salt solution than water at a given temperature, deicing salts increase the degree of saturation of concrete, keep concrete saturated during the drying stages, and increase the number of freezing-and-thawing cycles. Unless the concrete is dense enough to prevent the salt-induced saturation; is mature; and has a good air-void system of adequate, close-spaced, fine entrained air voids to protect the paste, the concrete will always be susceptible to scaling in the presence of salt. Deicing salts can cause and aggravate scaling in nonair-entrained or inadequately air-entrained concrete. The previous three case studies show that having a good air-void system is very important in maintaining a quality concrete in the deicing exposures. Exposure to salt prior to the attainment of maturity, however, can cause scaling even in properly air-entrained concrete. A magnesium chloride-based deicer can cause a chemical attack even in a properly air-entrained concrete and soften the surface by forming magnesium hydroxide (brucite) and decomposing the calcium-silicate-hydrate component of portland cement hydration (the main cementitious component of concrete) into a soft, friable product called magnesium-silicate-hydrate. Deicers containing ammonium sulfate or ammonium nitrate also attack the cement paste and should be avoided.

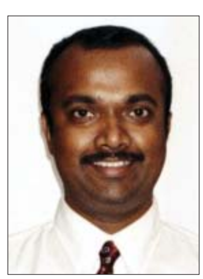
SALT VERSUS GOOD QUALITY CONCRETE

To return to the question in the title, salt should not cause scaling if the concrete is of good quality (that is, it has adequate entrained air, a good air-void system in the body and at the surface, and is made using well-graded, frost-resistant aggregates), properly constructed (that is, placed, finished, and cured), and mature prior to the first exposure to winter weather and salt. Due to the increased saturation of the concrete, salt not only increases the severity of scaling in an inadequately air-entrained concrete, but also in concrete that has a coarse air-void system. Over the years, many outdoor concrete slabs have performed well in harsh winter weathering and have been exposed to deicing salts without scaling because they were made using a good quality concrete, following good construction practices, and were protected from salts in the early stages before the attainment of maturity. In many places, salt may be needed for public safety and should not be blamed for scaling before verifying the quality of the concrete and the construction details. We cannot bypass the responsibility of providing a good, durable concrete before putting the blame on salt for scaling.

Acknowledgments

Sincere thanks to Bernard Erlin for providing help, guidance, and many suggestions during various projects on scaling and to four anonymous reviewers for their suggestions.

Received and reviewed under Institute publication policies.



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