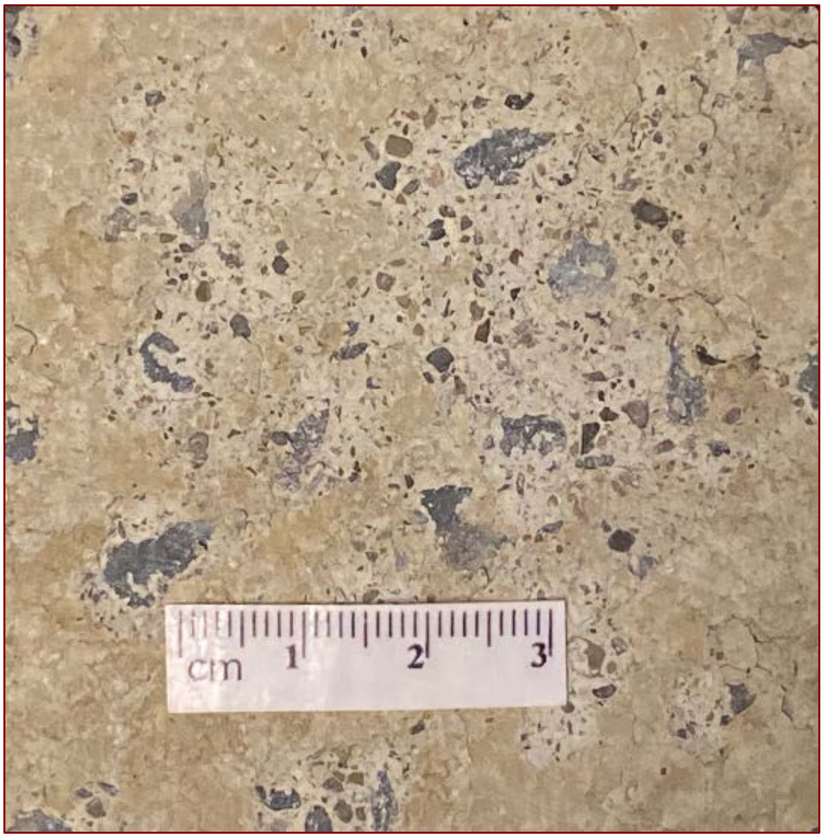
CONSTRUCTION MATERIALS CONSULTANTS, INC.

Surface Scaling of Residential Concrete Driveway – A Petrographic Study from Two Concrete Cores



71 Marvelle Road
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CMC 0620125

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EXECUTIVE SUMMARY

Surface distress of an outdoor residential concrete driveway slab in Fayetteville, New York has prompted this investigation. As a result, two hardened concrete cores, $3^{3}/_{4}$ in. (90 mm) in diameters and $4^{1}/_{2}$ in. (110 mm) and $4^{3}/_{4}$ in. (120 mm) in full-depth lengths were collected from a scaled and a sound area for detailed petrographic examinations according to the procedures of ASTM C 856. The purposes of the investigation are to evaluate: (a) the concrete quality including air entrainment, air-void systems, aggregates types and soundness, (b) construction practices, including consolidation, finishing and curing practices, and (c) effects of applications of deicing chemicals on the driveway, if confirmed, on scaling of surface at some areas whereas no such scaling at other locations.

The mix design of the concrete reportedly contained 616 pounds of Portland cement, 1630 pounds of ASTM C 33 #7 crushed stone coarse aggregate, 1390 pounds of fine aggregate, 0.5 oz/100 lbs. air-entraining agent, 6.0 oz/100 lbs. of water-reducing admixture, 270 pounds of water – all to produce a slump of 3 to 5 inches, an air content range of 4.5 to 7.5 percent, a water-cement ratio of 0.43, and a 28-day compressive strength of 4000 psi.

Concrete in both the distressed and sound cores are found to be compositionally similar and made using the same concrete mix having same aggregates, cement, and air entrainment. The determined concrete composition is found to be consistent with the reported concrete mix, except a major difference, in having embedded polypropylene-type fibers in concrete, which is not mentioned in the reported concrete mix.

Concrete in both cores are made using crushed limestone coarse aggregates having nominal maximum sizes of $^{3}/_{4}$ in. (19 mm), which are angular, dense and hard, medium beige to medium to dark gray, and contain varieties from fine-grained (*micritic*) limestone to limestones having dark brown argillaceous veins (*argillaceous limestone*) to limestones having fossils (*fossiliferous limestone, biomicrite*) to limestone having dolomite rhombs and argillaceous veins (*argillaceous dolomitic limestone*) all derived from a limestone quarry that has supplied the coarse aggregate for both samples. Coarse aggregate particles are well-graded, well-distributed, and present in sound conditions with no evidence of any potential unsoundness such as pop outs.

Fine aggregates are mixtures of sand-sized particles of crushed limestone coarse aggregate plus natural siliceous sand where sand contains major amount of quartz and subordinate amounts of quartzite, feldspar, and other siliceous components. Fine aggregate particles have nominal maximum sizes of $^{3}/_{8}$ in., which are well-graded, well-distributed, and present in sound condition with no evidence of any potentially deleterious reactions. Both coarse and fine aggregate particles did not contribute to the observed surface scaling of driveway.

The hardened paste is made using Portland cement as the sole cementitious component. The textural and compositional features of the pastes are indicative of Portland cement contents estimated to be $6^{1}/_{2}$ to 7 bags per cubic yard. The cores have similar water-cement ratios (*w/c)* estimated to be 0.40 to 0.45 in the body. The very top surface region shows a slightly higher ratio of 0.45 to 0.50 which has increased the porosity of paste at the finished surface. Concretes in both cores are dense, and well-consolidated. There is no evidence of any deleterious secondary deposits found in the cores. Carbonation was restricted to the top 5 mm from the scaled or finished surface. Bonds between the coarse and fine aggregate particles and paste are moderately tight. There is no evidence of microcracking due to any deleterious reactions in the concrete.

Concrete in both scaled and sound cores are air-entrained. The total air contents are estimated to be around 6 percent in the sound core and $4^{1}/_{2}$ percent in the scaled core. However, around 1 to $1^{1}/_{2}$ percent lesser air in the scaled core is judged not caused by preferential scaling since the interior as well as the surface region of scaled core showed adequate air entrainment as seen in the sound core. The extra air in the sound core is mostly from some coarse voids whereas the finer air bubbles responsible for the protection of paste during freezing is present in adequate amounts in both cores especially in their interiors. In summary, concrete delivered to the jobsite from the batch plant is found to be air entrained in conformance to the reported concrete mix design.

In both cores, 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 slabs at the locations of two examined cores.

The porous paste found at the top few millimeters in both cores is a consequence of finishing in the presence of water at the surface, which could be from the presence of bleed water during finishing and/or from addition of water during finishing. Such water has softened the paste, made it more porous and increased vulnerability to scaling, especially if the surface was exposed to deicing chemicals

Exposed surfaces of the cores showed no evidence of inadequate curing of concrete, e.g., no evidence of restricted cement hydration at the scaled or finished surfaces at least to cause the reported surface scaling. Cement particles showed adequate hydration at the exposed surface regions with remains of only brown ferrite residues. The original finished surfaces of both cores show a shiny appearance, which is indicative of application of a cure-seal compound, which is confirmed to be an acetone-based siloxane/acrylic hybrid sealer (marketed as Trinic Stamp Shield).

Mortar lift-off is the loss of thin sheet of the original finished surface of concrete from over the flat topside of near-surface aggregate particle. Mortar lift-off is found on the scaled surface, which has also contributed to the surface distress. Mortar lift-off is not due to the exposed aggregate, which is sound crushed limestone and did not fracture (as would have been in the case of aggregate popout). Instead, the thin sheet of surface mortar was lost due to inadequate bond to the near-surface coarse aggregate. Mortar lift-off should have been avoided by deep embedding of aggregates along with a better bond of finished surface to the coarse aggregate from proper finishing operations and curing. Improper finishing can lead to mortar lift-off where flat topsides of aggregates situated very near the exposed surface do not form a good bond with the finished surface either due to repeated finishing passes and/or from excess water or other reasons.

For adequate resistance to freezing-related stresses, the common industry (e.g., ACI Committee 201)-recommended compressive strength of concrete exposed to an outdoor environment of moisture and freezing is at least 4000 psi. A concrete having a compressive strength of at least 4500 psi is usually recommended for an outdoor concrete slab exposed to moisture, salts, and snow, where the good strength of concrete provides the necessary resistance against freezing-related tensile stresses in concrete. Excess water at the surface, either due to finishing with bleed water on the surface and/or due to addition of water during finishing of a sticky, high-air concrete would reduce the strength and hence the necessary protection against freezing-related stresses. Based on petrographic examinations the interior of the concrete in both cores (except the top 5 mm) is judged to have at least 4000 psi strength to confirm the specific design strength. The observed surface scaling is not due to placement of a low-strength concrete.

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. A concrete, therefore, needs to be ‘matured’ prior to the first exposure of freezing, especially during the winter weather constructions. If placed during the winter seasons and exposed to deicing chemicals prior to the attainment of maturity, the concrete surface could have scaled from such premature exposures to freezing and/or 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, *unless*: (i) salt is applied prior to the attainment of maturity of concrete, and/or (ii) a chemically aggressive (e.g., magnesium or ammonium sulphate or urea-based) salt is applied that can chemically decompose the paste (calcium-silicate-hydrate, the heart of concrete). A well-designed concrete placed, finished, and cured properly should resist the deleterious action of salt unless salt was brought in too early and/or a chemically corrosive salt (magnesium sulfate or ammonium-based) was present that has caused chemical erosion of paste. Water-soluble chloride analyses is, therefore, needed from the exposed and interior locations of both cores to determine the role of potential applications of deicing chemicals on the observed surface scaling.

Exposed surfaces of both scaled and sound cores showed evidence of application of a surface sealer (from the shiny appearance). Such an application, however, did not prevent scaling as seen by its present in the scaled core as well.

Based on detailed laboratory investigations, surface scaling of concrete driveway slab is determined to be due to a combination of various factors, e.g., (a) from potential application of deicing chemicals on the concrete surface, which is required to be confirmed from water-soluble chloride analysis of concrete cores (*a la* ASTM C 1218) examined here, especially if such application has occurred prior to the attainment of concrete maturity, to (b) softening of concrete surface due to finishing in the presence of excess water at the surface that has increased the susceptibility of scaling especially in the presence of deicing salts. Beneath the distressed surface, however, the interior concrete is sound, adequately air-entrained, of good strength, and hence should continue to be serviceable as long as the distressed surface can be repaired with a suitable durable coat to protect the interior concrete from environmental elements.

INTRODUCTION

Reported herein are the results of detailed petrographic examinations of two (2) of concrete cores collected from a residential driveway in Fayetteville, New York. One core was collected from an area that shows surface scaling from loss of the original finished surface at isolated locations. The other sample was collected from an area that shows no such distress to serve as a reference sample for comparison with the core from the distressed location.

SURFACE SCALING

Figure 1 shows the top exposed surface of the core collected from a scaled location of driveway, which shows many characteristic features typical of surface scaling. The surface shows losses of thin sheets of the original finished surface and hence exposures of near-surface coarse and fine aggregate particles from such losses. Remains of the original finished surface are still seen at some places, which show a light shiny appearance under reflected light indicating a possible application of a cure-seal compound after finishing. Figure 2 shows enlarged view of the top exposed surface of the core collected from a sound location. The surface shows no loss of the original finished surface as seen in the core from the scaled area, hence no exposure of near-surface coarse and fine aggregate particles. The original finished surface in the sound core also shows a light shiny appearance under reflected light indicating a possible application of a cure-seal compound after finishing.

BACKGROUND INFORMATION

The mix design of the concrete reportedly contained 616 pounds of Portland cement, 1630 pounds of ASTM C 33 #7 crushed stone coarse aggregate, 1390 pounds of fine aggregate, 0.5 oz/100 lbs. air-entraining agent, 6.0 oz/100 lbs. of water-reducing admixture, 270 pounds of water – all to produce a slump of 3 to 5 inches, an air content range of 4.5 to 7.5 percent, a water-cement ratio of 0.43, and a 28-day compressive strength of 4000 psi.

PURPOSES OF LABORATORY TESTING

The purposes of the investigation are to evaluate: (a) the concrete quality including air entrainment, air-void systems, aggregate types and soundness, (b) construction practices, including consolidation, finishing and curing practices, and (c) effects of applications of deicing chemicals on the driveway, if confirmed, on scaling of surface at some areas whereas no such scaling at other locations.

Figure 1: Enlarged view of the top exposed surface of the core collected from a scaled location. The surface shows losses of the original finished surface at isolated locations and exposures of near-surface coarse and fine aggregate particles from such losses. Remains of the original finished surface are still seen at some places, which show a light shiny appearance under reflected light indicating a possible application of a cure-seal compound after finishing.

Figure 2: Enlarged view of the top exposed surface of the core collected from a sound location. The surface shows no loss of the original finished surface as seen in the core from the scaled area hence no exposure of near-surface coarse and fine aggregate particles. The original finished surface shows a light shiny appearance under reflected light indicating a possible application of a cure-seal compound after finishing.

METHODOLOGIES

PETROGRAPHIC EXAMINATIONS

The cores were examined by detailed petrographic examinations by following the methods of ASTM C 856 “Standard Practice for Petrographic Examination of Hardened Concrete.” Details of petrographic examinations and sample preparation are described in Jana (2006). Air contents and air-void systems of concretes were also estimated from petrographic examinations.

The steps of petrographic examinations include (Jana 2006):

i. Visual examinations of the 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 compositions;
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 from the top 3 inches of cores in a petrographic microscope for detailed compositional and microstructural analyses;
vi. Photographing samples, as received and at various stages of preparation with a digital camera and a flatbed scanner;
vii. Photomicrographs of lapped sections and thin sections of samples taken with stereomicroscope and petrographic microscope, respectively, to provide detailed compositional and mineralogical information of concrete.

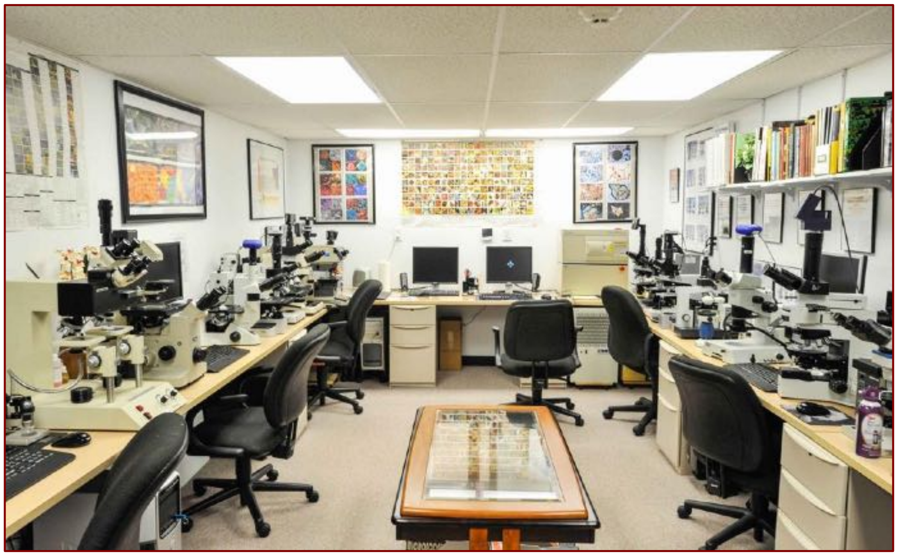


Figure 3: Microscopy laboratory of CMC that houses various low to high-power stereo-zoom microscopes for observations of as-received, fractured, sectioned, and lapped cross sections of samples, and petrographic microscopes with fluorescent light facilities for observations of thin sections of samples.

SAMPLES

PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figures 4 and 5 show the cores, as received, which are $3^3/_4$ in. (90 mm) in diameters and have respective nominal lengths of $4^1/_2$ in. (110 mm) and $4^3/_4$ in. (120 mm) for the cores from sound and scaled areas, respectively. Both cores represent the full-depth retrieval from their respective locations of driveway. From the nominal lengths of cores, thickness of driveway is estimated to be within $4^1/_2$ and 5 inches.

END SURFACES

The core from the distressed location shows many features that are typical of concrete surface scaling. The surface shows losses of thin sheets of the original finished surface (Figures 1 and 5) and hence exposures of near-surface coarse and fine aggregate particles from such losses. Remains of the original finished surface are still seen at some places, which show a light shiny appearance under reflected light indicating a possible application of a cure-seal compound after finishing. The core from the sound location shows no loss of the original finished surface, and a light shiny appearance under reflected light indicating a possible application of a cure-seal compound after finishing.

The bottom ends of both sound and distressed cores show crushed stone from subbase, indicating full-depth recovery of cores from the driveway slab.

CRACKING & OTHER VISIBLE DISTRESS, IF ANY

Despite surface scaling, interior of the core from the scaled location is sound, free of any visible cracks, and show a reasonably dense and well-consolidated concrete as also seen in the core from the sound location. There is no evidence of any visible coarse voids or distress, of course other than the surface distress in the scaled core.

EMBEDDED ITEMS

Both sound and distressed cores are free of any wire mesh or reinforcing steel. Distributed throughout the cores from both sound and scaled locations are fine, hair-like synthetic polypropylene-type fibers that are uniformly distributed throughout the depth indicating addition of a synthetic fiber in the concrete, which is not mentioned in the reported mix design.

RESONANCE

The cores have a ringing resonance, when hammered.

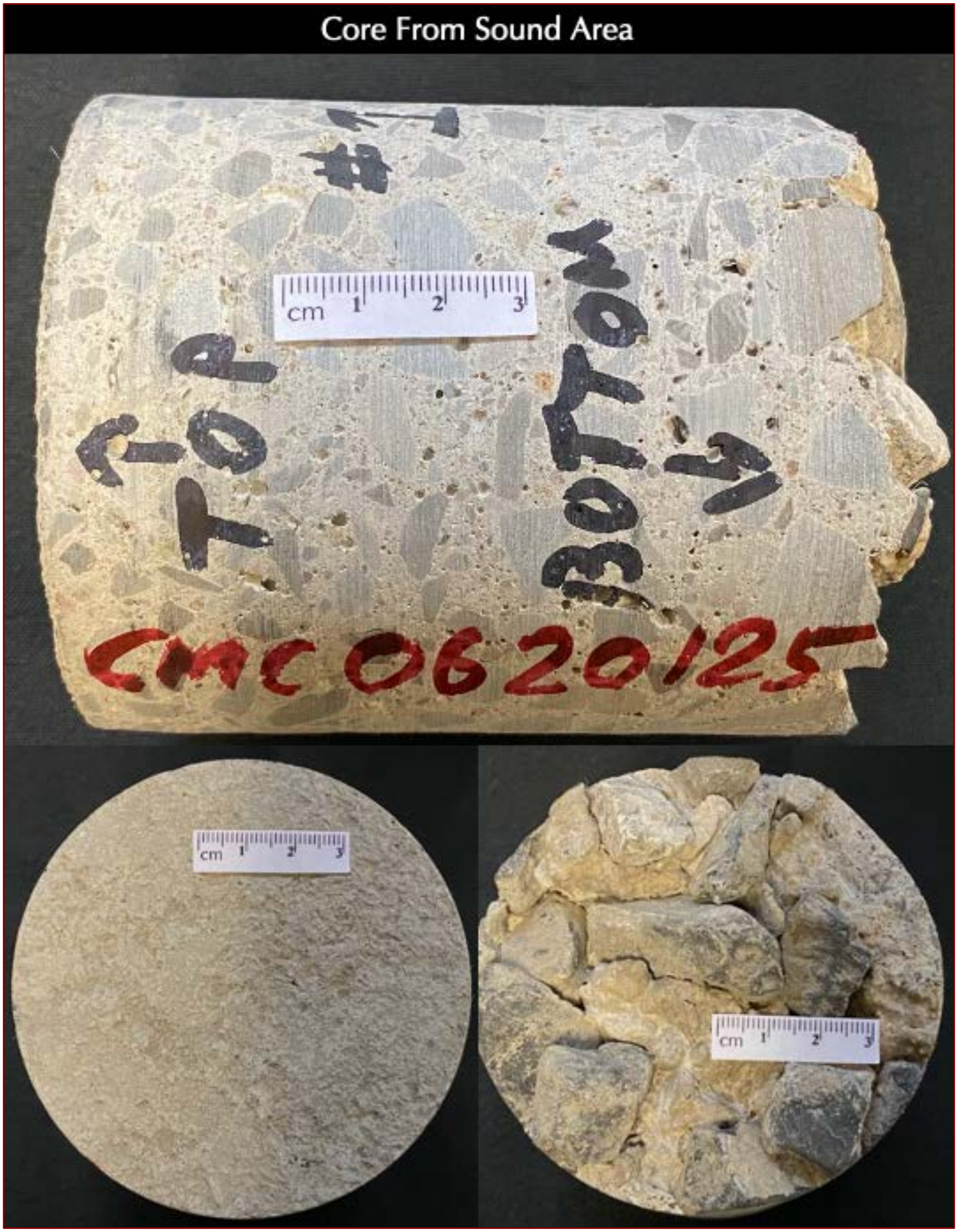


Figure 4: Shown are the cylindrical side view of the core at the top collected from the sound location of driveway, the exposed sound driveway surface on the core top shown in the bottom left, and adhered crushed stone of subbase at the core bottom shown in the bottom right photo.

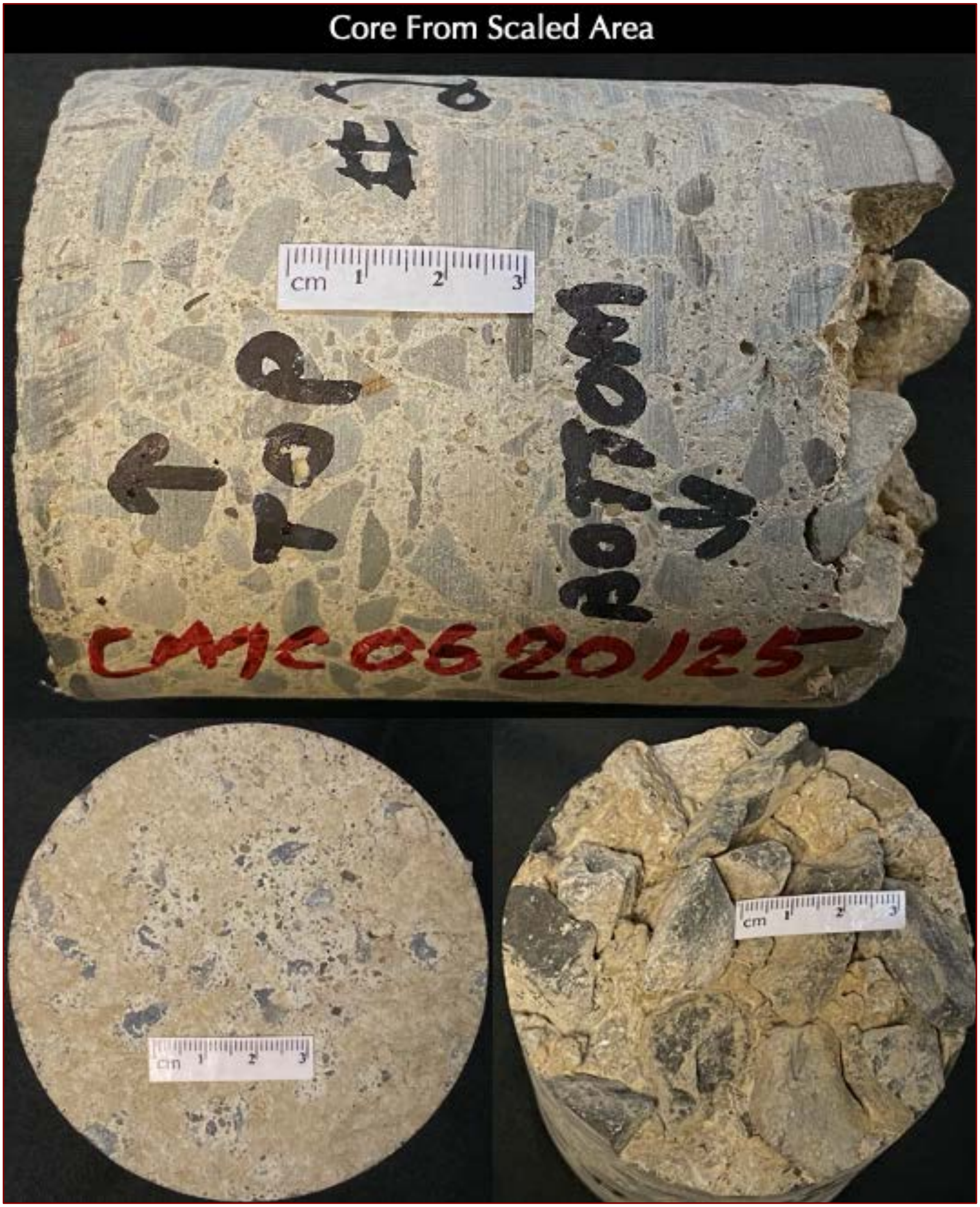

Core From Scaled Area

Figure 5: Shown are the cylindrical side view of the core at the top collected from the scaled location of driveway, the scaled driveway surface on the core top shown in the bottom left, and adhered crushed stone of subbase at the core bottom shown in the bottom right photo.

PETROGRAPHIC EXAMINATIONS

MORTAR LIFT-OFF ON SCALED SURFACE

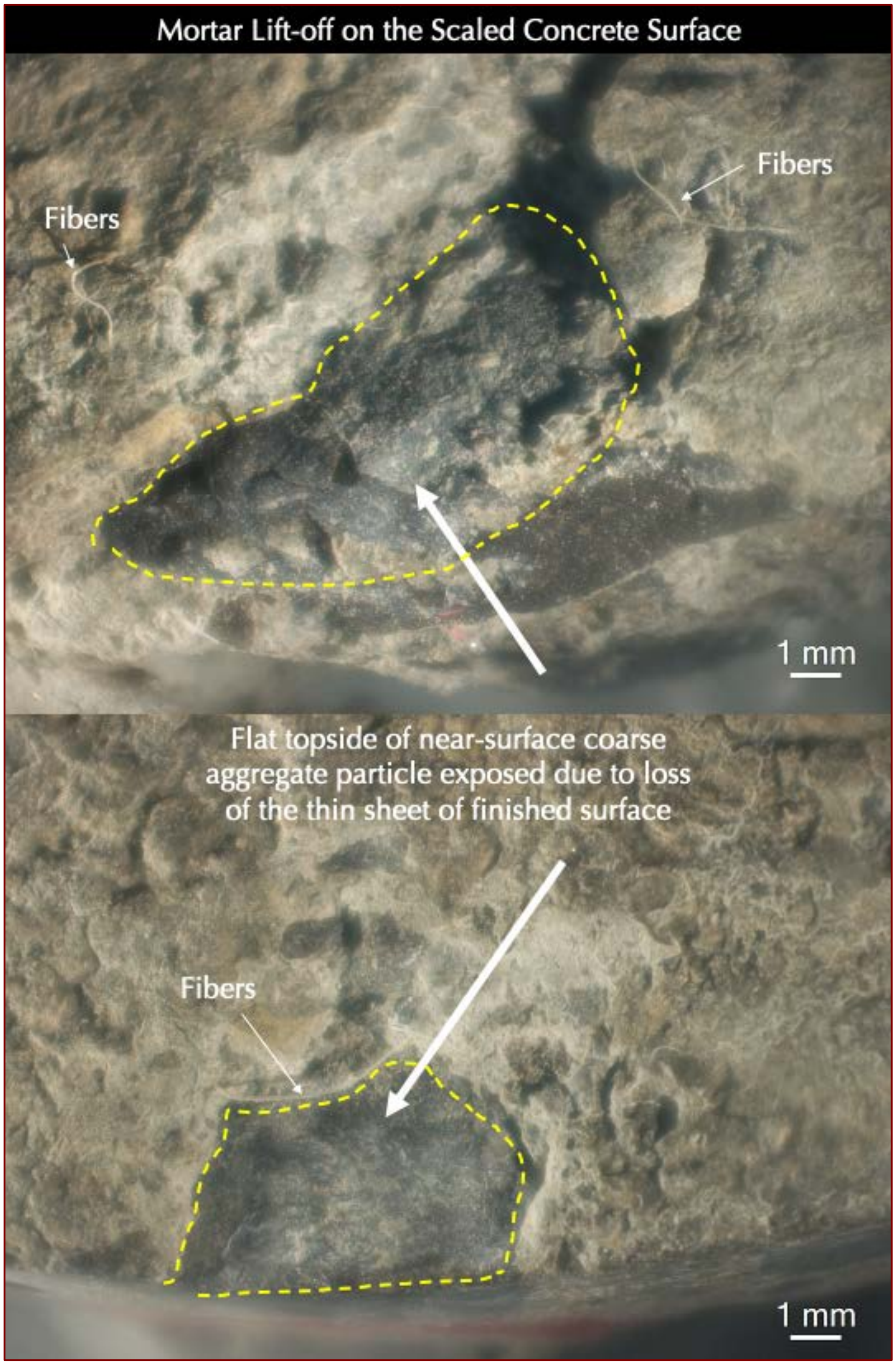


Figure 6: Mortar lift-off as loss of the thin sheet of original finished surface from the flat topside of near-surface crushed stone coarse aggregate particles thus exposing such aggregates at the scaled surface.

The exposed aggregates are sound but exposed due to weak bond between the flat topsides of those particles and the original finished surface which is lost.

Deep embedding of such aggregates and developmet of a good bond between the finished surface mortar and nearby crushed stone aggregates are two essential measures needed to prevent such mortar lift-offs.

Also shown on the exposed surface are some fine polypropylene-type synthetic fibers.

LAPPED CROSS SECTIONS

Figure 7: Lapped cross section of the core from sound area of driveway showing:

(a) Medium beige to medium gray to dark gray, angular, dense, hard crushed stone coarse aggregate particles that are well-graded and well-distributed throughout the depth of the core;

(b) Natural sand fine aggregate particles that are also well-graded and well-distributed;

(c) Overall dense and well-consolidated nature of concrete without any coarse voids or visible cracks;

(d) Uniform color tone of paste through depth;

(e) Crushed stone of subbase adhered to the bottom end; and,

(f) Lack of any wire mesh or steel reinforcment in the core.

Figure 8: A second lapped cross section of the core from sound area of driveway showing:

(a) Medium beige to medium gray to dark gray, angular, dense, hard crushed stone coarse aggregate particles that are well-graded and well-distributed throughout the depth of the core;

(b) Natural sand fine aggregate particles that are also well-graded and well-distributed;

(c) Overall dense and well-consolidated nature of concrete without any coarse voids or visible cracks;

(d) Uniform color tone of paste through depth;

(e) Crushed stone of subbase adhered to the bottom end; and,

(f) Lack of any wire mesh or steel reinforcment in the core.

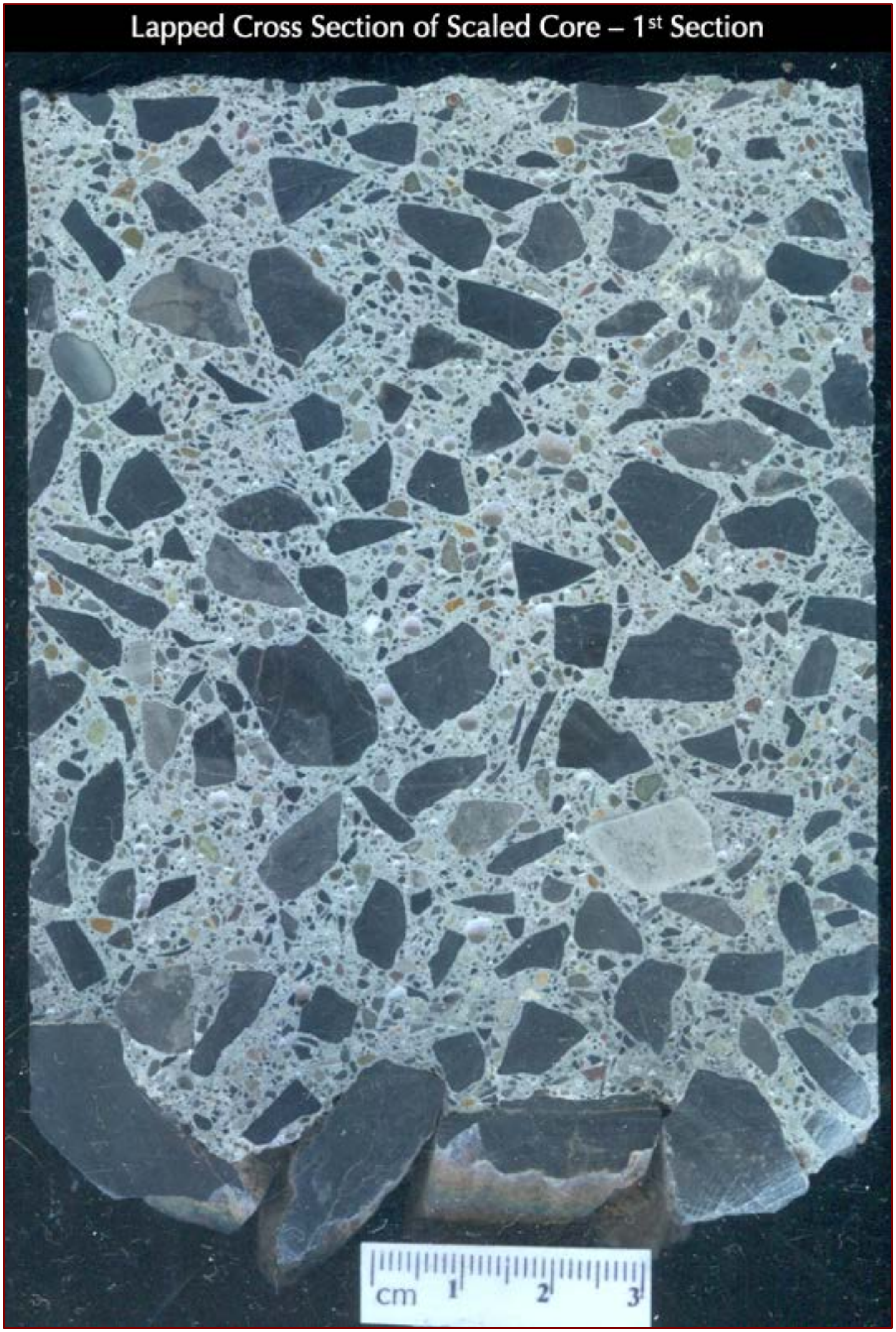


Figure 9: Lapped cross section of the core from scaled area of driveway showing:

(a) Medium beige to medium gray to dark gray, angular, dense, hard crushed stone coarse aggregate particles that are well-graded and well-distributed throughout the depth of the core;

(b) Natural sand fine aggregate particles that are also well-graded and well-distributed;

(c) Overall dense and well-consolidated nature of concrete without any coarse voids or visible cracks;

(d) Uniform color tone of paste through depth;

(e) Crushed stone of subbase adhered to the bottom end; and,

(f) Lack of any wire mesh or steel reinforcment in the core.

Figure 10: A second lapped cross section of the core from scaled area of driveway showing:

(a) Medium beige to medium gray to dark gray, angular, dense, hard crushed stone coarse aggregate particles that are well-graded and well-distributed throughout the depth of the core;

(b) Natural sand fine aggregate particles that are also well-graded and well-distributed;

(c) Overall dense and well-consolidated nature of concrete without any coarse voids or visible cracks;

(d) Uniform color tone of paste through depth;

(e) Crushed stone of subbase adhered to the bottom end; and,

(f) Lack of any wire mesh or steel reinforcment in the core.

AIR ENTRAINMENT AND CARBONATION

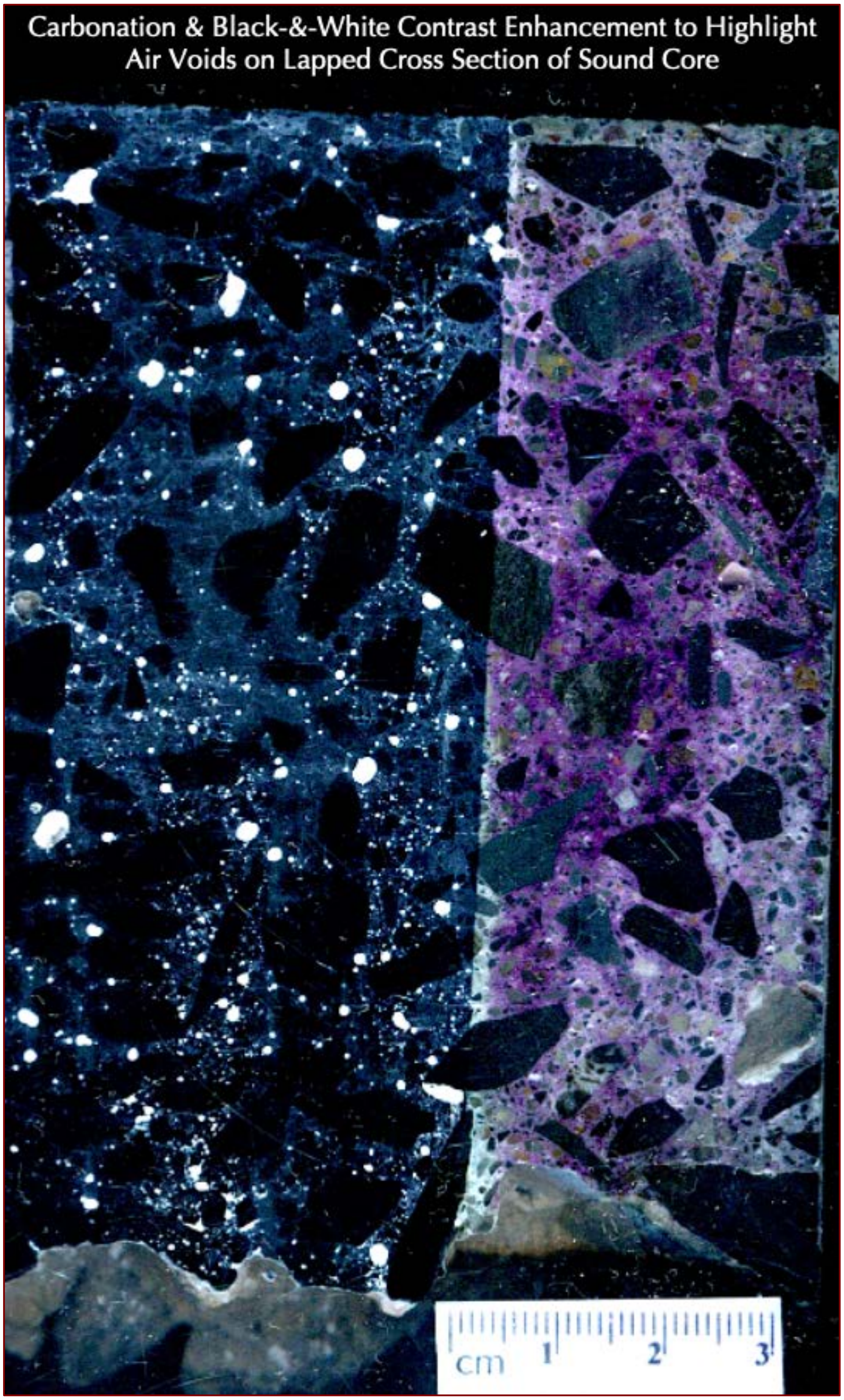


Figure 11: The lapped section of the sound core shown in Figure 8 but after:

(a) Highlighting air-entrainment in concrete by black and white contrast enhancement of one half of the section with a Sharpie marker pen followed by filling the air voids with a fine white zinc oxide power to highlight all voids in white against a black background of everything else, and,

(b) Highlighting shallow carbonation of concrete by treatment of the other half of lapped cross section with a phenolphthalein alcoholic solution to show the shallow depth of cabronation of concrete at the top few millimeters (< 5 mm) from the lack of pink discoloration in the shallow carbonated portion at the finished surface as opposed to pink discoloration of non-carbonated concrete in the interior.

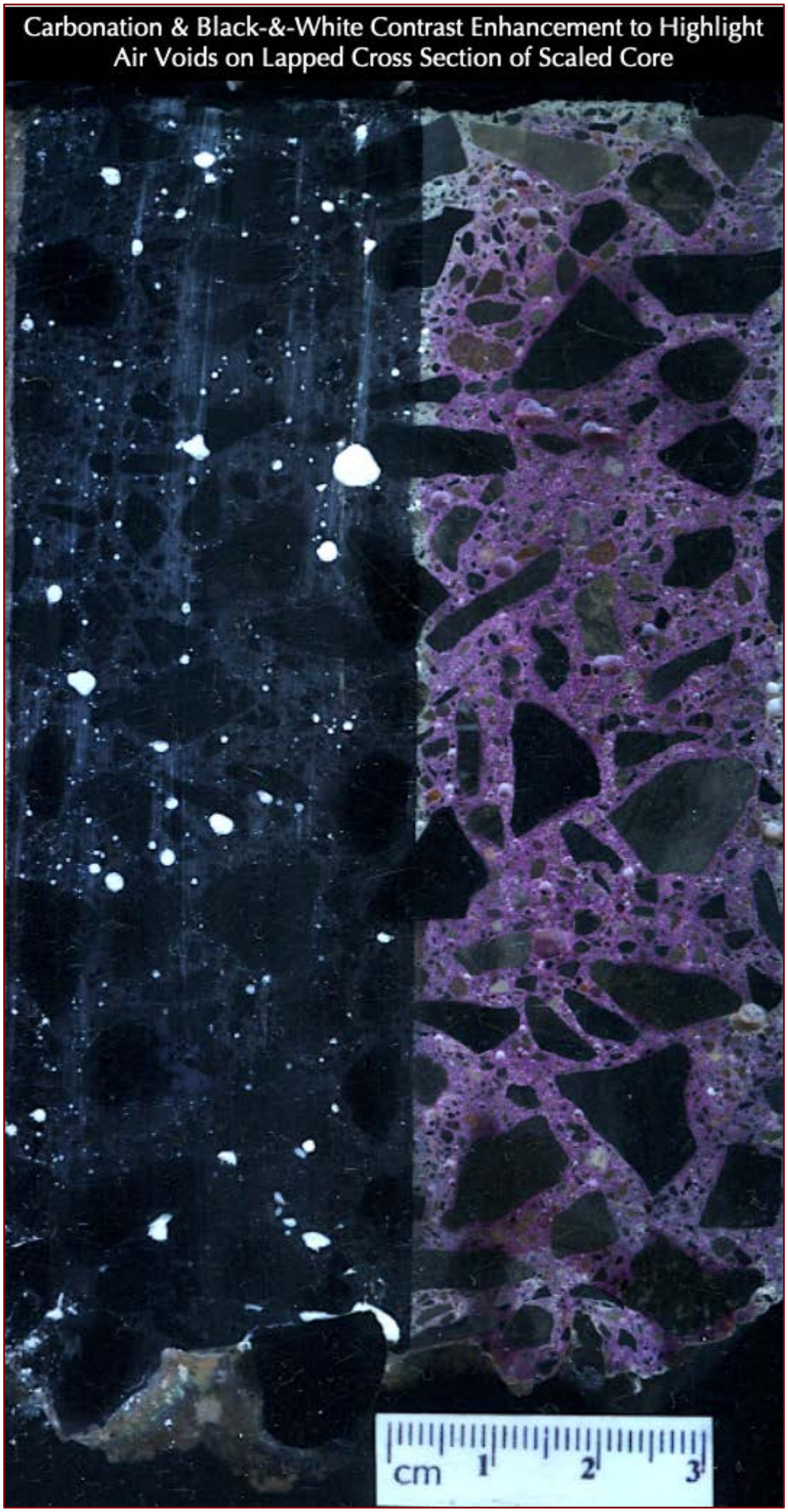


Figure 12: The lapped section of the scaled core shown in Figure 10 but after:

(a) Highlighting air-entrainment in concrete by black and white contrast enhancement of one half of the section with a Sharpie marker pen followed by filling the air voids with a fine white zinc oxide power to highlight all voids in white against a black background of everything else, and,

(b) Highlighting shallow carbonation of concrete by treatment of the other half of lapped cross section with a phenolphthalein alcoholic solution to show the shallow depth of cabronation of concrete at the top few millimeters (< 5 mm) from the lack of pink discoloration in the shallow carbonated portion at the finished surface as opposed to pink discoloration of non-carbonated concrete in the interior.

MICROGRAPHS OF LAPPED CROSS SECTIONS

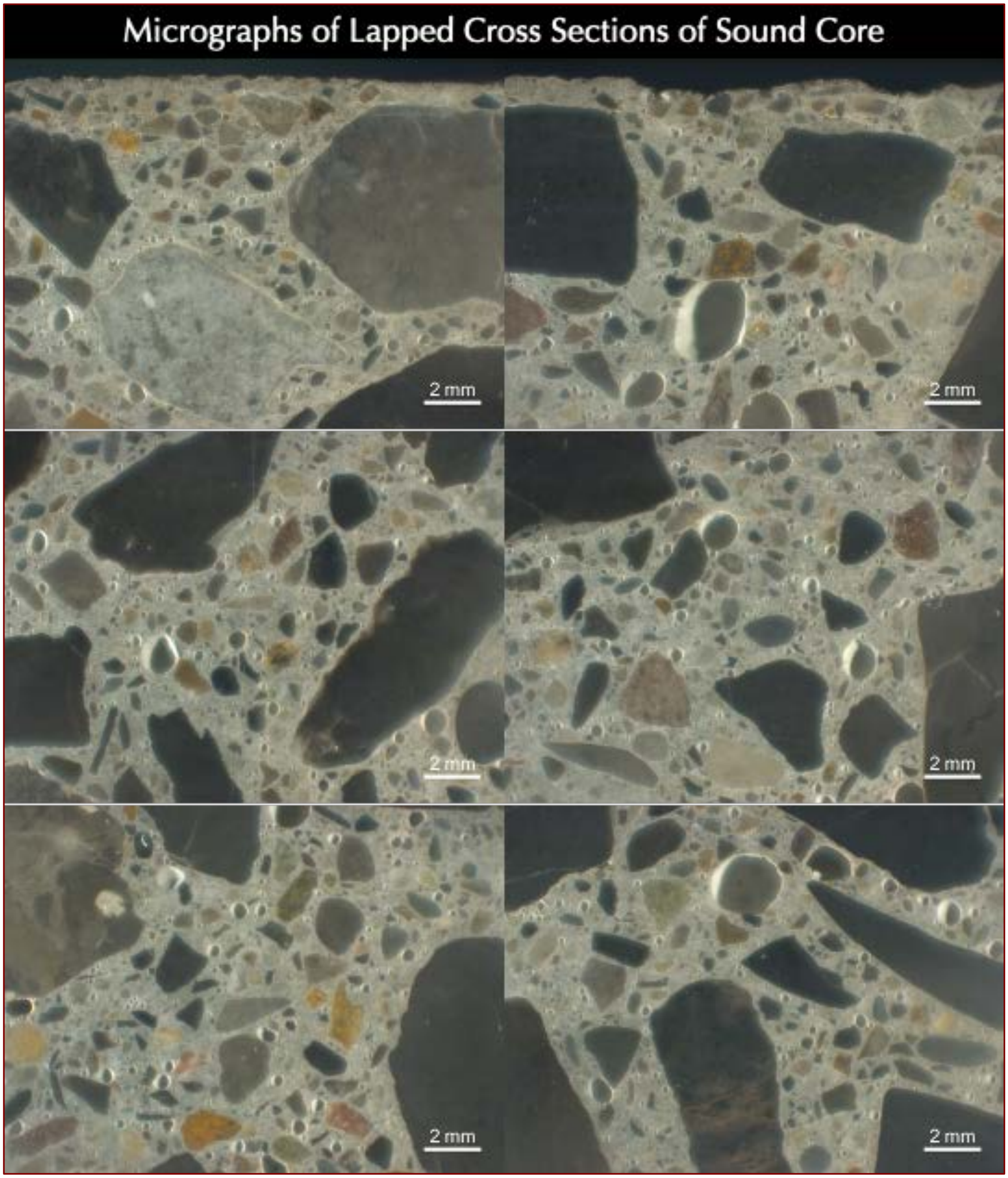


Figure 13: Micrographs of lapped cross section of sound core taken with a stereo-microscope showing: (a) air-entrained nature of concrete consisting of discrete, fine, spherical and near-spherical entrained air voids of sizes 1 mm or less, and, a few coarse near-spherical and irregularly-shaped entrapped air voids; (b) more or less uniform distribution of air voids from the near-surface region (top row) to mid-depth location of core (middle row) to the bottom end of core (bottom row); (c) dense and well-consolidated nature of concrete throughout the depth; and (d) lack of any cracks or any other distress at the surface region (top row) or in the interior of the core.

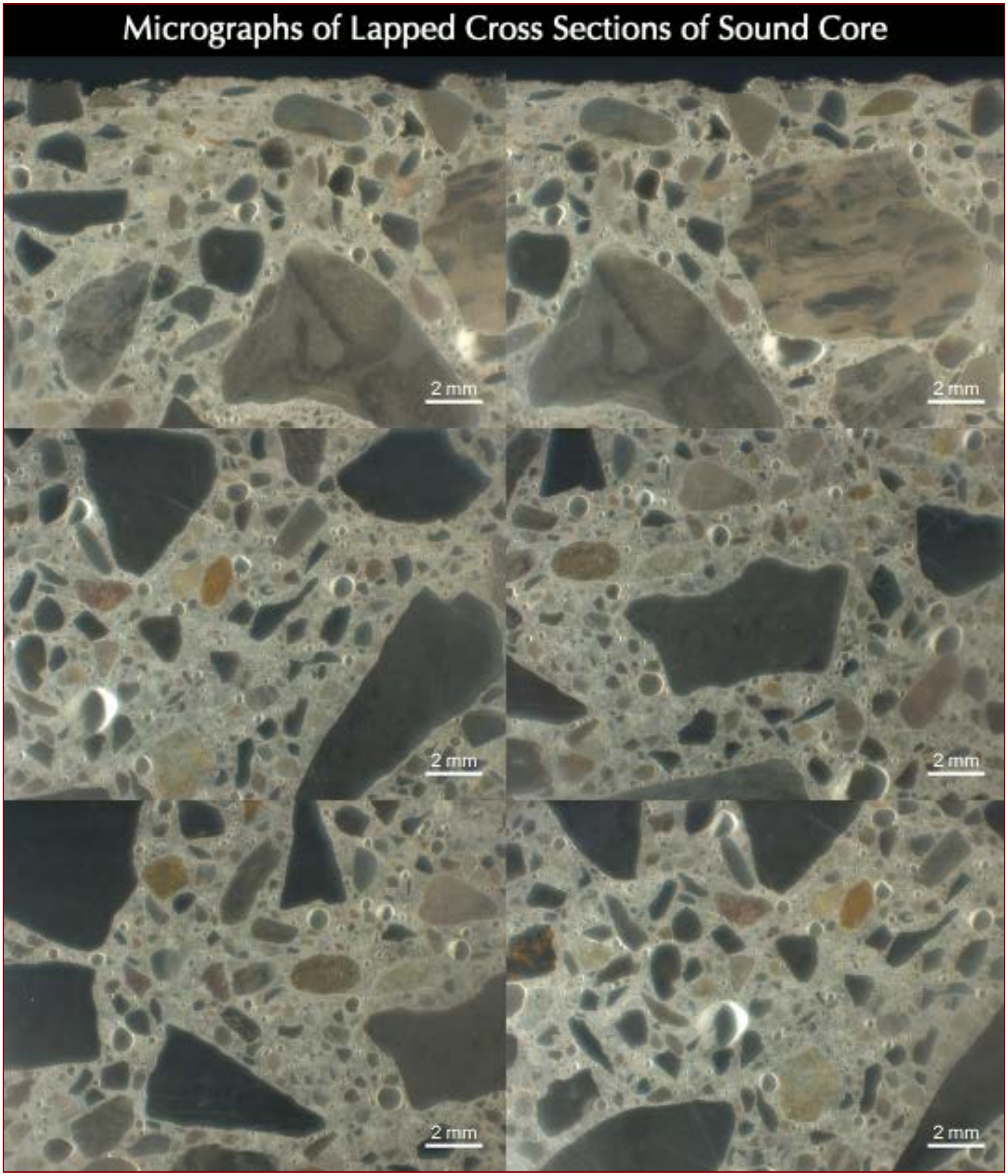


Figure 14: Micrographs of lapped cross section of sound core taken with a stereo-microscope showing: (a) air-entrained nature of concrete consisting of discrete, fine, spherical and near-spherical entrained air voids of sizes 1 mm or less, and, a few coarse near-sphecial and irregularly-shaped entrapped air voids; (b) more or less uniform distribution of air voids from the near-surface region (top row) to mid-depth location of core (middle row) to the bottom end of core (bottom row); (c) dense and well-consolidated nature of concrete throughout the depth; and (d) lack of any cracks or any other distress at the surface region (top row) or in the interior of the core.

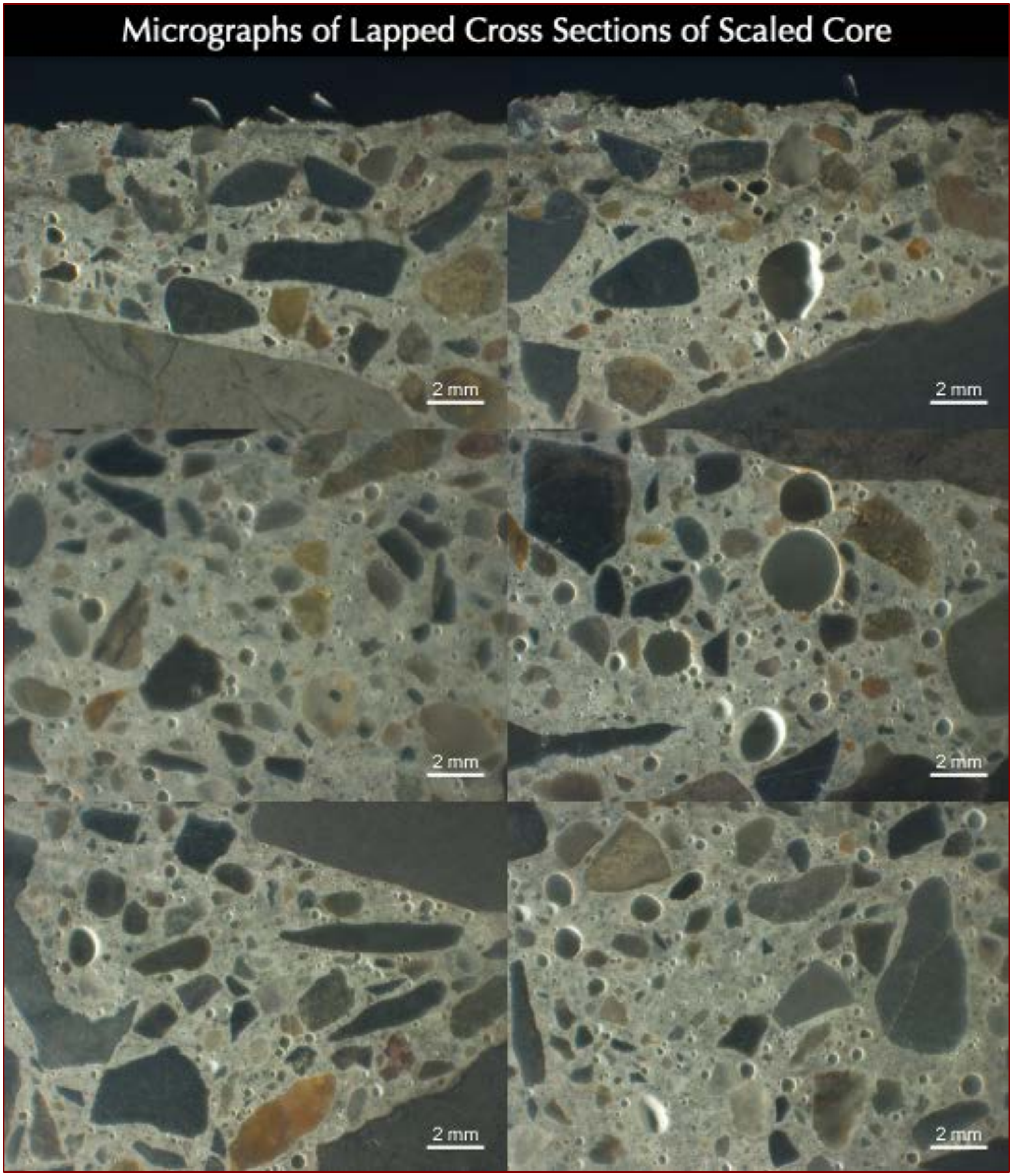


Figure 15: Micrographs of lapped cross section of scaled core taken with a stereo-microscope showing: (a) air-entrained nature of concrete consisting of discrete, fine, spherical and near-spherical entrained air voids of sizes 1 mm or less, and, a few coarse near-sphecial and irregularly-shaped entrapped air voids; (b) more or less uniform distribution of air voids from the near-surface region (top row) to mid-depth location of core (middle row) to the bottom end of core (bottom row); (c) dense and well-consolidated nature of concrete throughout the depth; and (d) lack of any cracks or any other distress (except scaling) at the surface region (top row) or in the interior of the core. Notice some fine hair-like synthetic polypropylene-type fibers protruding from the scaled surface in the top row photos.

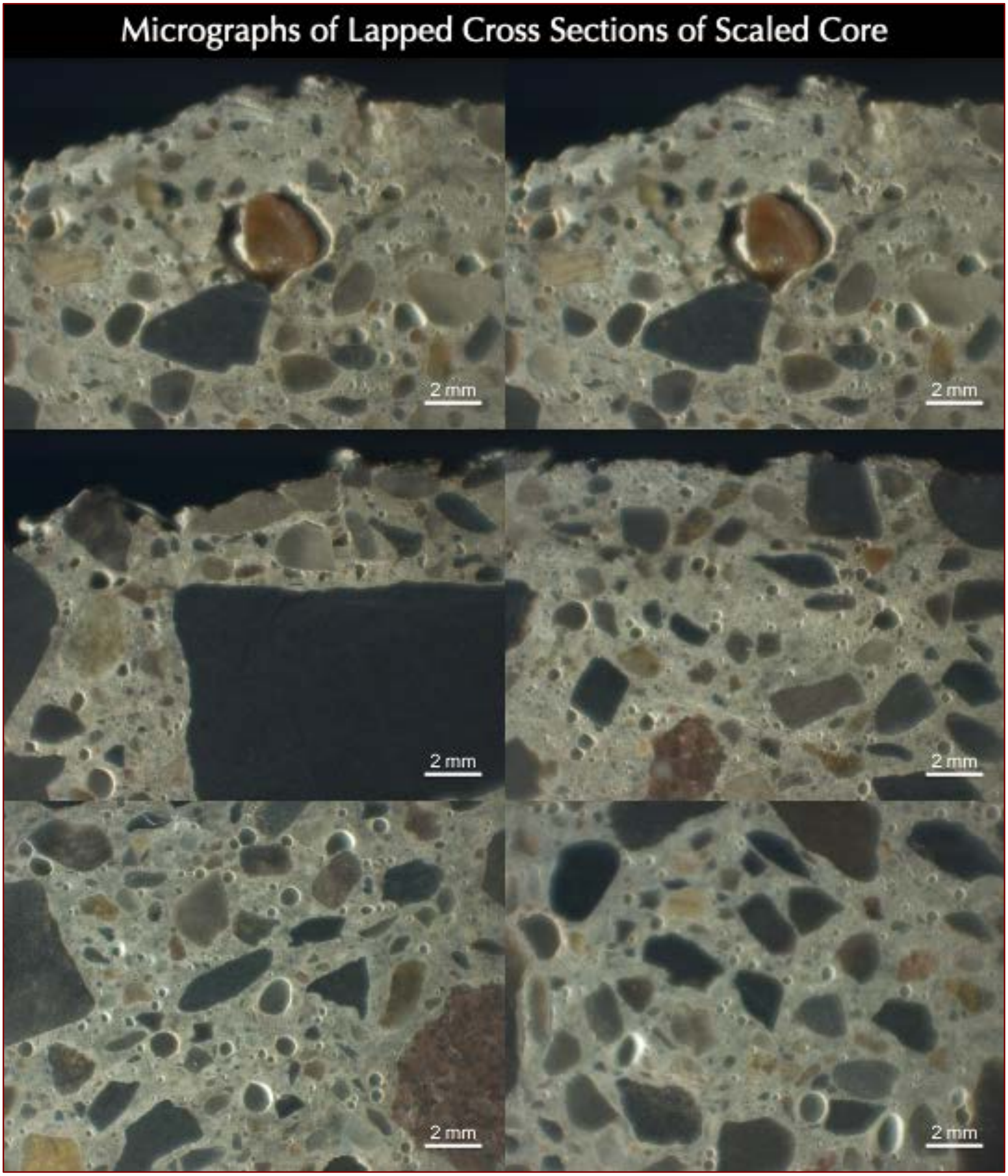


Figure 16: Micrographs of lapped cross section of scaled core taken with a stereo-microscope showing: (a) air-entrained nature of concrete consisting of discrete, fine, spherical and near-spherical entrained air voids of sizes 1 mm or less, and, a few coarse near-sphecial and irregularly-shaped entrained air voids; (b) more or less uniform distribution of air voids from the near-surface region (top row) to mid-depth location of core (middle row) to the bottom end of core (bottom row); (c) dense and well-consolidated nature of concrete throughout the depth; and (d) lack of any cracks or any other distress (except scaling) at the surface region (top row) or in the interior of the core.

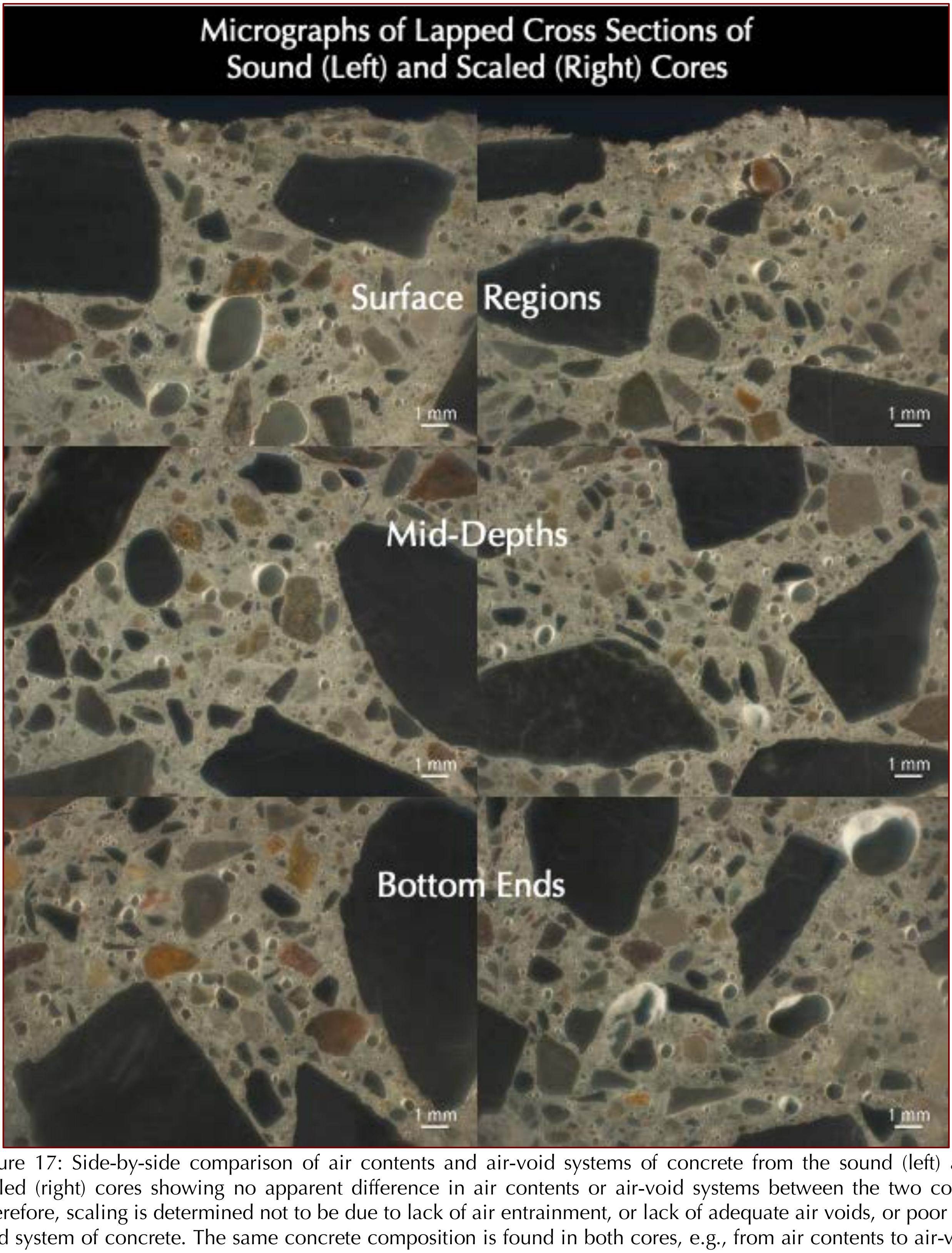
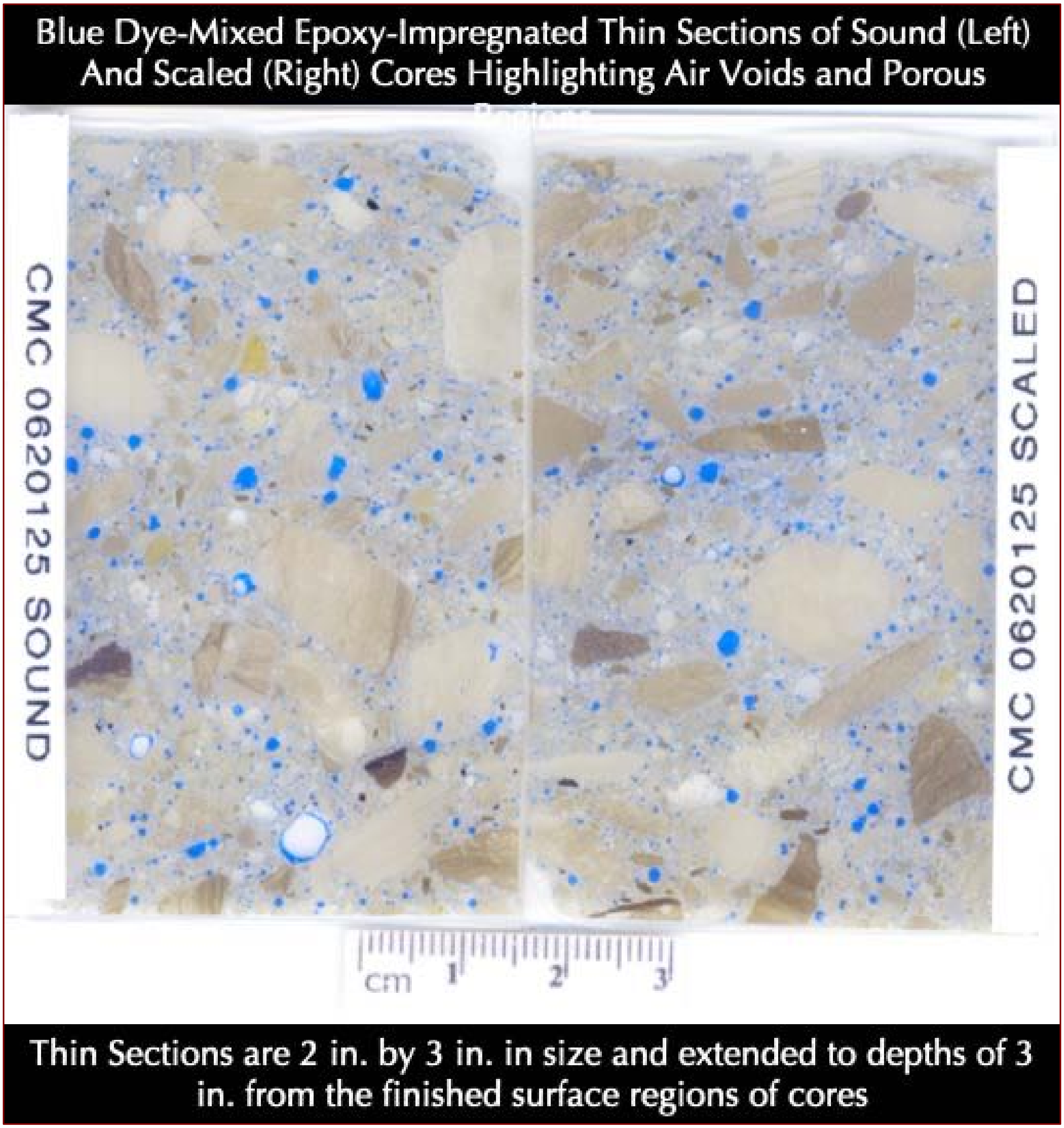


Figure 17: Side-by-side comparison of air contents and air-void systems of concrete from the sound (left) and scaled (right) cores showing no apparent difference in air contents or air-void systems between the two cores. Therefore, scaling is determined not to be due to lack of air entrainment, or lack of adequate air voids, or poor air-void system of concrete. The same concrete composition is found in both cores, e.g., from air contents to air-void distribution to crushed stone coarse aggregate types to natural sand fine aggregate types to dense well consolidated natures of concretes to lack of any cracking in the interior concretes. Therefore, concrete compositions and consolidation are found not to have contributed to the observed surface scaling problem in the driveway.

THIN SECTIONS

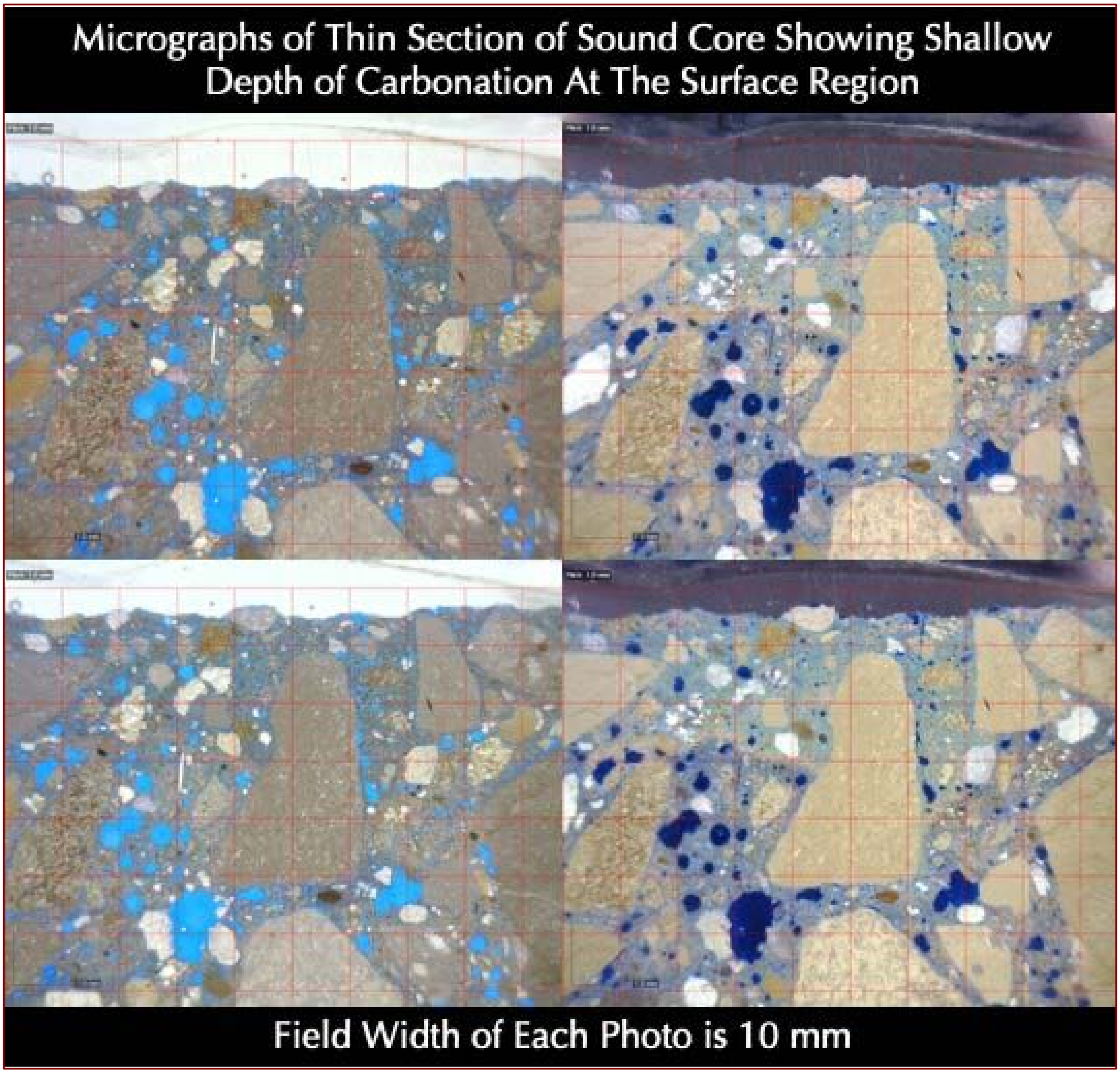


Blue Dye-Mixed Epoxy-Impregnated Thin Sections of Sound (Left) And Scaled (Right) Cores Highlighting Air Voids and Porous Regions

Thin Sections are 2 in. by 3 in. in size and extended to depths of 3 in. from the finished surface regions of cores

Figure 18: Blue dye-mixed epoxy-impregnated thin sections of top 3 inches of cores from the sound (left) and scaled (right) locations showing the adequately air-entrained natures of concretes in both cores. Blue dye-mixed epoxy helped to highlight the air voids along with any cracks, microcracks, voids, or porous areas of paste. Therefore, thin sections of concrete from both scaled and sound loctions show good air-entrained concretes at least to 3 inch depth of the total 4$^1/_2$ to 5 in. thick driveway slab. Micrographs of lapped cross sections of cores in Figures 14 to 19 show extension of good air entrainment to the bottom ends in both cores.

MICROGRAPHS OF THIN SECTION OF SOUND CONCRETE CORE


Micrographs of Thin Section of Sound Core Showing Shallow Depth of Carbonation At The Surface Region

Field Width of Each Photo is 10 mm

Figure 19: Micrographs of thin section of top 0.5 in. (10 mm) of sound core taken with a Dinolite digital camera with crossed polarization facility showing the concrete in plane (left) and crossed (right) polarized light modes. Left column shows adequte air entrainment even at the surface region and distribution of air voids, where voids are highlighted by blue epoxy filling the voids. Right column shows the limestone composition of crushed stone coarse aggregate particles that are well-graded, well-distributed, sound, dense, angular, and show typical characteristic golden brown to yellow interference color of fine-grained calcite in limestone. Interstitial mortar fraction between crushed limestone coarse aggregate particles show a mixture of fine limestone probably representing the finer (sand-sized) fraction of coarse aggregate, natural siliceous (quartz, quartzite, feldspar) sand fine aggregate particles, and a Portland cement paste. Paste shows surface carbonation from interaction with atmospheric carbon dioxide, which is shallow, extended to a depth of around 5 mm then diffused into non-carbonated interior concrete. Grids are of 1 mm squares.

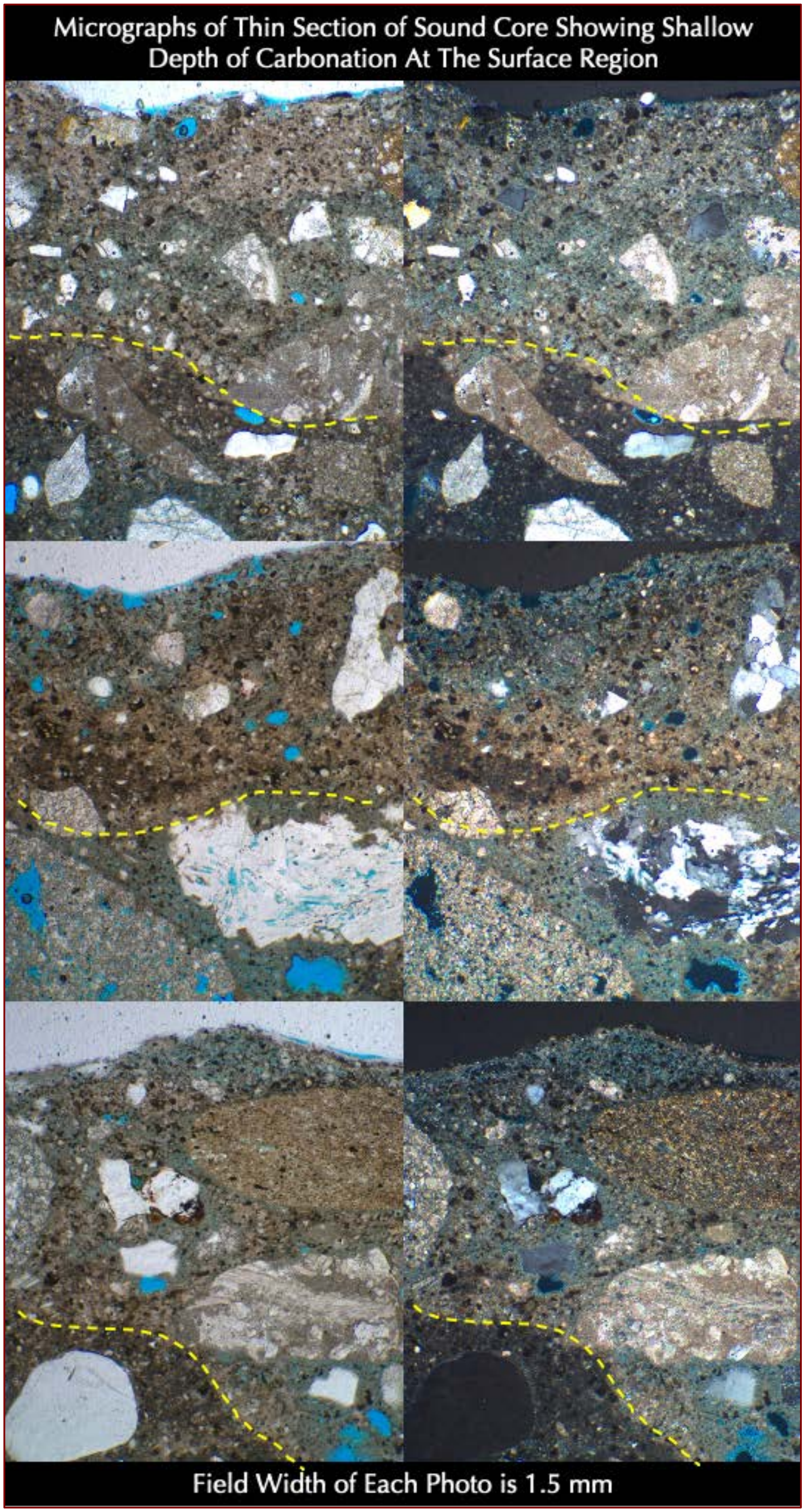
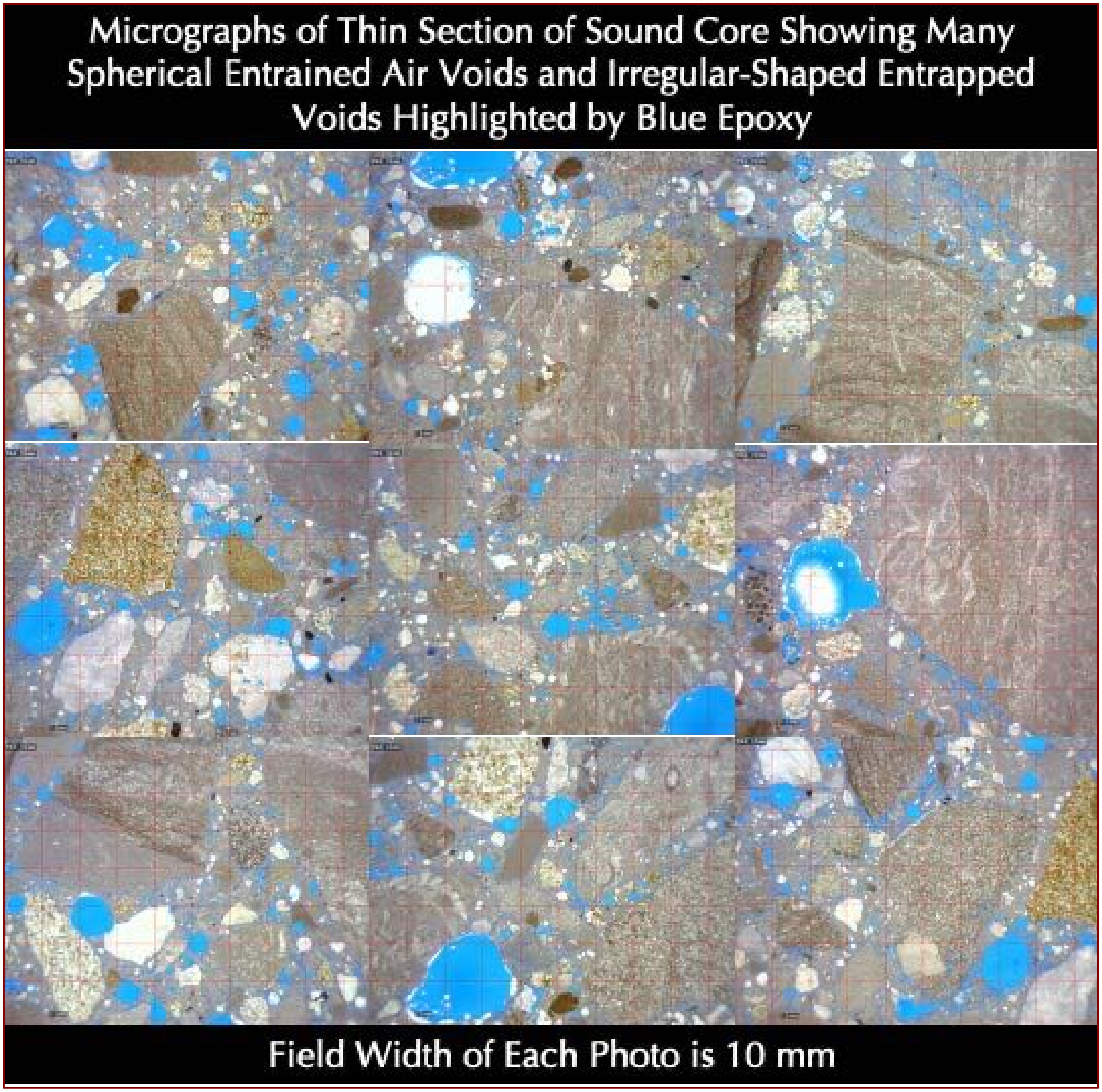


Figure 20: Micrographs of thin section of sound core showing the surface region of concrete where shallow carbonated finished surface is marked by yellow dashed lines, and separated from the interior non-carbonated concrete.

In all photos, the very top of surface shows a relatively porous paste compared to paste in the interior, which is due to the presence of water during finishining either due to finishing in the presence of bleed water and/or due to addition of water during finishing.

Micrographs were taken using a Nikon Eclipse E600 upright microscope wih polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope.



Micrographs of Thin Section of Sound Core Showing Many Spherical Entrained Air Voids and Irregular-Shaped Entrapped Voids Highlighted by Blue Epoxy

Field Width of Each Photo is 10 mm

Figure 21: Mosaic of nine micrographs of thin section of the interior of sound core taken with a Dinolite digital camera. Mosaic shows adequte air entrainment and distribution of air voids, where voids are highlighted by blue epoxy filling the voids. Micrographs also show the limestone composition of crushed stone coarse aggregate particles that are well-graded, well-distributed, sound, dense, angular, and show typical characteristic golden brown to yellow interference color of fine-grained calcite in limestone. Many limestone particles show fine parallel dark brown argillaceous veins indicating interbedded argillaceous limestone composition of crushed stone; many other particles lack such dark argillaceous veins but contain fossils (fossiliferous limestone, e.g., biomicrite). Interstitial mortar fraction between crushed limestone coarse aggregate particles show a mixture of fine limestone probably representing the finer (sand-sized) fraction of coarse aggregate, natural siliceous (quartz, quartzite, feldspar) sand fine aggregate particles, and a Portland cement paste. Grids are of 1 mm squares.

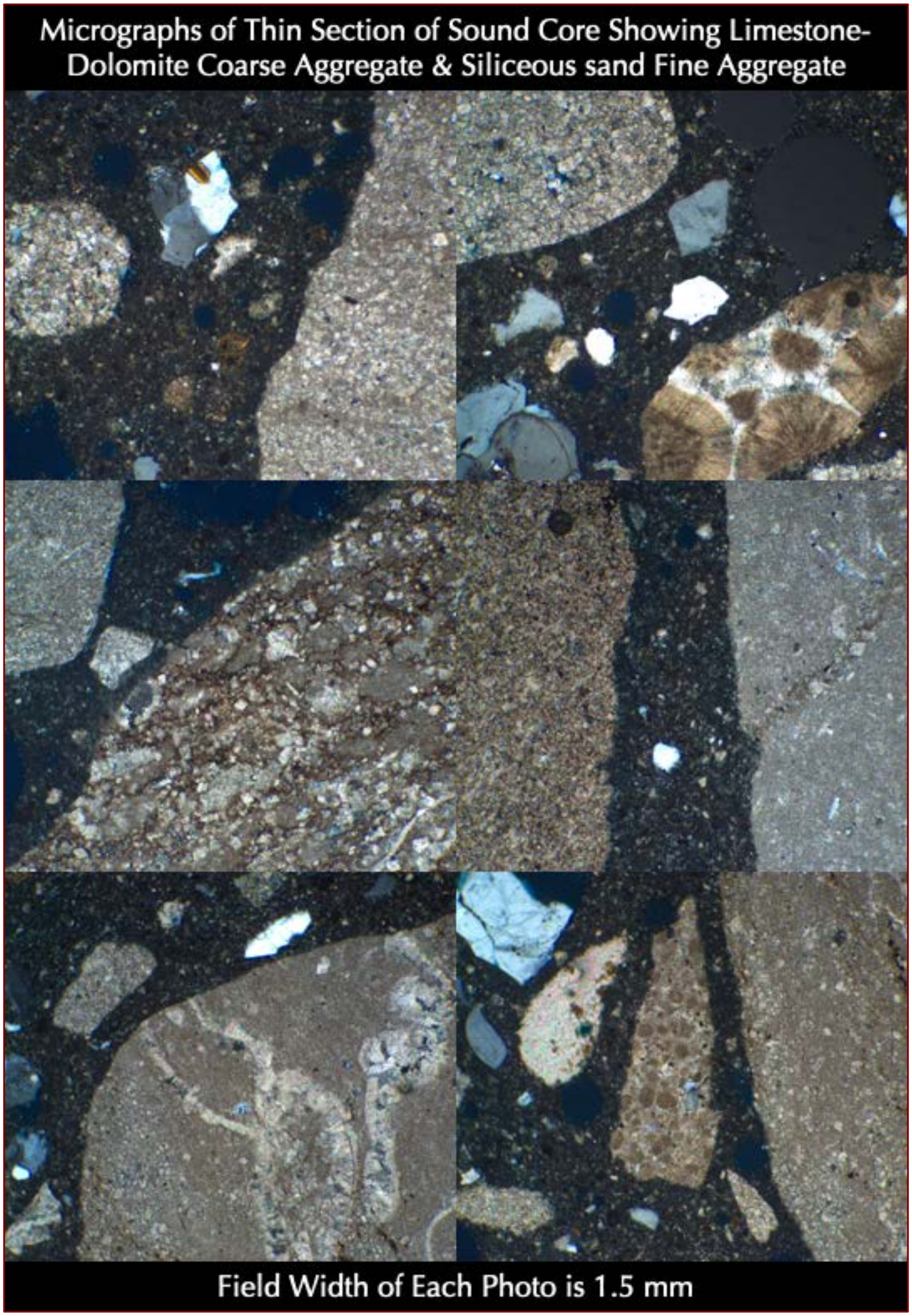


Figure 22: Micrographs of thin section of sound core showing:

(a) Crushed limestone coarse aggregate particles, and,

(b) Mixtures of sand-sized particles of limestone from coarse aggregate and natural siliceous sand fine aggregate particles.

Limestone shows fossiliferous, fine-grained (micritic) and argillaceous varieties.

Siliceous component of sand is dominated by quartz and quarztite particles along with a subordinate amount of feldspar and other siliceous particles.

Micrographs were taken using a Nikon Eclipse E600 upright microscope with polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope.

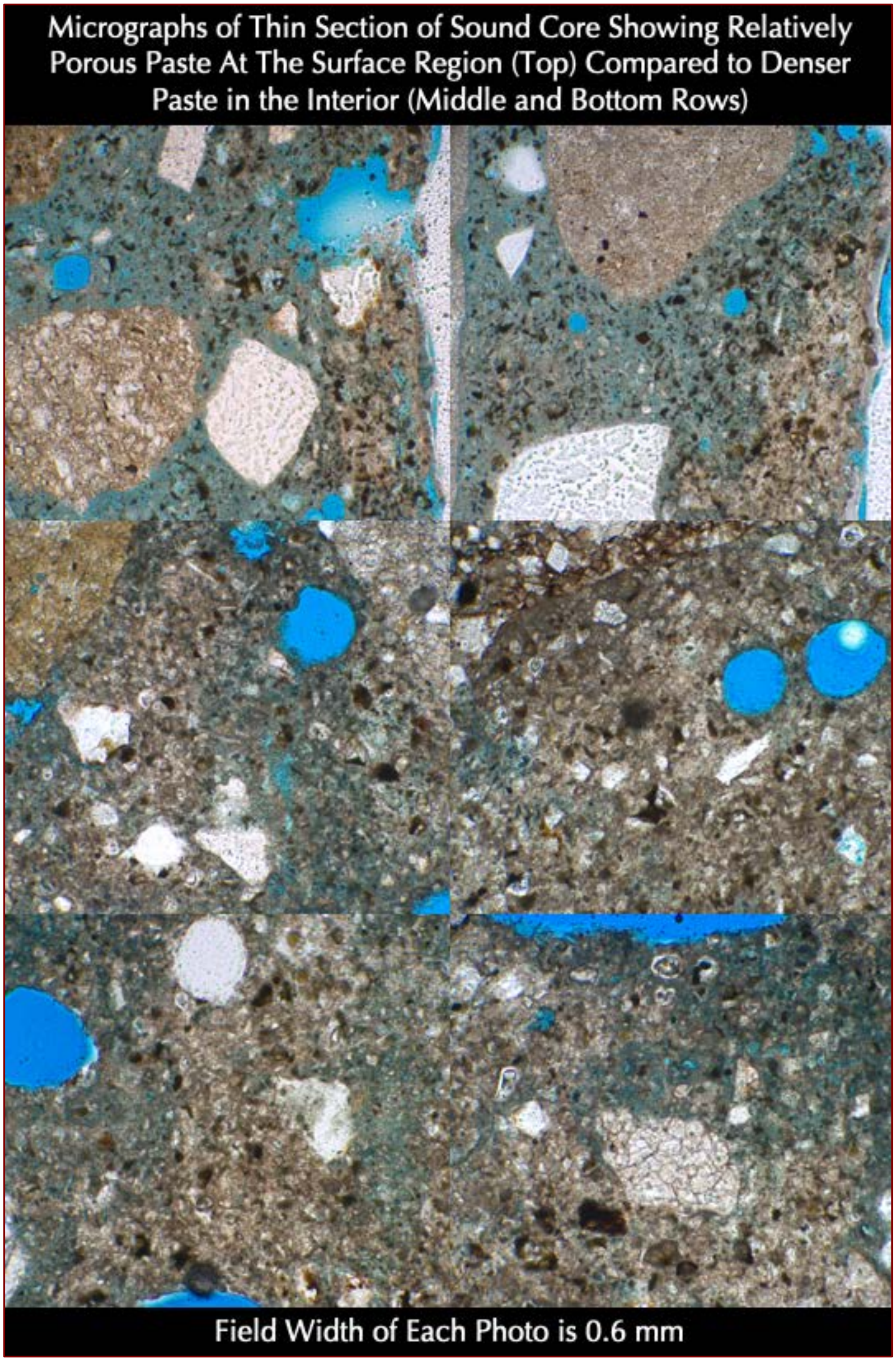


Figure 23: Micrographs of thin section of sound core at high magnifications showing many characteristic features of Portland cement paste at the surface region (top row) and in the interior (middle and bottom rows).

Paste shows a mixture of overwhelming cement hydration products (calcium-silicate-hyadrate, calcum hydroxide etc.) and relatively fewer residual Portland cement particles. Cement hydration products show atmopsheric carbonation at the surface region (top row).

Paste is also more porous at the very top than in the interior, which is highlighted by blue tone of porous paste at the surface compared to brown tone of denser paste in the interior.

Residual cement particles are mostly dark brown remnants of ferrite phases of cement in the top porous surface region, whereas mixtures of alite with hydration rims, spherical clusters of belite and dark brown ferrite in the interior, which indicates an advanced hydraiton of calcium silicate phases of cement at the surface region leaving only dark brown ferrite residues (which hydrate at a slower rate than alite). Interior paste is dense and show reasonably well hydration. Many hydration rims around alite particles are seen. Paste shows patchy areas of denser and less dense regions.

Micrographs were taken using a Nikon Eclipse E600 upright microscope with polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope.

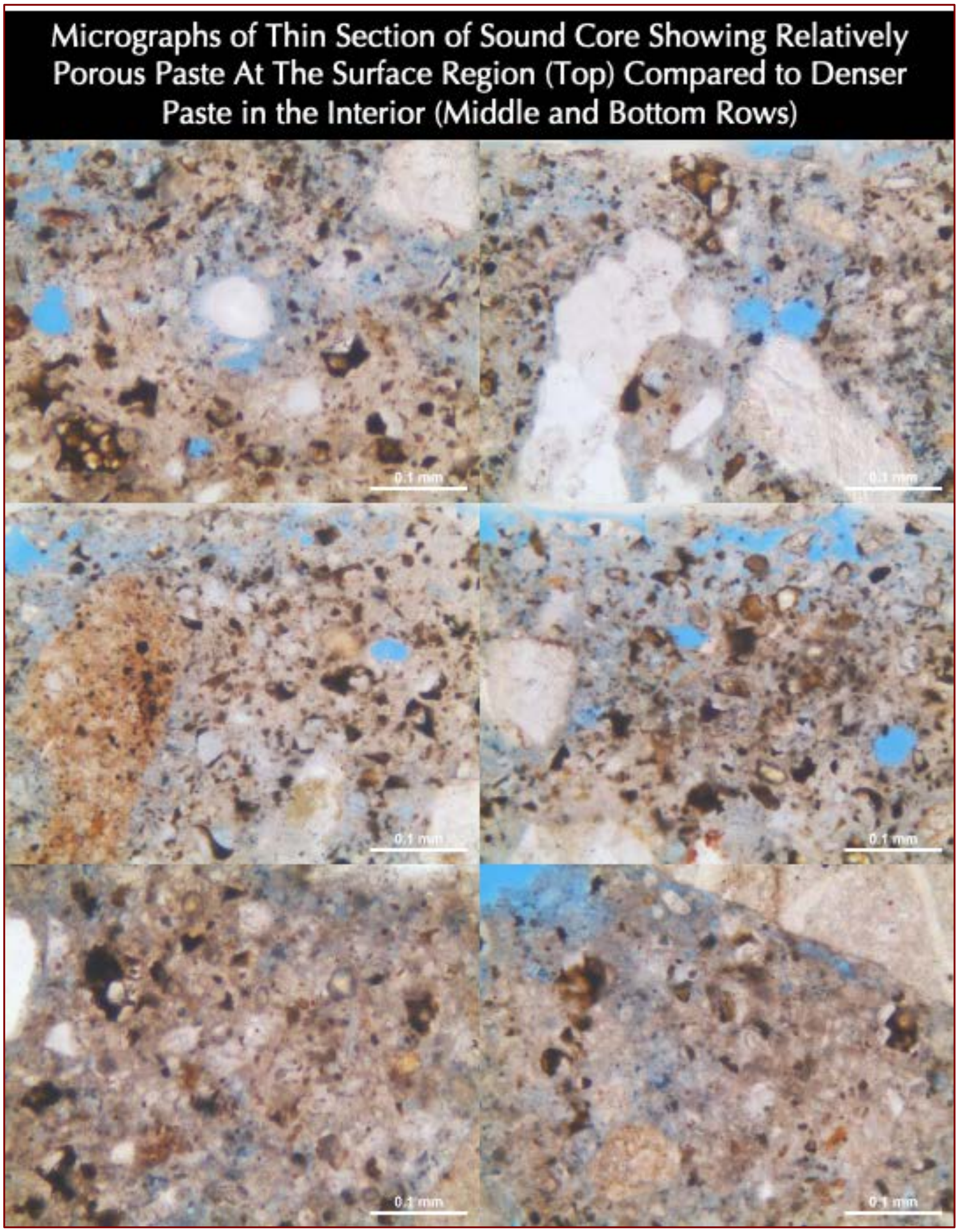

Micrographs of Thin Section of Sound Core Showing Relatively Porous Paste At The Surface Region (Top) Compared to Denser Paste in the Interior (Middle and Bottom Rows)

Figure 24: Micrographs of thin section of sound core showing many characteristic features of Portland cement paste at the surface region (top row) and in the interior (middle and bottom rows).

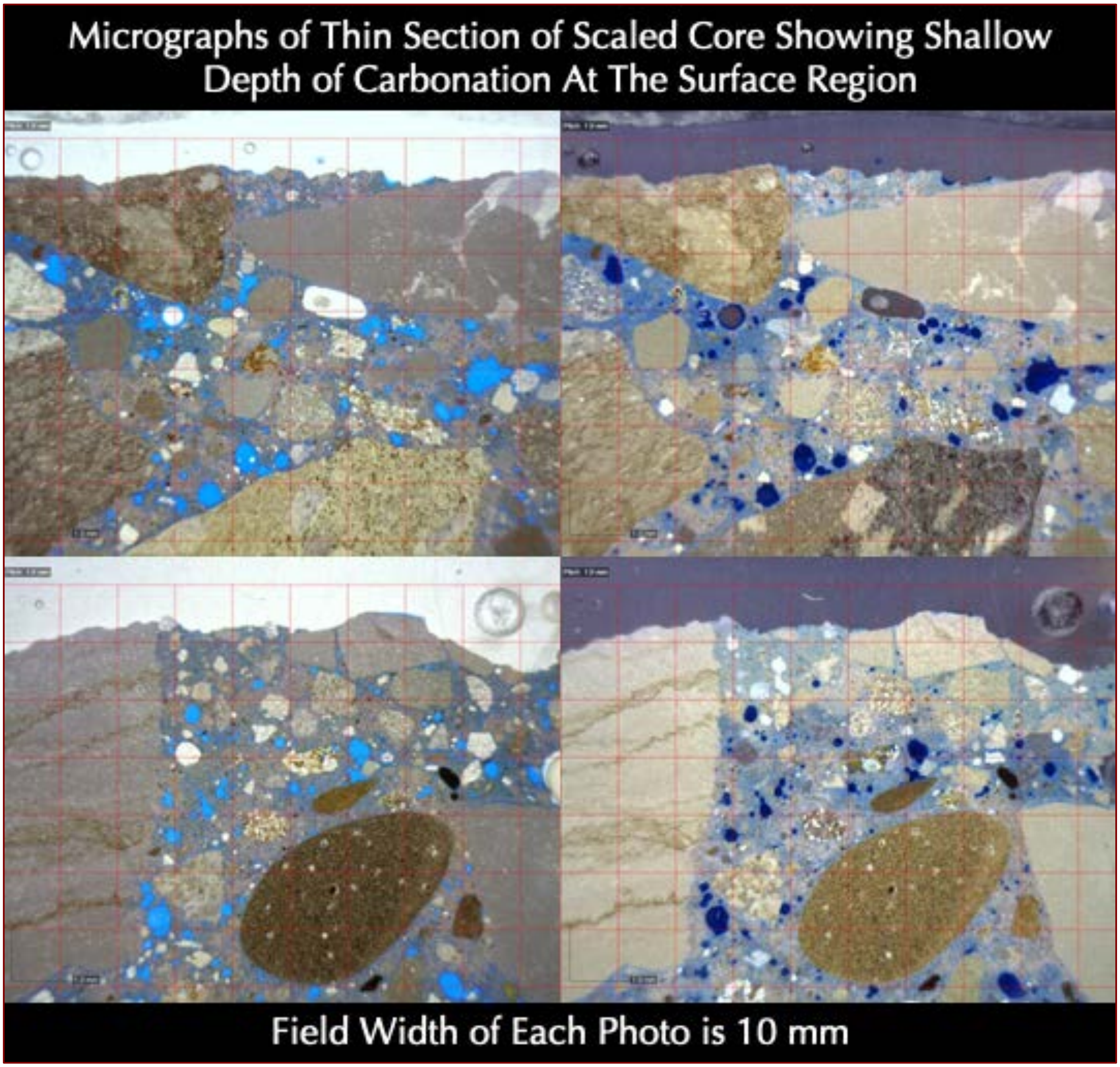
Paste shows a mixture of overwhelming cement hydration products (calcium silicate hyadrate, calcum hydroxide etc.) and relatively fewer residual Portland cement particles. Cement hydration products show atmopsheric carbonation at the surface region (top row).

Paste is also more porous at the very top than in the interior, which is highlighted by blue tone of porous paste at the surface compared to brown tone of denser paste in the interior.

Residual cement particles are mostly dark brown remnants of ferrite phases of cement in the top porous surface region, whereas mixtures of alite with hydraiton rims, spherical clusters of belite and dark brown ferrite in the interior, which indicates an advanced hydraiton of calcium silicate phases of cement at the surface region leaving only dark brown ferrite residues (which hydrate at a slower rate than alite). Interior paste is dense and show reasonably well hydration. Many hydration rims around alite particles are seen. Paste shows patchy areas of denser and less dense regions.

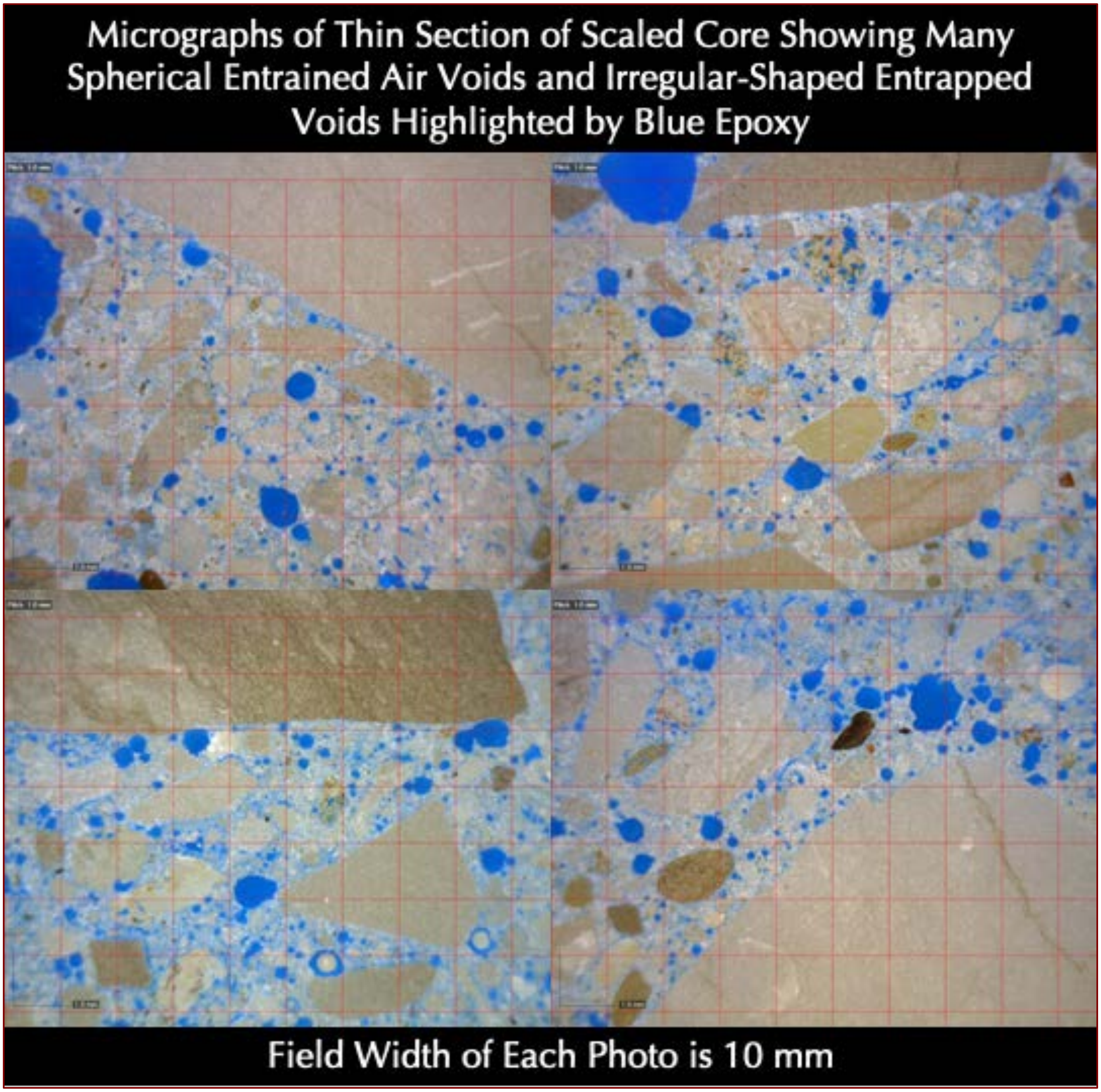
Micrographs were taken using a Nikon Eclipse E600POL petrographic microscope at 200 to 400x magnifications.

MICROGRAPHS OF THIN SECTION OF SCALED CONCRETE CORE


Micrographs of Thin Section of Scaled Core Showing Shallow Depth of Carbonation At The Surface Region

Field Width of Each Photo is 10 mm

Figure 25: Micrographs of thin section of top 0.5 in. (10 mm) of scaled core taken with a Dinolite digital camera with crossed polarization facility showing the concrete in plane (left) and crossed (right) polarized light modes. Left column shows adequte air entrainment even at the surface region and distribution of air voids, where voids are highlighted by blue epoxy filling the voids. Right column shows the limestone composition of crushed stone coarse aggregate particles that are well-graded, well-distributed, sound, dense, angular, and showing typical characteristic golden brown to yellow interference color of fine-grained calcite in limestone. Interstitial mortar fraction between crushed limestone coarse aggregate particles show a mixture of fine limestone probably representing the finer (sand-sized) fraction of coarse aggregate, natural siliceous (quartz, quartzite, feldspar) sand fine aggregate particles, and a Portland cement paste. Paste shows surface carbonation from interaction with atmopsheric carbon dioxide, which is shallow, extended to a depth of around 5 mm then diffused into non-carbonated interior concrete. Grids are of 1 mm squares.



Micrographs of Thin Section of Scaled Core Showing Many Spherical Entrained Air Voids and Irregular-Shaped Entrapped Voids Highlighted by Blue Epoxy

Field Width of Each Photo is 10 mm

Figure 26: Mosaic of nine micrographs of thin section of the interior of scaled core taken with a Dinolite digital camera. Mosaic shows adequte air entrainment and distribution of air voids, where voids are highlighted by blue epoxy filling the voids. Micrographs also show the limestone composition of crushed stone coarse aggregate particles that are well-graded, well-distributed, sound, dense, angular, and show typical characteristic golden brown to yellow interference color of fine-grained calcite in limestone. Many limestone particles show fine parallel dark brown argillaceous veins indicating interbedded argillaceous limestone composition of crushed stone; many other particles lack such dark argillaceous veins but contain fossils (fossiliferous limestone, e.g., biomicrite). Interstitial mortar fraction between crushed limestone coarse aggregate particles show a mixture of fine limestone probably representing the finer (sand-sized) fraction of coarse aggregate, natural siliceous (quartz, quartzite, feldspar) sand fine aggregate particles, and a Portland cement paste. Grids are of 1 mm squares.

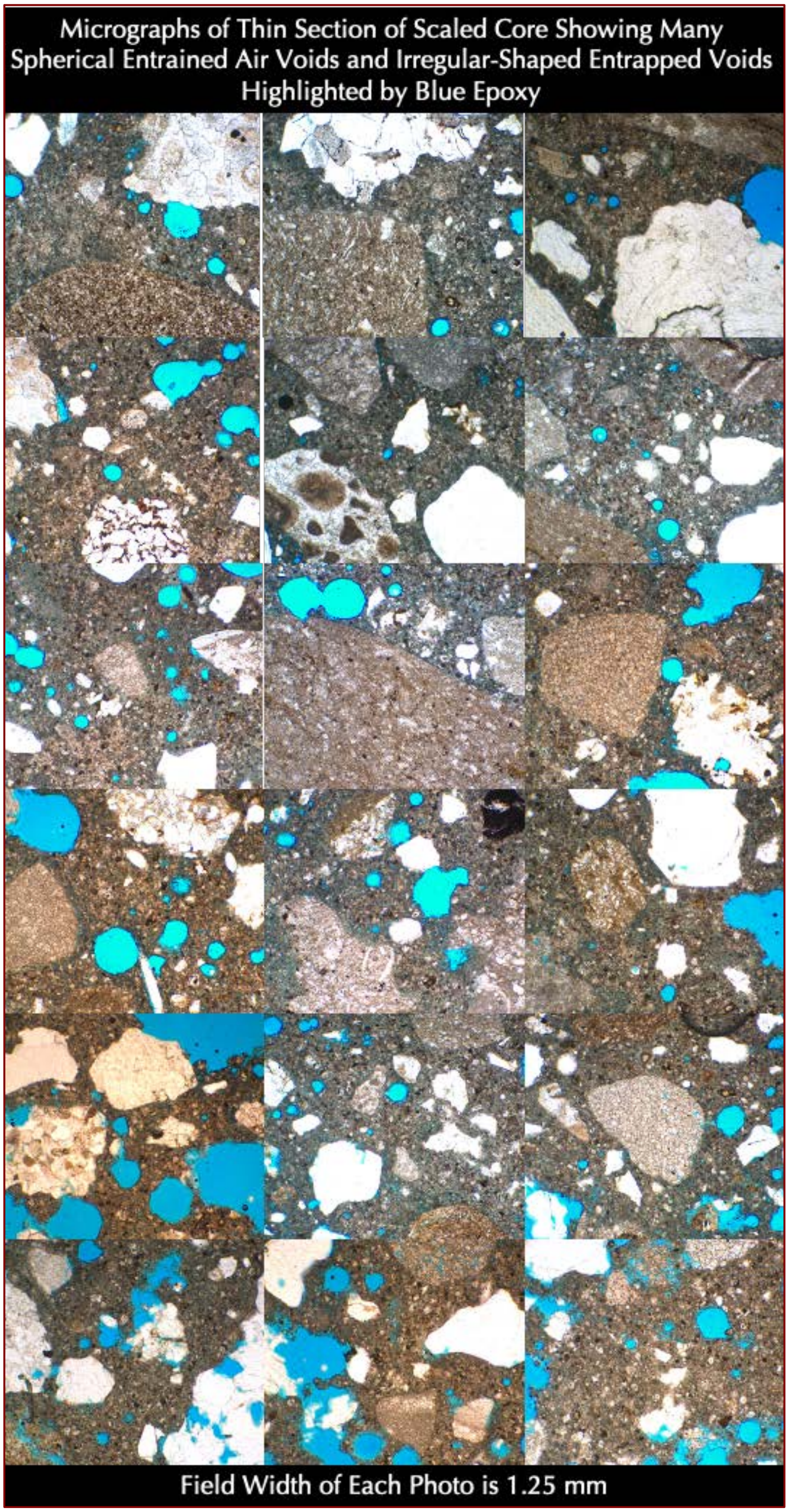


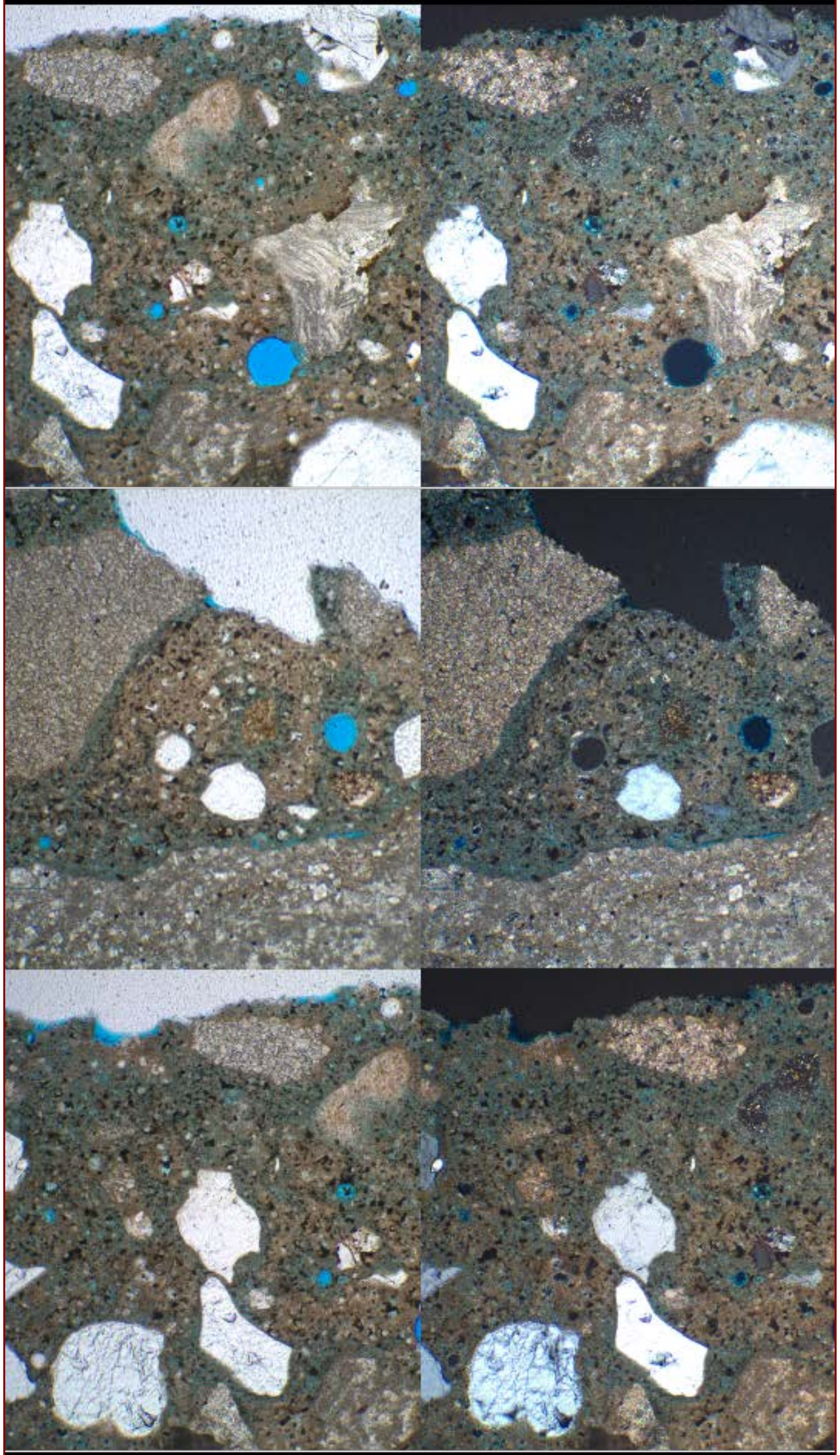
Figure 27: Mosaic of eighteen micrographs of thin section of the interior of scaled core. Mosaic shows adequte air entrainment and distribution of air voids, where voids are highlighted by blue epoxy filling the voids.

Micrographs also show the limestone composition of crushed stone coarse aggregate particles that are well-graded, well-distributed, sound, dense, angular, and showing typical characteristic golden brown to yellow interference color of fine-grained calcite in limestone. Many limestone particles show fine parallel dark brown argillacoeus veins indicating interbedded argillacoeus limestone composition of crushed stone; many other particles lack such dark argillaceous verins but contain fossils (fossiliferours limestone, e.g., biomicrite).

Interstitial mortar fraction between crushed limestone coarse aggregate particles show a mixture of fine limestone probably representing the finer (sand-sized) fraction of coarse aggregate, natural siliceous (quartz, quartzite, feldspar) sand fine aggregate particles, and a Portland cement paste.

Micrographs were taken using a Nikon Eclipse E600 upright microscope wih polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope.

Micrographs of Thin Section of Scaled Core Showing Relatively Porous Paste At The Surface Region (Top) Compared to Denser Paste in the Interior (Middle and Bottom Rows)



Field Width of Each Photo is 1.25 mm

Figure 28: Micrographs of thin section of scaled core showing the surface region of concrete where shallow carbonated finished surface is highlighted by characteristic golden yellow interference color at right column in crossed polarized light, and separated from the interior non-carbonated concrete.

In all photos, the very top of surface shows a relatively porous paste compared to paste in the interior, which is due to the presence of water during finishining either due to finishing in the presence of bleed water and/or due to addition of water during finishing.

Micrographs were taken using a Nikon Eclipse E600 upright microscope wih polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope.

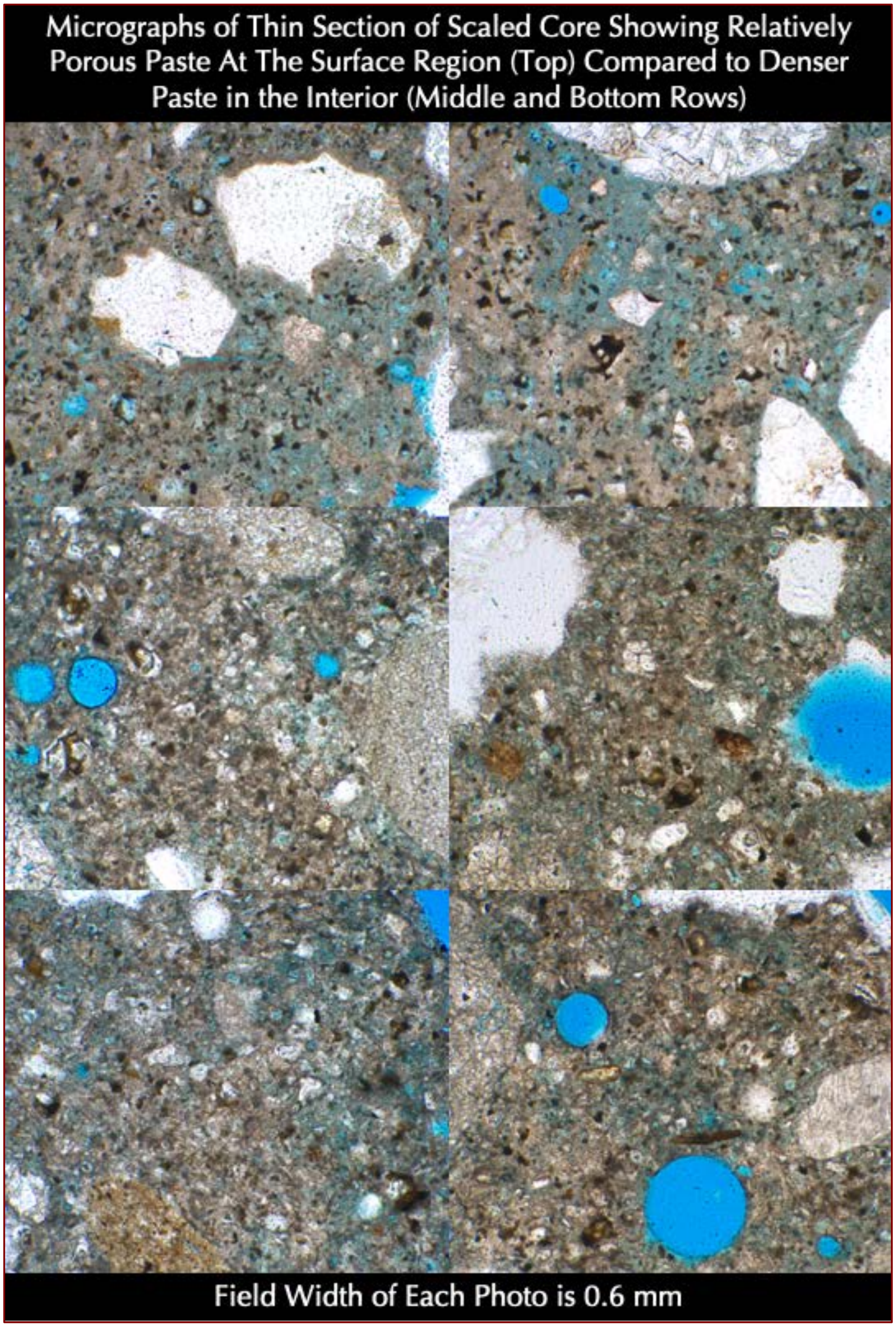


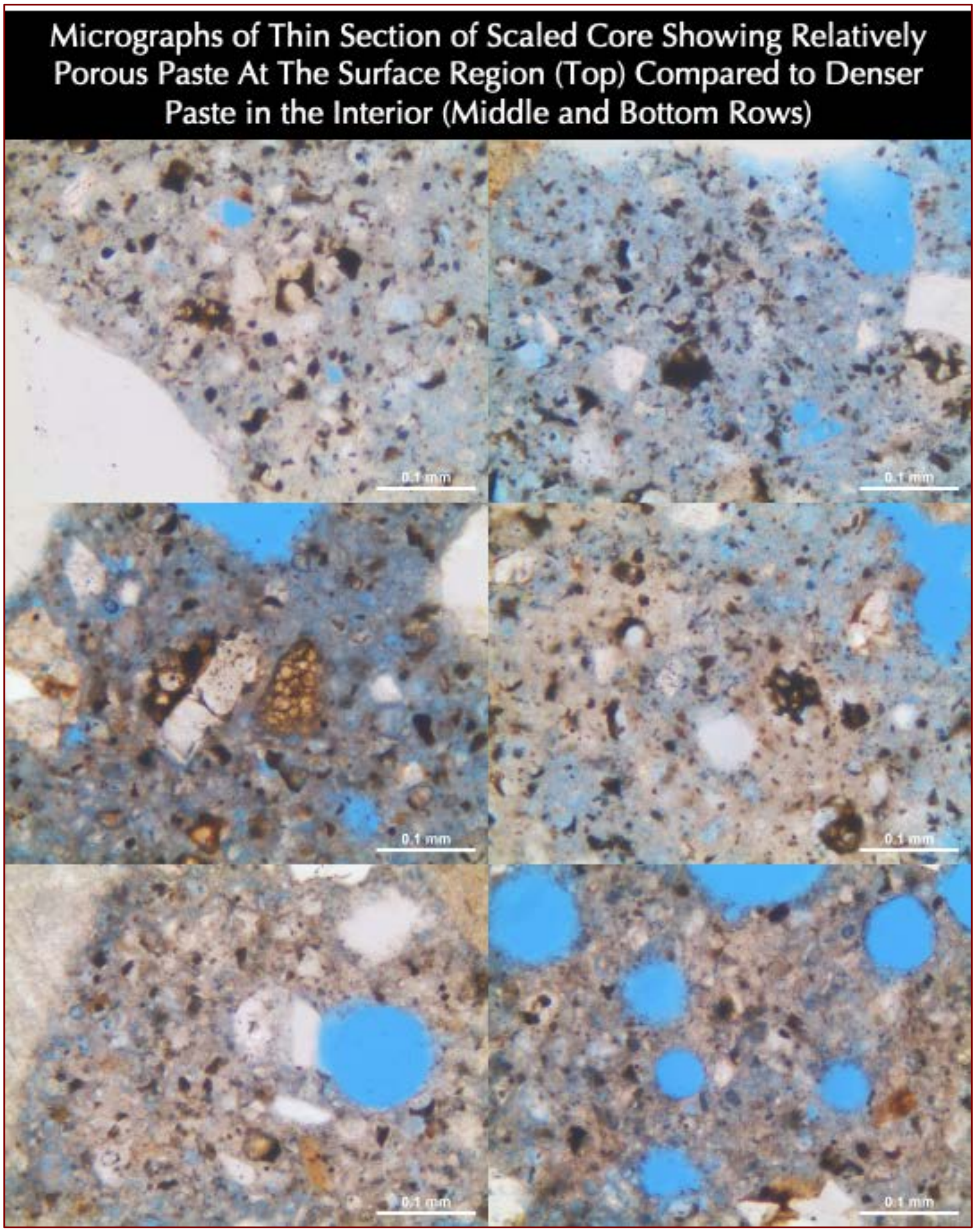
Figure 29: Micrographs of thin section of scaled core at high magnifications showing many characteristic features of Portland cement paste at the surface region (top row) and in the interior (middle and bottom rows).

Paste shows a mixture of overwhelming cement hydration products (calcium-silicate-hyadrate, calcum hydroxide etc.) and relatively fewer residual Portland cement particles. Cement hydration products show atmopsheric carbonation at the surface region (top row).

Paste is also more porous at the very top than in the interior, which is highlighted by blue tone of porous paste at the surface compared to brown tone of denser paste in the interior.

Residual cement particles are mostly dark brown remnants of ferrite phases of cement in the top porous surface region, whereas mixtures of alite with hydration rims, spherical clusters of belite and dark brown ferrite in the interior, which indicates an advanced hydration of calcium silicate phases of cement at the surface region leaving only dark brown ferrite residues (which hydrate at a slower rate than alite). Interior paste is dense and show reasonably well hydration. Many hydration rims around alite particles are seen. Paste shows patchy areas of denser and less dense regions.

Micrographs were taken using a Nikon Eclipse E600 upright microscope with polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope.



Micrographs of Thin Section of Scaled Core Showing Relatively Porous Paste At The Surface Region (Top) Compared to Denser Paste in the Interior (Middle and Bottom Rows)

Figure 30: Micrographs of thin section of scaled core showing many characteristic features of Portland cement paste at the surface region (top row) and in the interior (middle and bottom rows).

Paste shows a mixture of overwhelming cement hydration products (calcium-silicate-hydrate, calcum hydroxide etc.) and relatively fewer residual Portland cement particles. Cement hydration products show atmopsheric carbonation at the surface region (top row).

Paste is also more porous at the very top than in the interior, which is highlighted by blue tone of porous paste at the surface compared to brown tone of denser paste in the interior.

Residual cement particles are mostly dark brown remnants of ferrite phases of cement in the top porous surface region, whereas mixtures of alite with hydration rims, spherical clusters of belite and dark brown ferrite in the interior, which indicates an advanced hydration of calcium silicate phases of cement at the surface region leaving only dark brown ferrite residues (which hydrates at a slower rate than alite). Interior paste is dense and show reasonably well hydration. Many hydration rims around alite particles are seen. Paste shows patchy areas of denser and less dense regions.

Micrographs were taken using a Nikon Eclipse E600POL petrographic microscope at 200 to 400x magnifications.

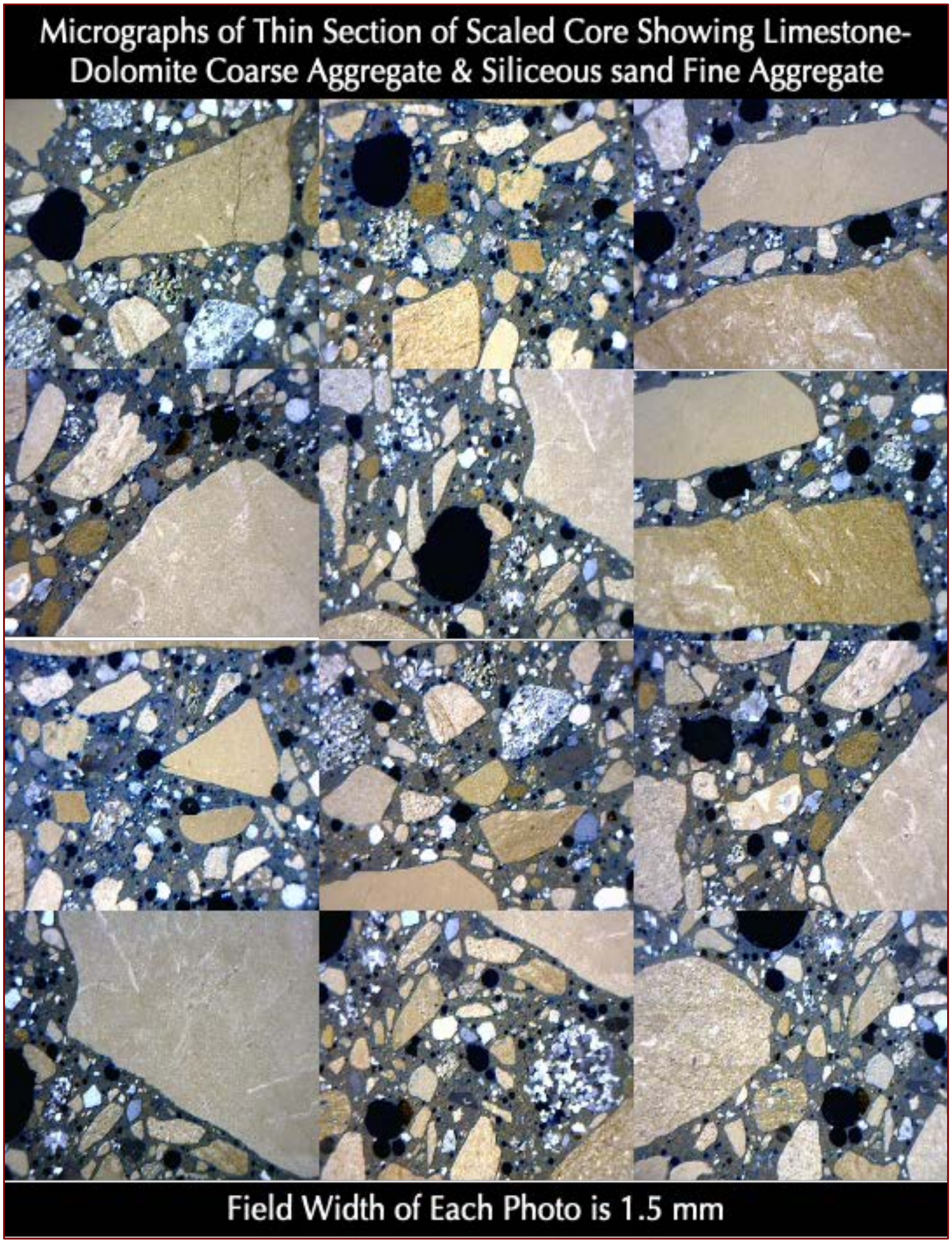


Figure 31: Micrographs of thin section of scaled core showing:

(a) Crushed limestone coarse aggregate particles, and,

(b) Mixtures of sand-sized particles of limestone from coarse aggregate and natural siliceous sand fine aggregate particles.

Limestone shows fossiliferous, fine-grained (micritic) and argillaceous varieties.

Siliceous component of sand is dominated by quartz and quarztite particles along with a subordinate amount of feldspar and other siliceous particles.

Micrographs were taken using a Nikon Eclipse E600 upright microscope with polarizing filter attachments to generate plane and crossed polarized views of relatively larger areas to cover than that covered by a typical petrographic microscope).

COARSE AGGREGATES

Concrete from both scaled and sound regions of driveway contain similar crushed limestone coarse aggregates that contain major amount of fine-grained (micritic) limestone, subordinate amounts of micritic limestone with fossil fragments (biomicrite), limestone with dark brown argillaceous veins (argillaceous limestone), and limestone with dark brown argillaceous and carbonaceous particles and rhombic dolomite grains (argillaceous dolomitic limestone). Particles have nominal maximum sizes of $^3/_4$ in. (19 mm). Particles are angular, dense, hard, medium beige to medium gray to dark gray (darkness of particles depend on the amount of argillaceous materials), massive textured typical of limestone, equidimensional to elongated, unaltered, uncoated, and uncracked. Coarse aggregate particles are well-graded, well-distributed, have been sound during their service in the concrete with no evidence of any potentially deleterious alkali-aggregate reactions, and are judged not to have contributed to the observed surface distress of the concrete.

FINE AGGREGATES

Fine aggregates are compositionally similar natural siliceous sands having nominal maximum sizes of 4 mm. Particles contain major amounts of quartz, moderate amounts of quartzite and feldspar, and subordinate amounts of sandstone, quartz siltstone, feldspar, and ferruginous rocks. Sand-sized particles of crushed limestone coarse aggregate are also present in the particle sizes of fine aggregate. Fine aggregate particles are light gray to clear, angular to subangular, dense, hard, equidimensional to elongated, unaltered, uncoated, and uncracked. Fine aggregate particles are well-graded and well-distributed. There is no evidence of alkali-aggregate reaction of fine aggregate particles. Fine aggregate particles have been sound during their service in the concrete.

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

Properties and Compositions of Aggregates	Cores From Scaled and Sound Areas of Driveway
Coarse Aggregate	
Types	Crushed Limestone
Nominal maximum size	$^3/_4$ in. (19 mm)
Rock Type	Fine-grained (micritic) limestone, subordinate amounts of micritic limestone with fossil fragments (biomicrite), limestone with dark brown argillaceous veins (argillaceous limestone), and limestone with dark brown argillaceous and carbonaceous particles and rhombic dolomite grains (argillaceous dolomitic limestone)
Angularity, Density, Hardness, Color, Texture, Sphericity	Angular, dense, hard, dark gray, massive textured, equidimensional to elongated
Cracking, Alteration, Coating	Unaltered, uncoated, and uncracked
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None

Properties and Compositions of Aggregates	Cores From Scaled and Sound Areas of Driveway
Fine Aggregates	
Types	Natural siliceous sand
Nominal maximum size	4 mm
Rock Types	Major amounts of quartz, moderate amounts of quartzite and feldspar, and subordinate amounts of sandstone, quartz siltstone, feldspar, and ferruginous rocks. Sand-sized particles of crushed limestone coarse aggregate are also present in the particle sizes of fine aggregate
Cracking, Alteration, Coating	Light gray to clear, subangular to subrounded, dense, hard, equidimensional to elongated
Grading & Distribution	Well-graded and Well-distributed
Soundness	Sound
Alkali-Aggregate Reactivity	None

Table 1: Properties of coarse and fine aggregates of concrete in the cores.

PASTE

Properties and composition of hardened cement pastes are summarized in Table 2. Pastes in both cores are dense, and show more or less uniform color tones throughout the depths of the cores in the interior concretes with a slightly lighter gray paste at the top 5 mm than the rest. Slight light color tone at the surface in both cores is due to atmospheric carbonation and the presence of some water at the finished surface. The latter aspect has increased the overall porosity of paste at the top 5 mm in both scaled and sound cores compared to the interiors.

Freshly fractured surfaces of pastes have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present and estimated to constitute 8 to 10 percent of the paste volume in the bodies of the cores. Besides Portland cement, no other pozzolanic or cementitious materials are found. Hydration of Portland cement is normal.

Properties and Compositions of Paste	Cores From Scaled and Sound Areas of Driveway
Color, Hardness, Porosity, Luster	Dense, dark gray and hard
Residual Portland Cement Particles	Normal, 8 to 10 percent by paste volume in the bodies
Calcium hydroxide from cement hydration	Normal, 10 to 14 percent by paste volume in the bodies
Pozzolans, Slag, etc.	None
Water-cementitious materials ratio (*w/c*), estimated	0.40 to 0.45
Cement contents, estimated (bags of portland cement per cubic yard)	$6^1/2$ to 7
Secondary Deposits	None
Depth of Carbonation, mm	Less than 5 mm from the scaled or finished surface
Microcracking	None

Properties and Compositions of Paste	Cores From Scaled and Sound Areas of Driveway
Aggregate-paste Bond	Tight
Bleeding, Tempering	None
Chemical deterioration	None

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

The textural and compositional features of the pastes are indicative of Portland cement contents estimated to be $6^1/_2$ to 7 bags per cubic yard. The cores have similar water-cement ratios (*w/c)* estimated to be 0.40 to 0.45 in the body. The very top surface region shows a slightly higher ratio of 0.45 to 0.50 which has increased the porosity of paste at the finished surface (Figures 23, 28, and 29).

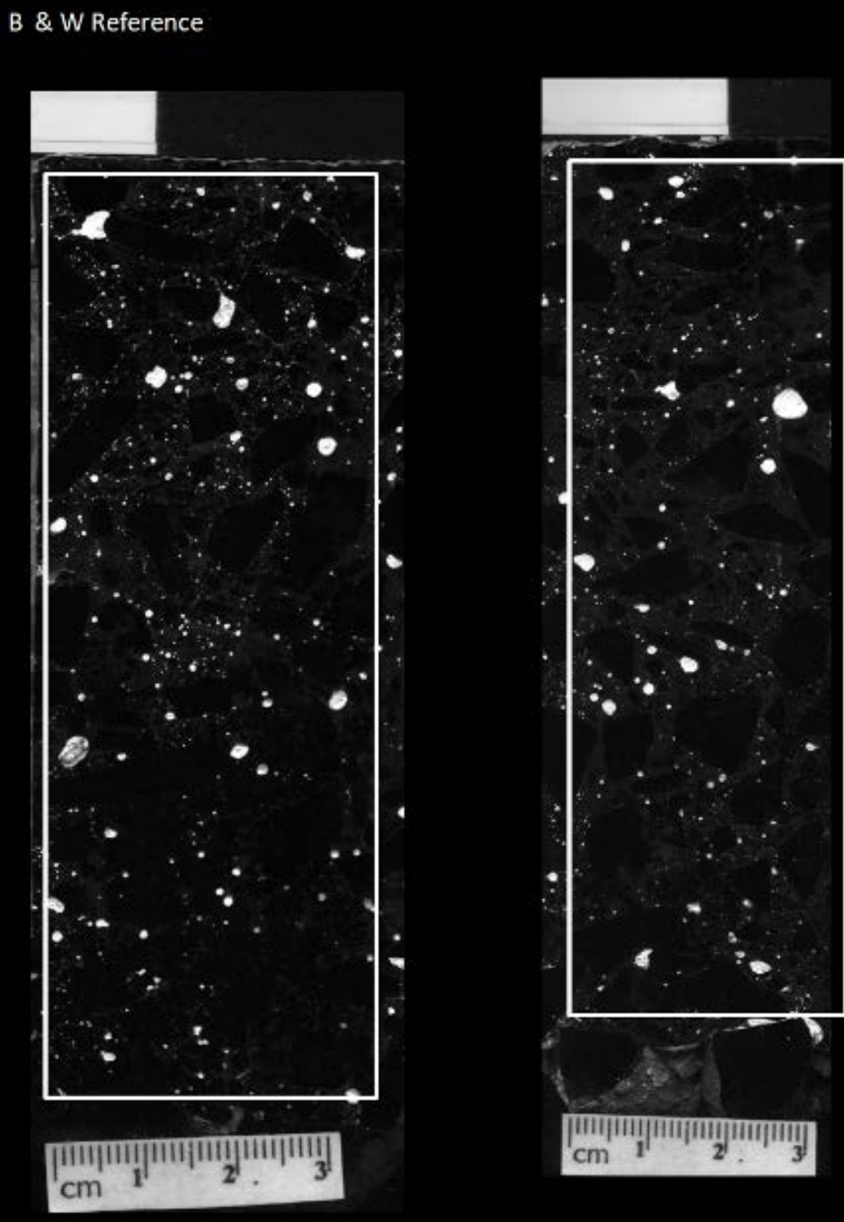
There is no evidence of any deleterious secondary deposits found in the cores. Carbonation was restricted to the top 5 mm from the scaled or finished surface. Bonds between the coarse and fine aggregate particles and paste are moderately tight to weak where cracks have circumscribed the aggregate particles. There is no evidence of microcracking due to any deleterious reactions in the concrete.

AIR

Concrete in both scaled and sound cores show adequate air entrainments even at the finished surface regions to provide the necessary protection of paste against distress due to cyclic freezing and thawing at critically water-saturated conditions. Air occurs as: (a) numerous, fine, discrete, spherical and near-spherical voids of sizes 1 mm or less, and (b) 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 are typical of entrapped air. There is clear evidence of intentional addition of an air entraining agent to generate a network of fine, discrete, spherical and near-spherical entrained air voids in concrete, which confirms the reported mix design of concrete that indicates addition of an air-entraining agent at a dosage of 0.5 oz/100 lbs.

Figure 32 shows scanned photo of black and white contrast enhancement of half of lapped cross section of each core where air voids are highlighted by a white zinc oxide powder applied over the surface after darkening the surface with a black Sharpie marker pen so that only air voids are highlighted. Air content and parameters of air void systems are calculated by the flatbed scanner method of Peterson et al. (2016) where a minimum 3 percent air is detected in both cores, which represents mostly the coarser air voids. Other air-void parameters are consistent with an air-entrained concrete. Subsequent image analysis of blue dye-mixed epoxy-impregnated thin sections of cores show more reasonable air contents of 4.2 to 6.1 percent in two cores in Figure 33 where finer air voids are also counted. Based on detailed petrographic examinations, including assessments of contents and air void parameters from flatbed scanner method and image analysis of thin section micrographs, the most reasonable air contents are estimated to be 4.5 percent in the scaled core and 6 percent in sound core.

Black and White Contrast Enhancements of Lapped Cross Sections of Sound (Left) and Scaled (Right) Cores Used For Measurements of Air-Void Parameters By Flatbed Scanner Method of Peterson et al. 2016



Sound Core:
Air = 3.0%
Paste/Air Ratio = 9.89
Specific Surface = 59.95 mm^{-1}
Void Frequency = 0.454 mm
Spacing Factor = 0.105 mm

Scaled Core:
Air = 3.0%
Paste/Air Ratio = 10.65
Specific Surface = 55.28 mm^{-1}
Void Frequency = 0.389 mm
Spacing Factor = 0.118 mm

Figure 32: Scanned photo of black and white contrast enhancement of half of lapped cross section of each core where air voids are highlighted by a white zinc oxide powder applied over the surface after darkening the surface with a black Sharpie marker pen so that only air voids are highlighted.

Air content and parameters of air-void systems are calculated by the flatbed scanner method of Peterson et al. (2016).

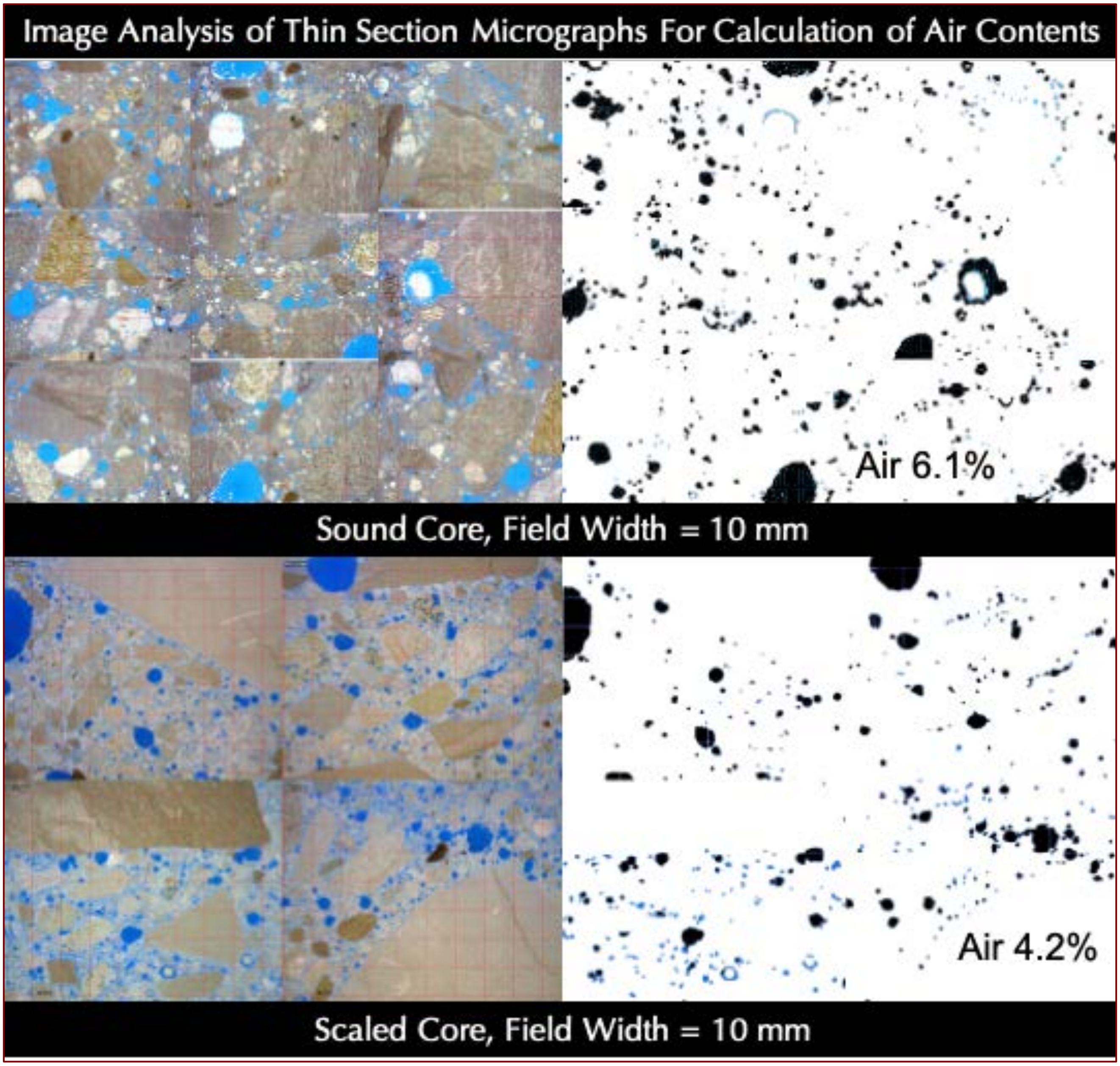


Figure 33: Image analysis (in Image J) of blue dye-mixed epoxy-impregnated thin sections of cores to calculate air contents in the images. Air contents are estimated to be around 6 percent in the sound core and 4 to $4^{1}/_{2}$ percent in the scaled core.

DISCUSSIONS

MIX DESIGN OF CONCRETE

The mix design of the concrete reportedly contained 616 pounds of Portland cement, 1630 pounds of ASTM C 33 #7 crushed stone coarse aggregate, 1390 pounds of fine aggregate, 0.5 oz/100 lbs. air-entraining agent, 6.0 oz/100 lbs. of water-reducing admixture, 270 pounds of water – all to produce a slump of 3 to 5 inches, an air content range of 4.5 to 7.5 percent, a water-cement ratio of 0.43, and a 28-day compressive strength of 4000 psi.

According to common industry specifications (e.g., ACI documents), an outdoor concrete slab exposed to cyclic freezing and thawing should be air-entrained and should have a minimum compressive strength of 4000 psi, preferably 4500 psi in a moist outdoor environment. The reported design strength of concrete is in conformance to the common industry specification for an outdoor slab exposed to freezing, salt, and snow in a moist environment.

However, the concrete examined in two cores show the presence of fine polypropylene-type synthetic fibers, which is not mentioned in the mix design. Addition of such fibers is beneficial to improve the flexural strength of concrete but it requires careful handling of concrete especially during finishing practices. Fiber makes concrete sticky and increases difficulty during finishing, often requiring addition of excess water during finishing. Both cores show potential for such water addition from the porous regions of pastes at the exposed surface regions. However, such practice is judged not continued to an extent to cause surface scaling since the sound core also shared similar surface features (e.g., porous paste) from water additions as the scaled one.

AIR CONTENTS AND AIR-VOID SYSTEMS

Concrete in both scaled and sound cores are air-entrained. The total air contents are estimated to be around 6 percent in the sound core and $4^1/_2$ percent in the scaled core. However, around 1 to $1^1/_2$ percent lesser air in the scaled core is judged not to have caused preferential scaling since the interior as well as the surface region of scaled core showed adequate air entrainment as seen in the sound core. The extra air in the sound core is mostly from some coarse voids whereas the finer air bubbles responsible for the protection of paste during freezing is present in adequate amounts in both cores especially in their interiors. In summary, concrete delivered to the jobsite from the batch plant is found to be air entrained in conformance to the reported concrete mix design.

AGGREGATES

The crushed limestone coarse aggregate and siliceous sand fine aggregate particles are present in sound conditions and did not contribute to the observed surface distress. Both coarse and fine aggregate particles are compositionally similar in scaled and sound cores and showed no preferential deterioration in the scaled core to contribute to surface scaling.

PLACEMENT, FINISHING, AND CURING

In both cores, 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 slabs at the locations of two examined cores.

The porous paste found at the top few millimeters in both cores is a consequence of finishing in the presence of water at the surface, which could be from the presence of bleed water during finishing and/or from addition of water during finishing. Such water has softened the paste, made it more porous and increased vulnerability to scaling, especially if the surface was exposed to deicing chemicals.

Curing is essential for adequate cement hydration at the surface, and, thereby, development of the necessary strength of concrete at the surface by providing enough moisture and optimum temperature for cement hydration. Exposed surfaces of the cores showed no evidence of inadequate curing of concrete, e.g., no evidence of restricted cement hydration at the scaled or finished surfaces at least to cause the reported surface scaling. Cement particles showed adequate hydration at the exposed surface regions with remains of only brown ferrite residues. The original finished surfaces of both cores show a shiny appearance, which is indicative of application of a cure-seal compound, which is confirmed to be an acetone-based siloxane/acrylic hybrid sealer (marketed as Trinic Stamp Shield).

MORTAR LIFT-OFF

Mortar lift-off is the loss of thin sheet of the original finished surface of concrete from over the flat topside of near-surface aggregate particle. Mortar lift-off is found on the scaled surface (Figure 6), which has also contributed to the surface distress. Mortar lift-off is not due to the exposed aggregate, which is sound crushed limestone and did not fracture (as would have been in the case of aggregate popout). Instead, the thin sheet of surface mortar was lost due to inadequate bond to the near-surface coarse aggregate. Mortar lift-off should have been avoided by deep embedding of aggregates along with a better bond of finished surface to the coarse aggregate from proper finishing operations and curing. Improper finishing can lead to mortar lift-off where flat topsides of aggregates situated very near the exposed surface do not form a good bond with the finished surface either due to repeated finishing passes and/or from excess water or other reasons.

COMPRESSIVE STRENGTHS

For adequate resistance to freezing-related stresses, the common industry (e.g., ACI Committee 201)-recommended compressive strength of concrete exposed to an outdoor environment of moisture and freezing is at least 4000 psi. A concrete having a compressive strength of at least 4500 psi is usually recommended for an outdoor concrete slab exposed to moisture, salts, and snow, where the good strength of concrete provides the necessary resistance against freezing-related tensile stresses in concrete. Excess water at the surface, either due to finishing with bleed water on the surface and/or due to addition of water during finishing of a sticky, high-air concrete would reduce the strength and hence the necessary protection against freezing-related stresses.

Based on petrographic examinations the interior of the concrete in both cores (except the top 5 mm) is judged to have at least 4000 psi strength to confirm the specific design strength. The observed surface scaling is not due to placement of a low-strength concrete.

CONCRETE MATURITY

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

DEICING SALTS

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

Water-soluble chloride analyses is needed from the exposed and interior locations of both cores to determine the role of potential applications of deicing chemicals on the observed surface scaling.

BENEFICIAL ASPECT OF A SURFACE SEALER

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

CONCLUSIONS

Based on detailed laboratory investigations, surface scaling of concrete driveway slab is determined to be due to a combination of various factors, e.g., (a) from potential application of deicing chemicals on the concrete surface, which is required to be confirmed from water-soluble chloride analysis of concrete cores examined here, especially if such application has occurred prior to the attainment of concrete maturity, to (b) softening of concrete surface due to finishing in the presence of excess water at the surface that has increased the susceptibility of scaling especially in the presence of deicing salts. Beneath the distressed surface, however, the interior concrete is sound, adequately air-entrained, of good strength, and hence should continue to be serviceable as long as the distressed surface can be repaired with a suitable durable coat to protect the interior concrete from environmental elements.

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END OF REPORT[1]

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[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.