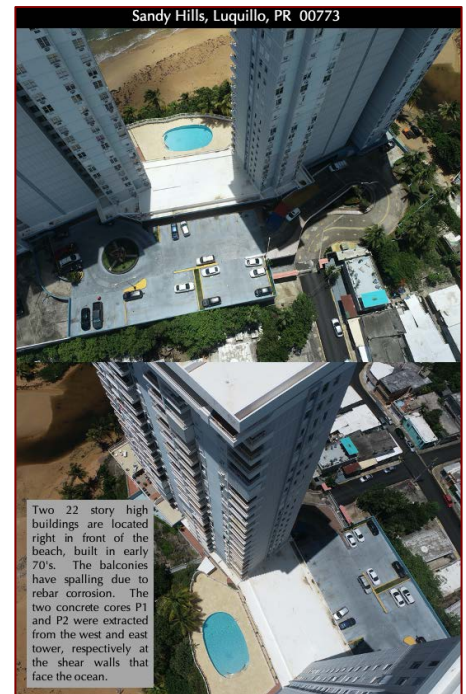




CONSTRUCTION MATERIALS CONSULTANTS, INC.

Investigation of Reinforcing Steel Corrosion-Related Spalling of Balconies in Two 22-Story 1970s Highrise Buildings in an Oceanfront Environment in Luquillo, Puerto Rico



Sandy Hills
Luquillo, PR 00773

August 21, 2020
CMC 0720138



Table of Contents

Executive Summary	1
Introduction	3
Background Information	3
Purposes of Present Investigation.....	3
Methodologies.....	3
Petrographic Examinations.....	3
Water-Soluble Chloride Contents from Potentiometric Titration (ASTM C 1218).....	5
Samples	6
Photographs, Identification, Integrity, and Dimensions	6
End Surfaces.....	6
Cracking & Other Visible Distress, If Any	6
Embedded Items.....	6
Resonance	6
Petrographic Examinations.....	9
Lapped Cross Sections	9
Micrographs of Lapped Cross Sections.....	12
Thin Sections	16
Micrographs of Thin Sections.....	28
Protective Coatings.....	36
Coarse Aggregates in Concrete.....	37
Fine Aggregates in Concrete.....	37
Paste in Concrete	38
Air in Concrete.....	39
Chloride Profiles.....	40
Discussions	42
References.....	43



EXECUTIVE SUMMARY

Concrete spalling from corrosion of reinforcing steel in the balconies of two 22-story Sandy Hills high-rise buildings constructed circa early 1970s in the oceanfront environment in Luquillo, Puerto Rico has prompted this investigation. As a result, two concrete cores, P-1 and P-2 were obtained from the West and East walls from locations where no spalling is present but needed to investigate the condition of concrete, especially the depth of carbonation and chloride ingress into the concrete, the two essential ingredients to cause corrosion of steel in concrete. The purposes of the present investigation are to determine the conditions, compositions, and qualities of the concretes in the cores, diagnose evidence of any chemical and/or physical deterioration of concretes in the cores, and if so, determine the depths or extents of such deteriorations. The cores were analyzed by detailed petrographic examinations *a la* ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete."

Walls at the locations of both cores showed evidence of applications of protective coatings as a means to prevent penetration of corrosive agents from the oceanfront environment, i.e., chloride and atmospheric carbon dioxide into the concrete.

At the location of Core P-1 in the West Wall, the concrete is protected by the following two successive layers of paint and cementitious mortar coats from the exposed end towards the concrete:

- a. The **paint coat** consisting of a thin, dark gray, acrylic paint coat at the very top having a nominal thickness of <0.5 mm, which comprises two successive applications of paint coats with and without mineral (talc) fillers; and,
- b. The **cementitious mortar coat** consisting of: a dense, carbonated cementitious coat of Portland cement and mixed seashell and silica sand of <1 mm size in a layer having a nominal thickness of 5 mm; and, a relatively porous main body of the mortar coat consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm.

The paint and mortar topping protective layers were applied over the **main concrete body**, which has a thin dense dark gray, carbonated finished surface region having a nominal thickness of 5 mm, above the main concrete body of 150 mm recovered length, containing: (i) crushed gravel coarse aggregate having nominal maximum sizes of $\frac{3}{4}$ in., well-graded, well-distributed, subangular to subrounded, sound, which shows the typical volcanic texture and mineralogy of basalt-andesite-trachyte-dacite clan, (ii) natural siliceous sand fine aggregate with some calcareous seashells and finer fractions of volcanic rock fragments, (iii) Portland cement paste, having cement contents estimated to be $5\frac{1}{2}$ to 6 bags per cubic yard, without any other pozzolanic or cementitious materials, and water-cement ratios uniform throughout the depth and estimated to be 0.40 to 0.45, and (iv) many interstitial voids except any intentionally introduced entrained air for the concrete to be non-air-entrained (estimated 1 to 2 percent total air).

The protective layers of paint coat (two layers) and cementitious mortar coat (two layers from dense carbonated to porous non-carbonated) are applied over the concrete, where the main concrete body itself has a densified finished surface region having a nominal thickness of 2 to 3 mm above the main concrete body, which is relatively more porous than the densified surface region having a recovered length of 150 mm.

At the location of Core P-2 in the East Wall, the concrete is protected by the following two successive layers of paint and cementitious mortar coats from the exposed end towards the concrete:

- a. The top **protective coating** consisting of alternating layers of **paint coats**, and, a middle dense, carbonated **cementitious coat** of Portland cement paste and seashell (<1 mm size, only seashell no silica sand) where the cementitious seashell-cement paste coat is sandwiched between two applications of paint coats.

These protective layers were applied over the **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate (still volcanic and volcanoclastic rocks of the volcanic setting of Puerto Rico), and some air entraining agent to generate 3 to 4 percent



air and a marginally air-entrained concrete compared to the lack of such agent in the concrete used in the West Wall at the location of Core P-1. No protective cementitious mortar coating is found in P-2 as seen in P-1, but a dense dark gray, carbonated finished top surface region of concrete is present, which is also found in Core P-1 of the main concrete body.

Therefore, both cores from both West and East Walls showed protective measures taken to combat penetration of potentially corrosive agents (chloride, carbon dioxide) from the oceanfront environment into the concrete.

As a result of these protective measures, the main concrete body at the locations of both cores showed minimum atmospheric carbonation, which is judged to have occurred during service prior to the application of protective coatings. Depth of carbonation is measured to be only 5 to 6 mm mostly within the densified finished surface region of the main concrete body beyond which the concrete is not carbonated.

Water-soluble chloride analyses at the top exposed surface regions, at the mid-depth locations, and at the bottom ends of two cores showed very high chloride at the exposed surface regions of both cores, as anticipated in an ocean front environment, where high chloride at the exposed surface regions within the top $\frac{1}{2}$ inch of the concrete are judged to have occurred from penetration of chloride and moisture from the air into the concrete prior to the application of the protective coatings. The mid-depth locations, as well as the bottom ends of cores have chloride levels mostly below the maximum threshold chloride level of 0.2 percent chloride by mass of cementitious materials to initiate corrosion of steel in concrete in the presence of oxygen and moisture. Therefore, the chloride-induced corrosion potential of steel in concrete is found to be prominent at the surface regions of concrete, i.e., beneath the protective coatings, where such levels were already established prior to the applications of coating and were not stripped away before the coatings were installed. Due to only three depths of chloride measurements requested from top, mid-depth, and bottom ends of cores, the actual depth of high chloride (i.e. higher-than-threshold 0.2% chloride) beyond the top $\frac{1}{2}$ in. depth could not be measured, except seeing some still high chloride at the mid-depth location of Core P-1 from the West Wall (0.5 percent as opposed to maximum 0.2 percent chloride threshold by mass of cement to initiate corrosion) but not such level at the mid-depth of Core P-2 from the East Wall. Therefore, after the initial chloride ingress prior to the installation of protective measures, the interior concrete probably did not receive as high chloride as before the coatings were installed. Protective coatings are definitively helping the interior concrete from continued penetration of corrosive agents of chloride, moisture, and carbon dioxide from the air.

Therefore, durability of the interior concrete in both walls depends very much on the serviceability of the protective coatings in this marine environment where importance of having a coating of impermeable paint, dense low water-cementitious materials ratio cementitious coat, etc. as seen in this case in the two cores examined is paramount. The overall qualities and conditions of concretes in the main bodies of both cores are judged to be sound with no evidence of any physical or chemical deterioration. The interior concretes are dense, well-consolidated, and should be serviceable in their intended environment as long as they are well-protected by the protective coatings to prevent penetration of moisture, chloride, and other corrosive agents to cause further corrosion of steel, and corrosion-related spalling. Due to the high chloride level found at the surface regions further penetration of moisture is essential since moisture in the presence of inherent chloride at the surface region can trigger corrosion of steel if present at the surface region.

INTRODUCTION

Reported herein are the results of detailed petrographic examinations and water-soluble chloride analyses of two cores, P-1 and P-2 collected from the West and East Walls of two 22-story high-rise buildings in Luquillo, Puerto Rico.

BACKGROUND INFORMATION

Concrete spalling from corrosion of reinforcing steel in the balconies of two 22-story Sandy Hills high-rise buildings constructed circa early 1970s has prompted this investigation.

As a result, two concrete cores, P-1 and P-2 were obtained from locations where no spalling is present but needed to investigate the condition of concrete, especially the depth of carbonation and chloride ingress into the concrete, the two essential ingredients to cause corrosion of steel in concrete.

PURPOSES OF PRESENT INVESTIGATION

The purposes of the present investigation are to determine the conditions, compositions, and qualities of the concretes in the cores, diagnose evidence of any chemical and/or physical deterioration of concretes in the cores, and if so, determine the depths or extents of such deteriorations.

METHODOLOGIES

PETROGRAPHIC EXAMINATIONS

The concrete cores were examined by detailed petrographic (microscopical) examinations by following the methods of ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete."

Details of concrete petrography, and sample preparation techniques for petrographic examinations of concrete are provided in Jana (2006).

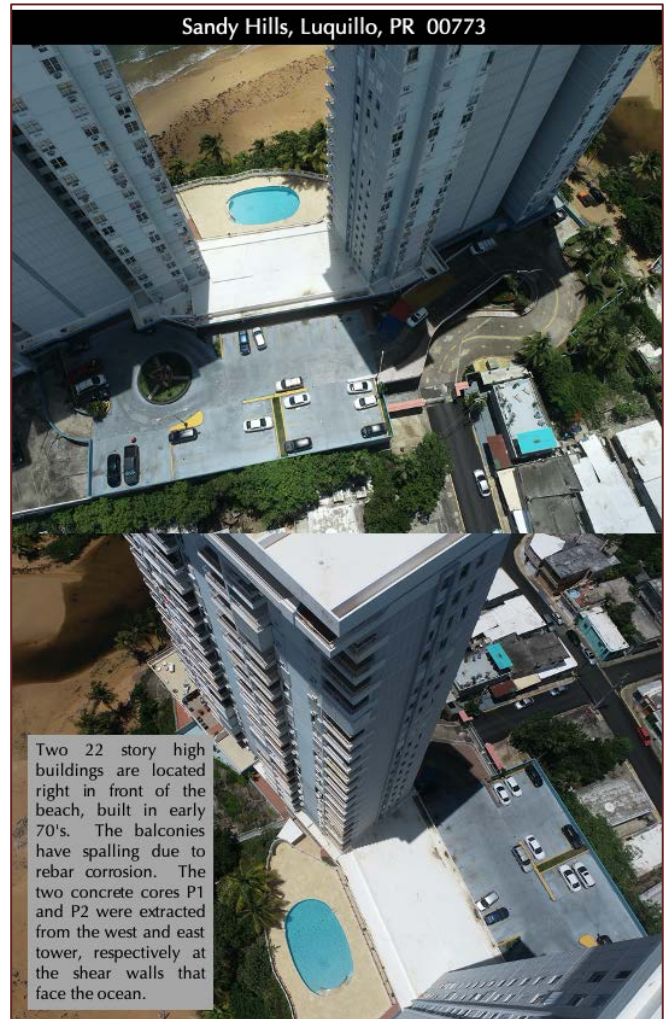


Figure 1: Towers at Sandy Hills, Luquillo, Puerto Rico.

Briefly, the steps followed during petrographic examination of the samples include:

- i. Visual examinations of samples, as received, with particular reference of any visible cracking near the exposed surfaces;
- ii. Low-power stereo-microscopical examinations of as-received, saw-cut and freshly fractured sections, and lapped cross sections of samples for evaluation of textures, and compositions, and diagnosis of any distress;
- iii. Examinations of oil immersion mounts in a petrographic microscope for mineralogical compositions of specific areas of interest;
- iv. Examinations of blue dye-mixed (to highlight open spaces, cracks, voids, etc.) epoxy-impregnated large area (50 mm × 75 mm) thin sections of concretes in a petrographic microscope for detailed compositional and microstructural analyses;
- v. Determination of depth of carbonation and other alterations of paste from the surfaces in contact with the oceanfront elements;
- vi. Photographing the samples, as received and at various stages of preparation with digital camera and scanner;
- vii. Micrographs of lapped sections and thin sections of samples taken with stereomicroscope and petrographic microscope, respectively, to provide detailed compositional and mineralogical information of concrete.
- viii. A Jenoptik Progres GRYPHAX camera attached to a Nikon Eclipse 600 POL petrographic microscope (equipped with reflected, transmitted, polarized and fluorescent-light facilities), a Jenoptik Progres C14 camera attached to an Olympus SZH reflected and transmitted-light stereomicroscope, and an OMAX digital camera attached to a Nikon SMZ-10A low-power stereomicroscope were used together for detailed optical microscopical examinations and associated digital photomicrography (Figure 1).



Figure 2: CMC's optical microscopy lab that houses microscopes used in this study.

WATER-SOLUBLE CHLORIDE CONTENTS FROM POTENTIOMETRIC TITRATION (ASTM C 1218)

The concretes of Cores P-1 and P-2 were selected for determination of chloride contents at the exposed surface region, at the mid-depth location of concrete, and at the bottom end of concrete. The purposes of such sample selection are: (a) to determine the effectiveness of protective coatings in mitigation of migration of chloride, moisture and other corrosive agents into the concrete since its installation in the early 1970s, and, (b) determination of chloride levels present inside the concrete since its installation in early 1970s.

Samples for chloride analyses were selected by trimming small pieces from each depth with a water-cooled diamond saw. Trimmed pieces were pulverized down to finer than 0.3 mm size. Approximately 10 grams of pulverized sample 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 a period of 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. The filtrates thus prepared were used for potentiometric titration with a silver nitrate titrant *a la* ASTM C 1218 by using Metrohm 916 Ti-Touch titration apparatus with attached 814 Auto Sample Processor to determine the chloride contents. The instruments were calibrated with standard sodium chloride solutions for confirmation of known chloride contents in the blank solutions. The leftmost two instruments in the following Figure 3 set-up were used for the present study.



Figure 3: Set-ups for fully automated chloride analysis of concrete by potentiometric titration.



SAMPLES

PHOTOGRAPHS, IDENTIFICATION, INTEGRITY, AND DIMENSIONS

Figures 4 and 5 show the two cores as received.

Both cores are 2 in. (50 mm) in diameters, and have respective nominal lengths of 6½ in. (165 mm) and 5 in. (125 mm) for P-1 from West Wall and P-2 from East Wall, respectively.

END SURFACES

The top exposed end of Core P-1 is painted light blue, where paint is well-bonded to the concrete; the opposite end is fresh fractured. The core showed the top paint coat, followed by a 17 mm thick cementitious mortar coat, which is well-bonded to the paint coat above and to the main concrete body below.

The top exposed end of Core P-2 is also painted light blue, well-bonded to concrete but the concrete in P-2 lacks a cementitious mortar coating found in P-1, the opposite end is fresh fractured.

CRACKING & OTHER VISIBLE DISTRESS, IF ANY

Core P-1 is free of any visible cracks, but P-2 shows cracking and separation of a bottom 1½ in. thick portion of concrete at the No. 4 reinforcing steel situated at 3½ in. depth.

EMBEDDED ITEMS

A No. 4 steel is present at 2½ in. depth from exposed end of Core P-1. A similar No. 4 steel is present in Core P-2 as well at 3½ in. depth from the exposed end.

Steel in both cores are free of any corrosion products, however, as mentioned Core P-2 was broke at the steel, probably during the coring operations.

RESONANCE

The cores have a ringing resonance, when hammered



Figure 4: Shown are the exterior painted surface (top left), interior fractured end (top right) and side cylindrical surfaces of the Core P-1 from West Wall.



Figure 5: Shown are the exterior painted surface (top left), interior fractured end (top right) and side cylindrical surfaces of the Core P-2 from East Wall.

PETROGRAPHIC EXAMINATIONS

LAPPED CROSS SECTIONS

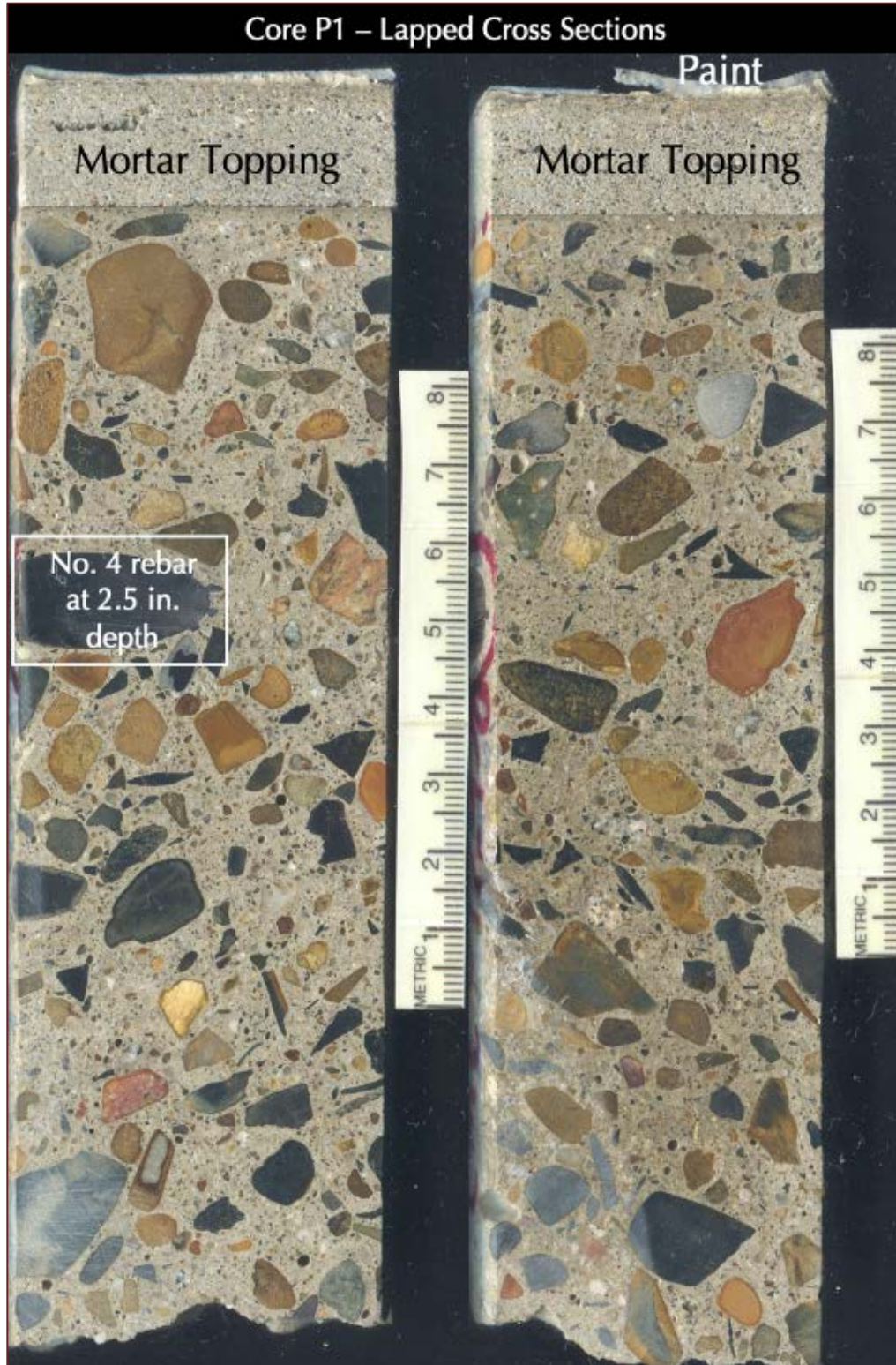


Figure 6: Two parallel lapped cross sections of Core P-1 from West Wall showing:

(a) A thin **paint coat** at the top well-bonded to mortar topping, having a nominal thickness of < 1 mm;

(b) A **mortar topping** layer initially bonded to the main body of concrete but subsequently detached from concrete during lapping process, having a nominal maximum thickness of 16-17 mm;

(c) The **main concrete body** of a recovered length of 150 mm, consisting of crushed gravel coarse aggregate, showing good grading and well-distribution of the crushed gravel coarse aggregate and siliceous sand fine aggregate particles;

(d) The overall sound, dense, well-consolidated nature of the concrete in the body of the core; and,

(e) A No. 4 reinforcing steel at the mid-depth location in one lapped section, which is boxed.

The mortar topping was bonded to concrete beneath when received but de-bonded during the lapping operations.



Figure 7: Two parallel lapped cross sections of Core P-2 from East Wall showing: (a) a thin paint coat at the top well-bonded to concrete; (b) no repair coat mortar topping found in the Core P- 1 from West; (c) good grading and well-distribution of the crushed stone coarse aggregate which is very different from the crushed gravel coarse aggregate found in Core P-1 from West, and siliceous sand fine aggregate particles; and (d) the overall sound, dense, well-consolidated nature of the concrete in the body of the core.

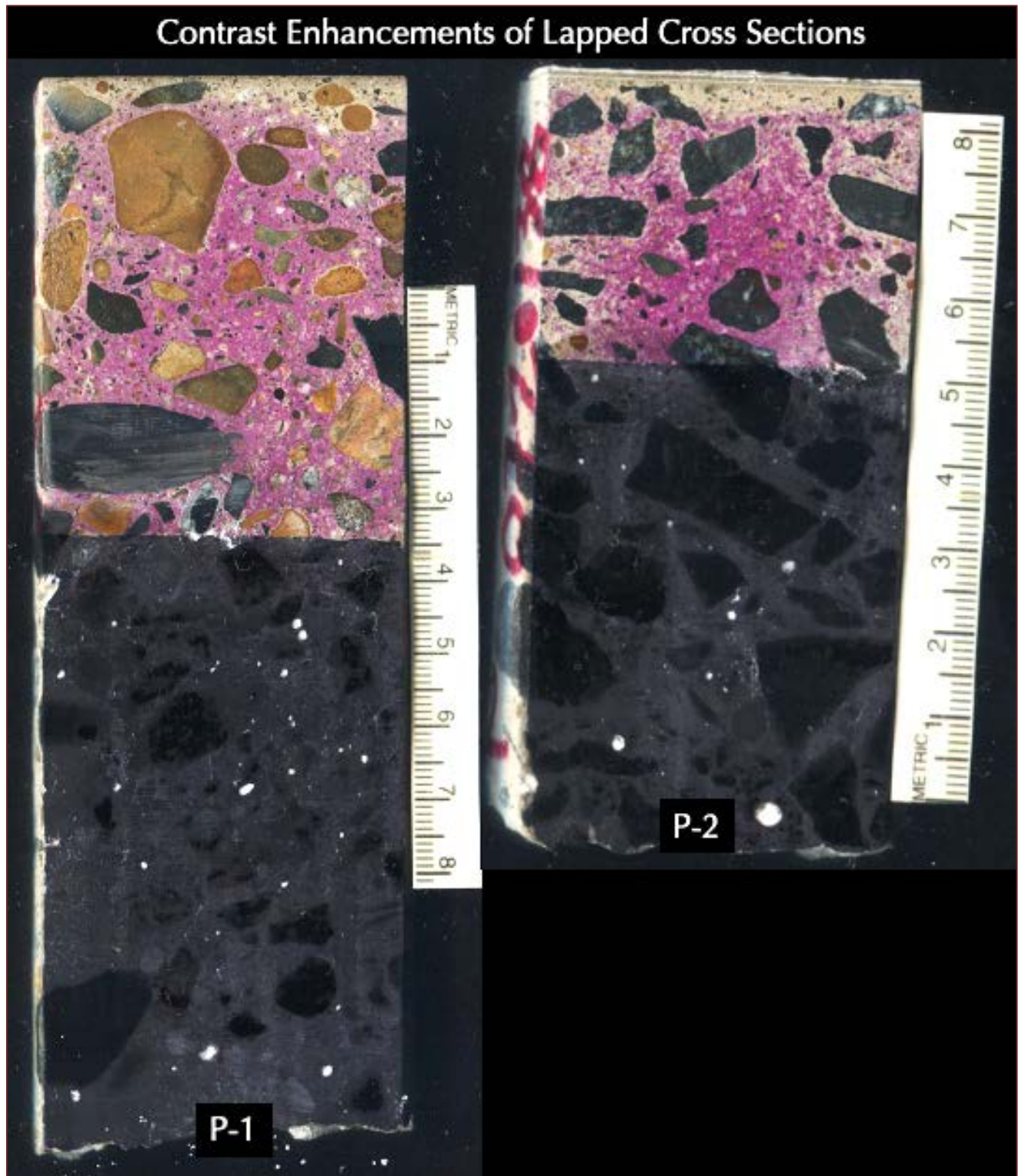


Figure 8: Lapped cross sections of cores after contrast enhancement to show: (a) the depth of carbonation of concrete by treatment of top halves of the cores with a phenolphthalein alcoholic solution where carbonated portion remained in its natural color tone of paste, whereas the non-carbonated interior paste has turned into pink discoloration; and (b) black and white contrast enhancement to highlight air voids in white against everything else in black for determining air content and air-void systems of concretes.

MICROGRAPHS OF LAPPED CROSS SECTIONS

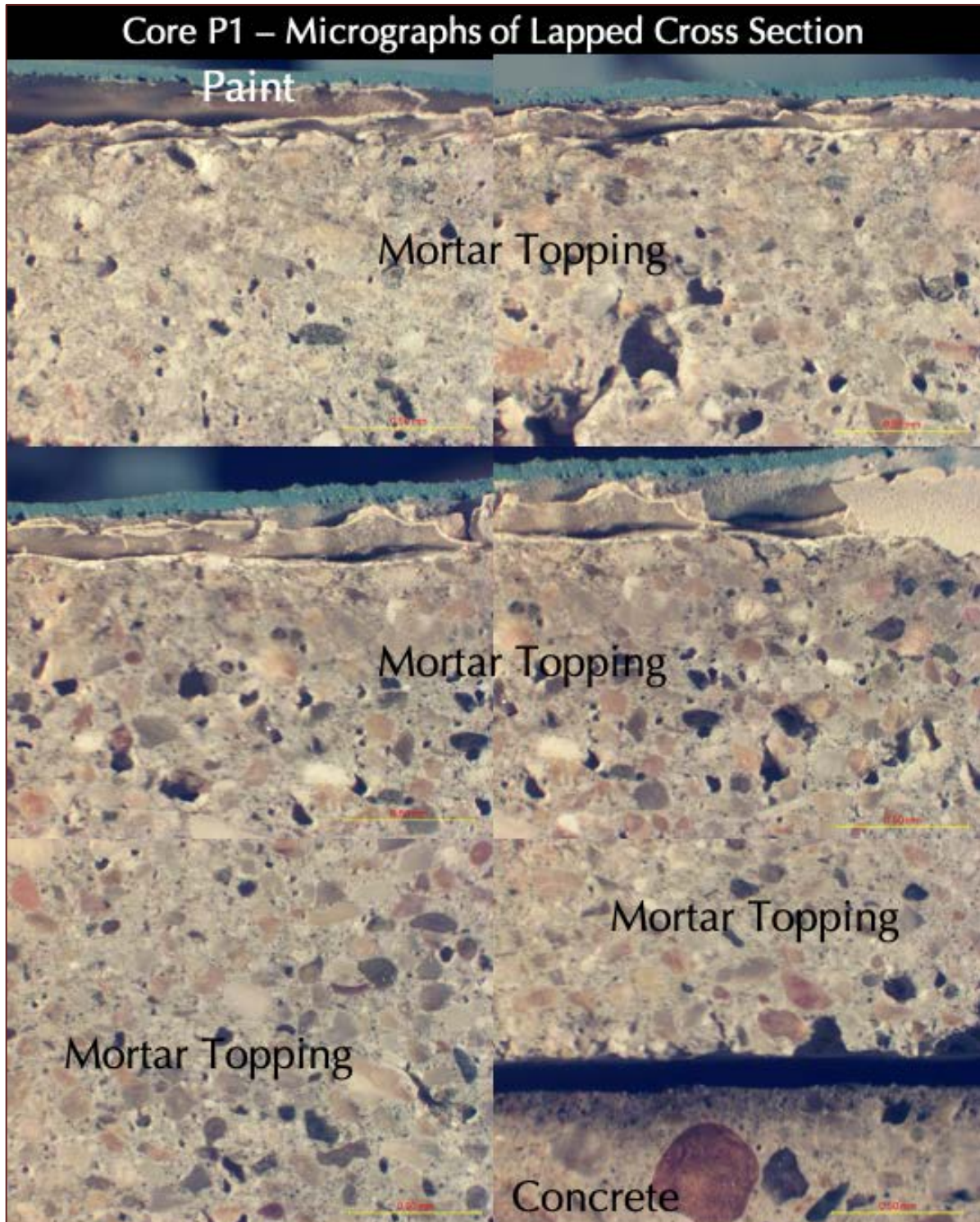


Figure 9: Micrographs of lapped cross section of the core from P- 1 West Wall showing: (a) the **paint coat** at the top bonded to the **mortar topping**; (b) the dense mortar topping containing sand particles, medium gray paste and many coarse entrapped air voids; (c) de-bonding of mortar topping from the concrete beneath, which has occurred during the lapping operations (the topping was bonded to concrete when received); (d) the dark gray dense paste at the top end of concrete seen in the bottom right photo, and dense sound nature of the **main concrete body** beneath the mortar topping as seen in the bottom right photo. Scale bars are 0.5 mm.

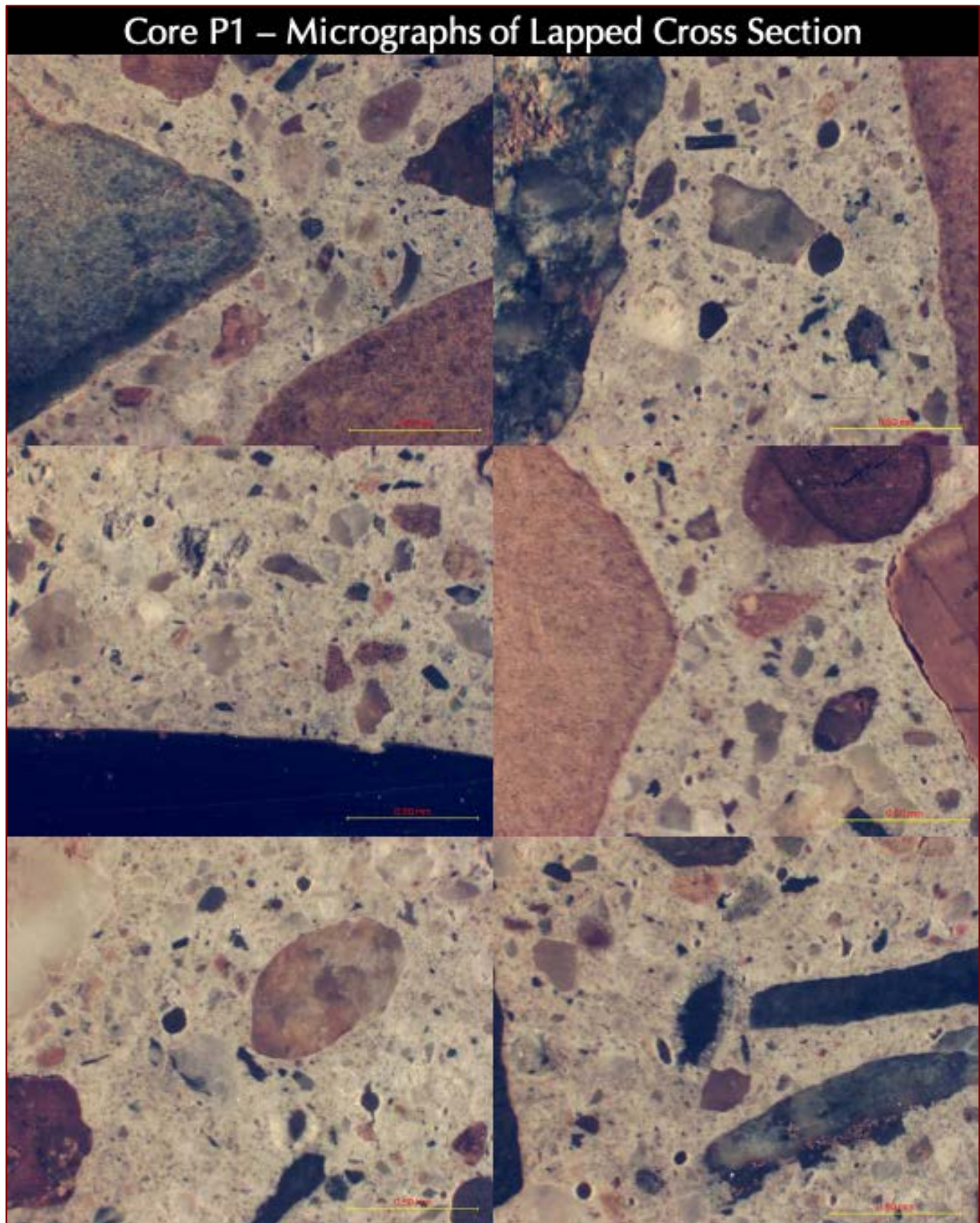


Figure 10: Micrographs of lapped cross section of the Core P-1 from West Wall showing the **main concrete body**, consisting of: (a) the crushed gravel coarse aggregate and natural siliceous sand fine aggregate, (b) lack of any entrained air voids indicating the non-air-entrained nature of the concrete, and (c) overall dense and well-consolidated nature of concrete. Scale bars are 0.5 mm.

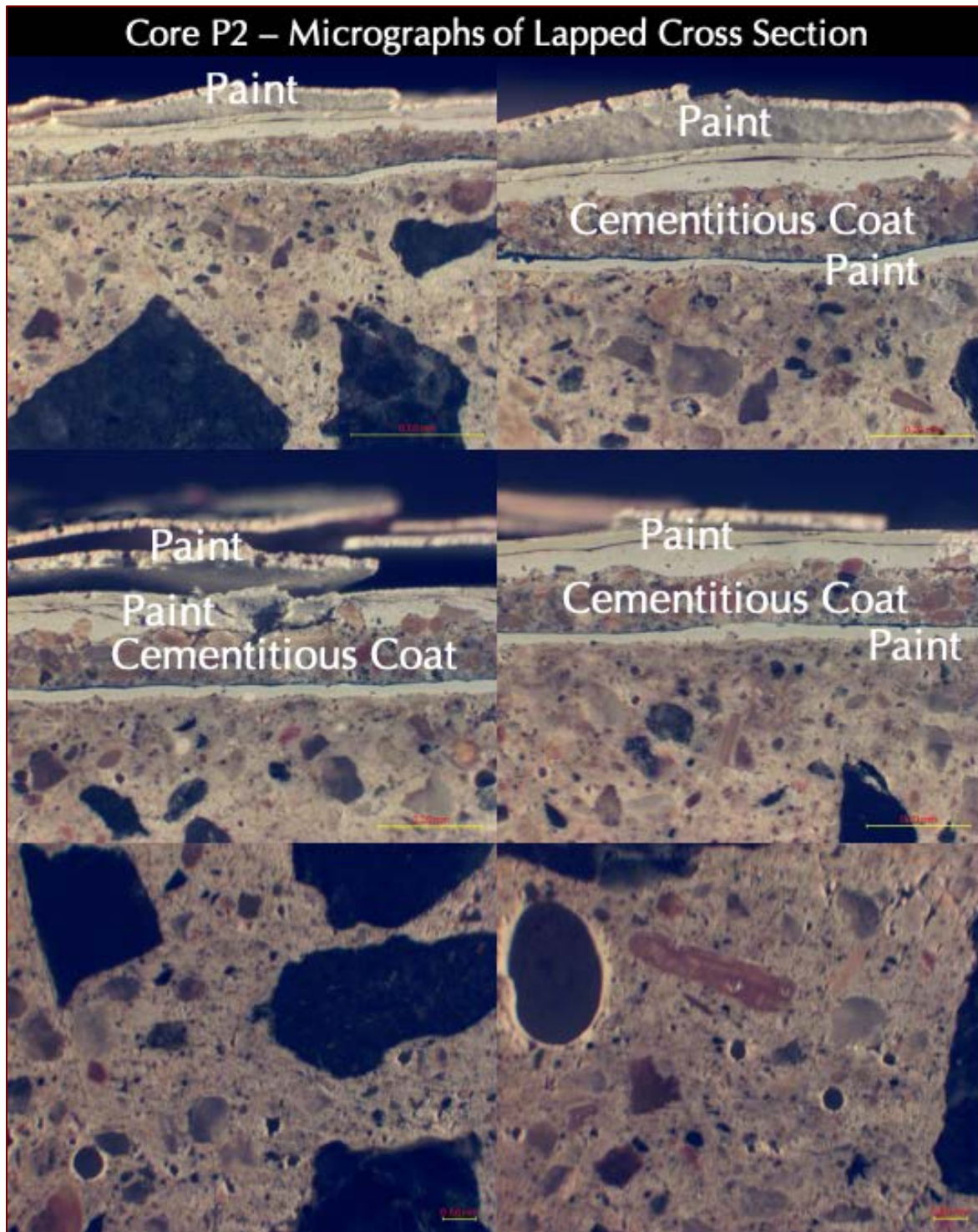


Figure 11: Micrographs of lapped cross section of the Core P-2 from East Wall showing the top **protective coating** of concrete consisting of alternating layers of **paint coats** and a middle **cementitious coat** where the latter is sandwiched between two paint coats, altogether applied over the **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-2 from West Wall, and overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Scale bars are 0.5 mm.

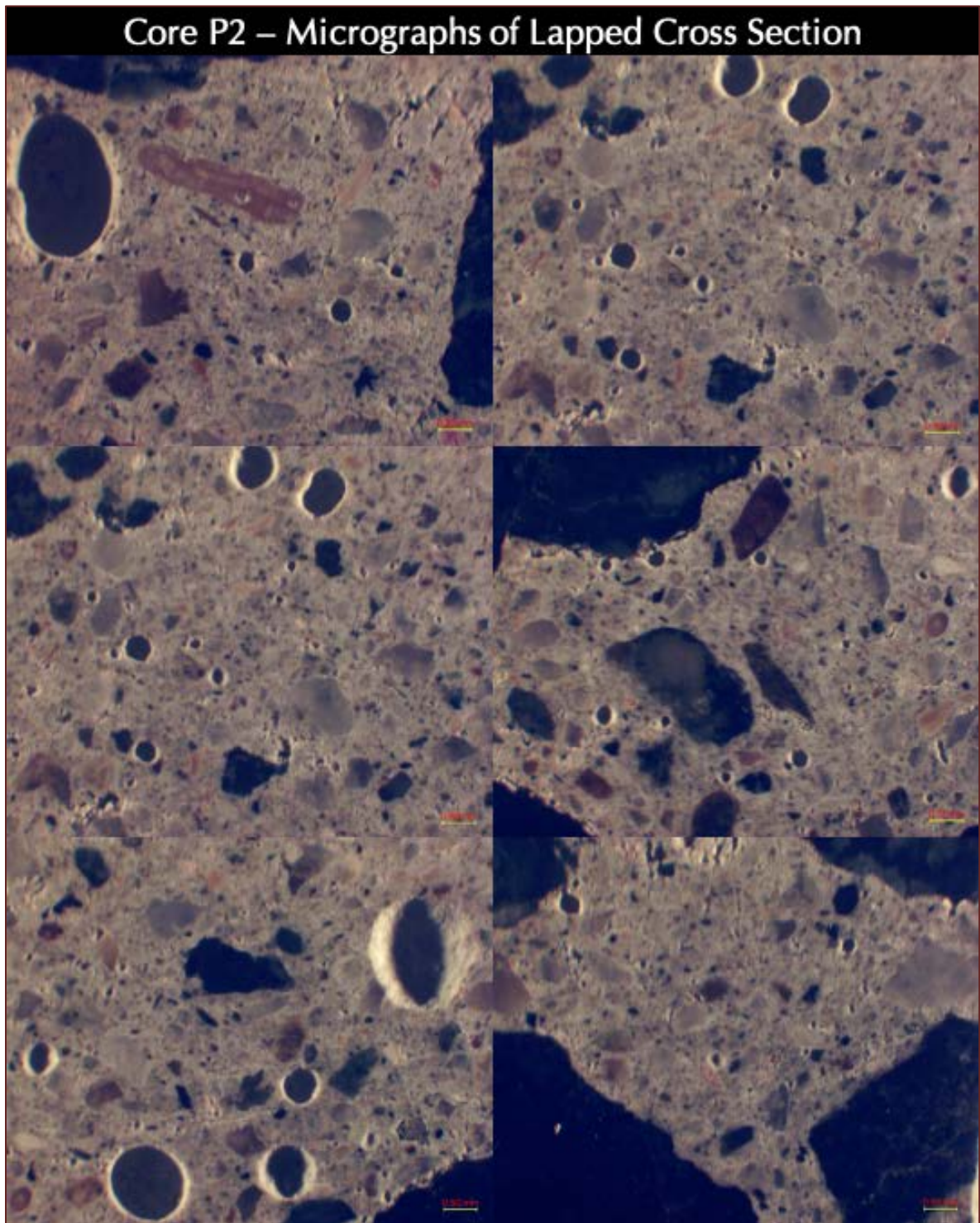


Figure 12: Micrographs of lapped cross section of the Core P-2 from East Wall showing the **main concrete body** consisting of: (a) the dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, (b) natural siliceous sand fine aggregate, (c) Portland cement paste, (d) some spherical entrained air voids indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and (e) overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air entraining agent compared to the concrete used in the West Wall at the location of Core P-1, and (d) overall dense and well-consolidated nature of concrete. Scale bars are 0.5 mm.

THIN SECTIONS

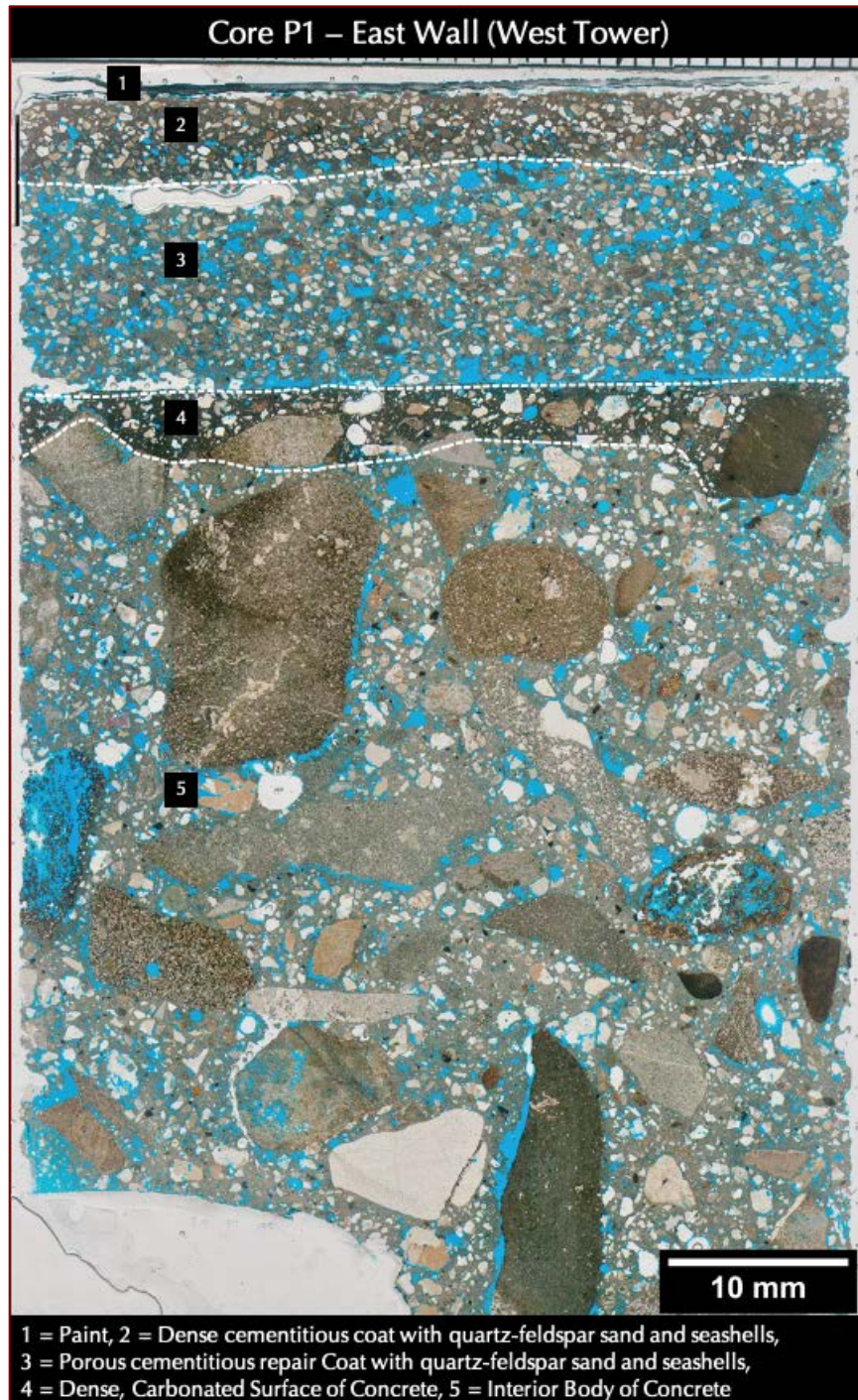


Figure 13: Blue dye-mixed epoxy-impregnated thin section of Core P-1 from West Wall seen in PPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The **paint coat** consisting of: a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

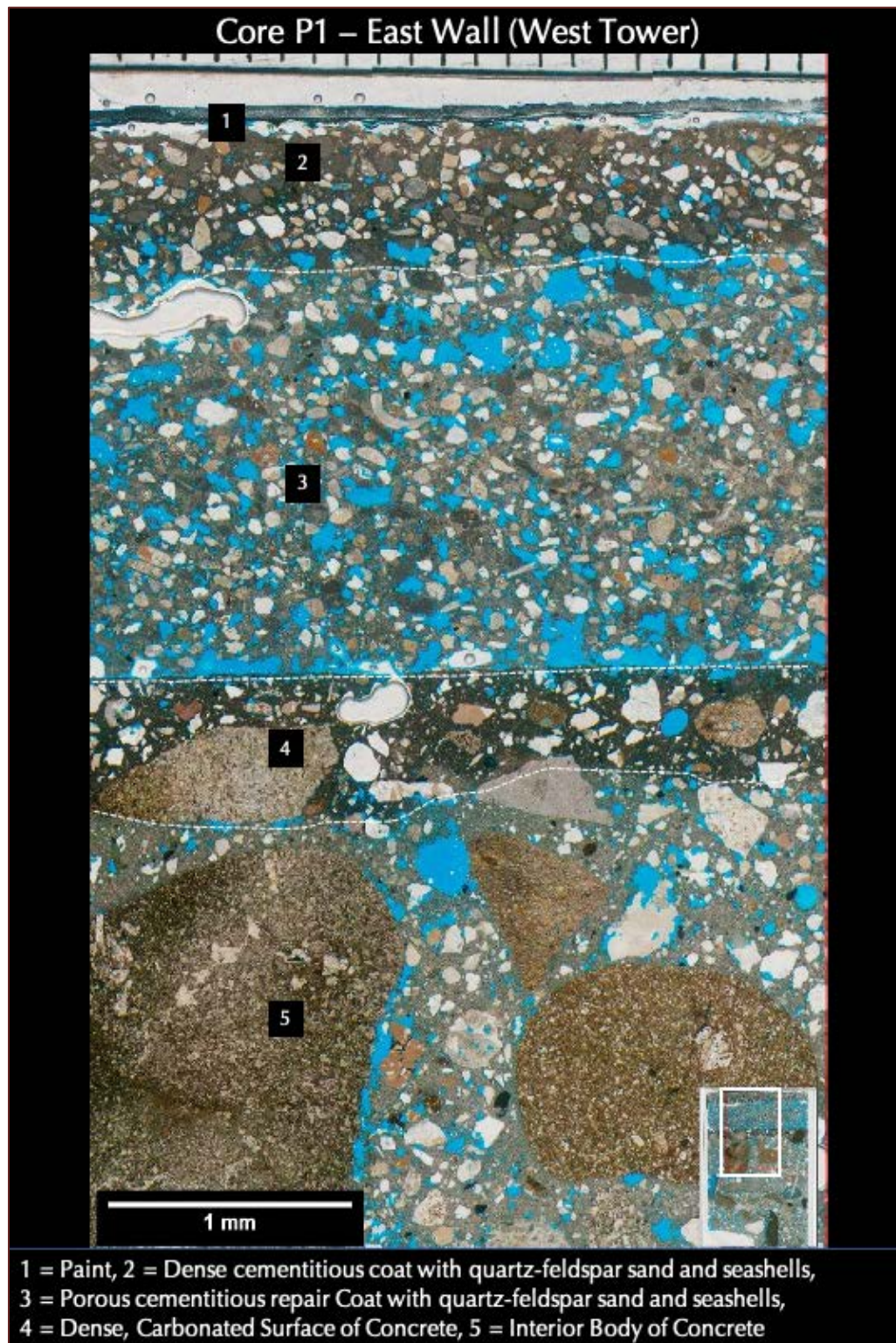


Figure 14: Blue dye-mixed epoxy-impregnated thin section of Core P-1 from West Wall seen in PPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The **paint coat** consisting of a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm; and,

(B) The **mortar topping** consisting of:
(B1) a dense, carbonated cementitious coat of Portland cement and mixed seashell and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed sea shell and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which

has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as # 5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

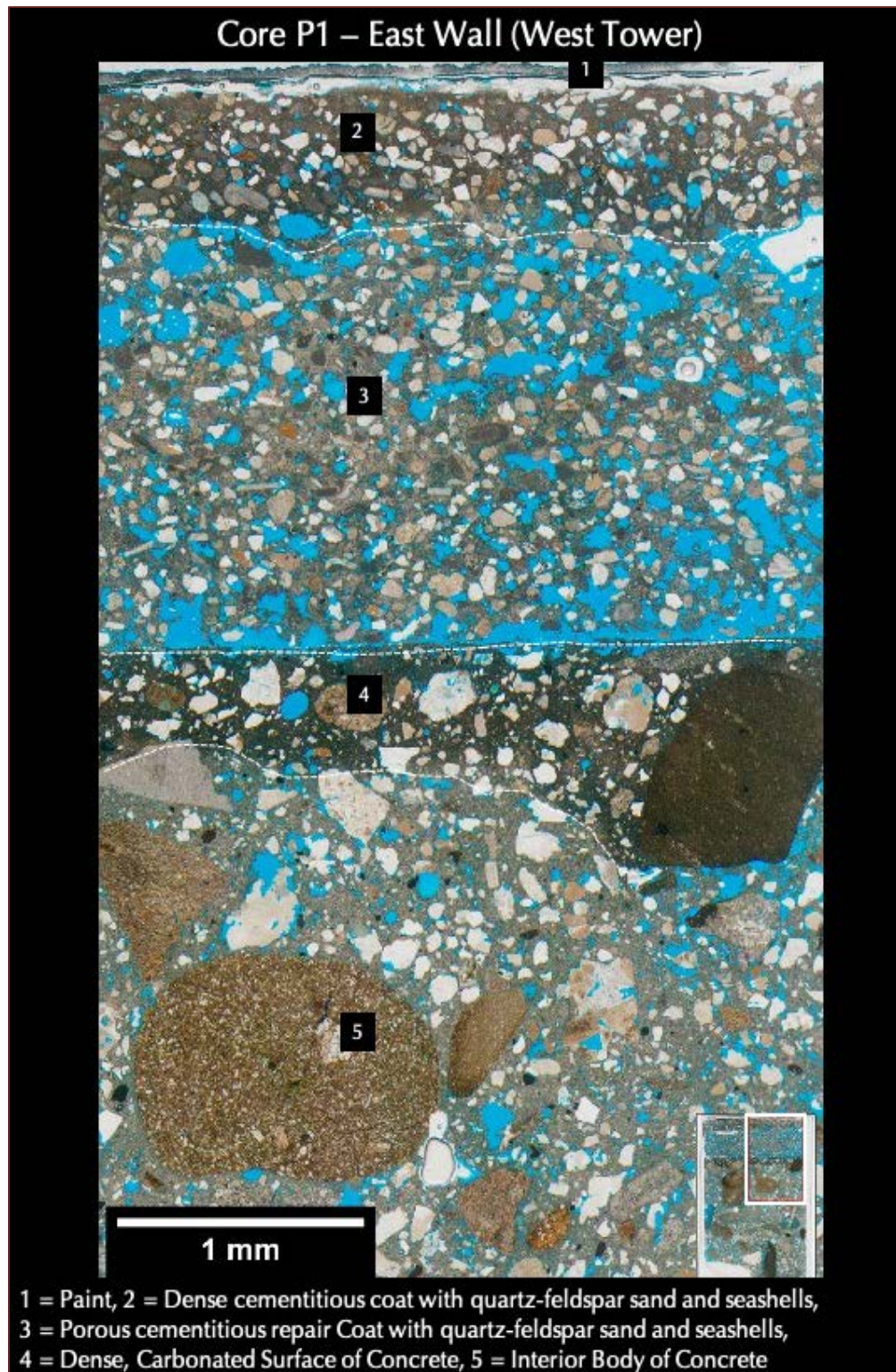


Figure 15: Blue dye-mixed epoxy-impregnated thin section of Core P-1 from West Wall seen in PPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The **paint coat** consisting of: a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal

thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

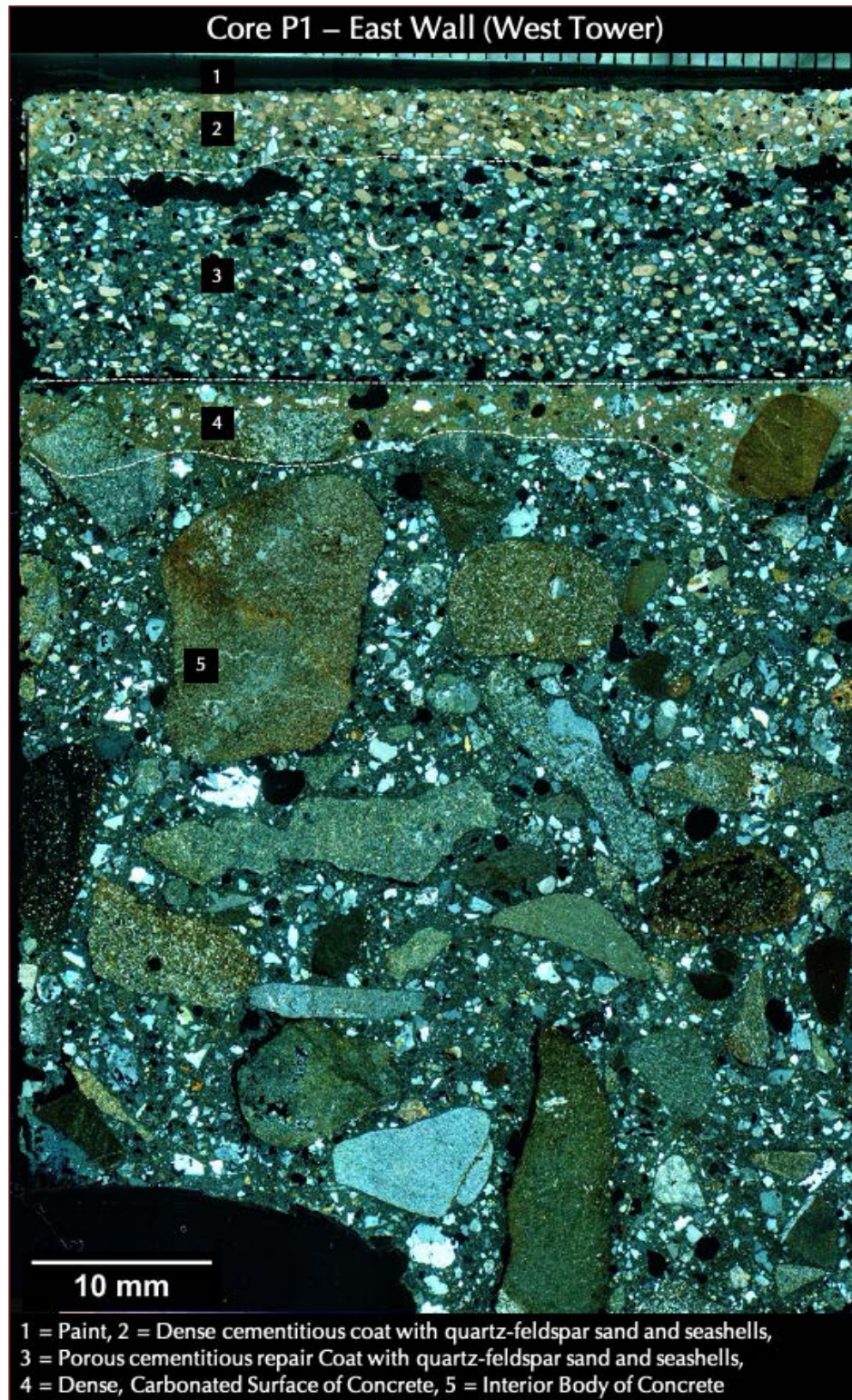


Figure 16: Blue dye-mixed epoxy-impregnated thin section of Core P-1 from West Wall seen in XPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The **paint coat** consisting of: a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

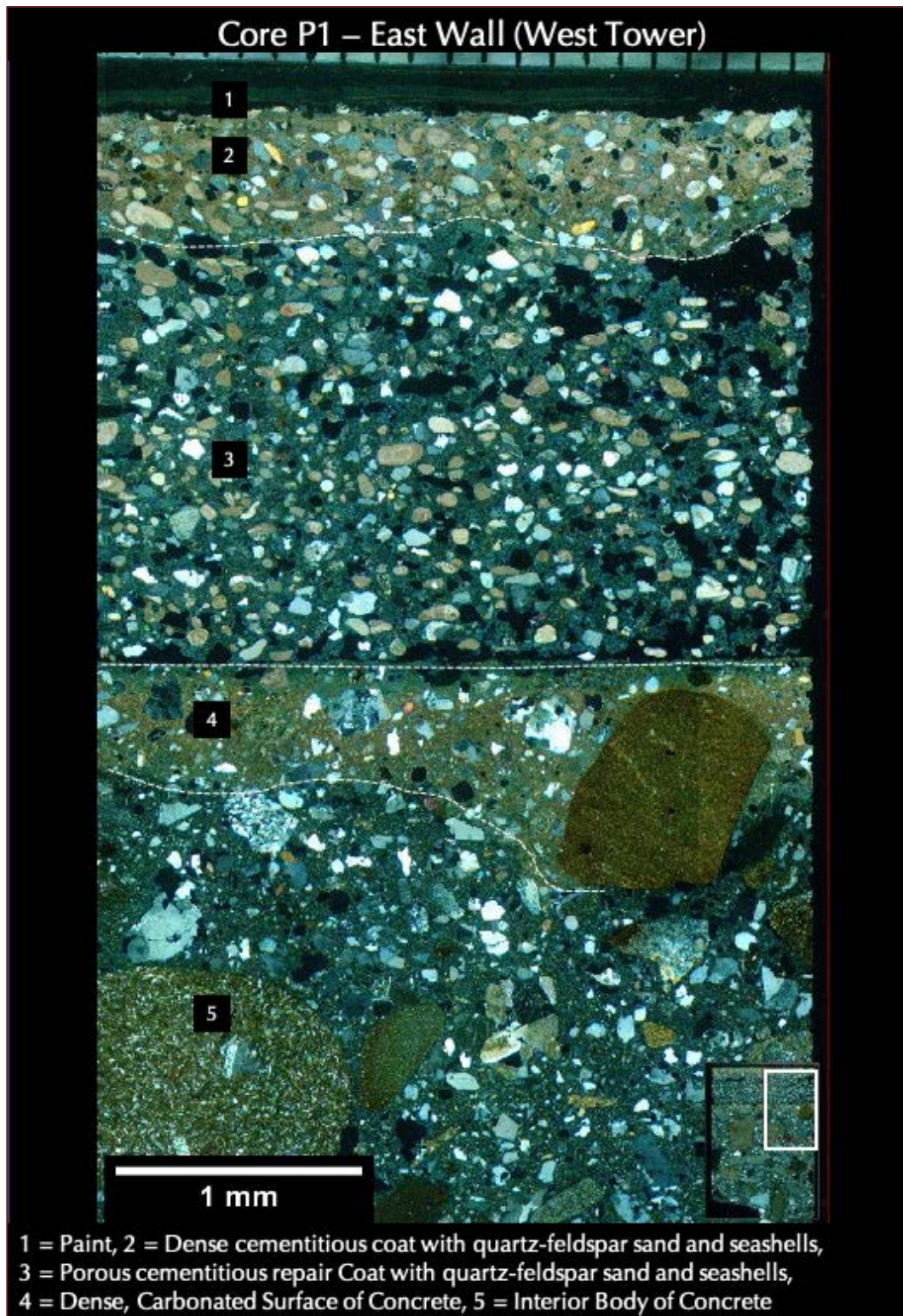


Figure 17: Blue dye-mixed epoxy-impregnated thin section of Core P-1 from West Wall seen in XPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The **paint coat** consisting of: a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region,

marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

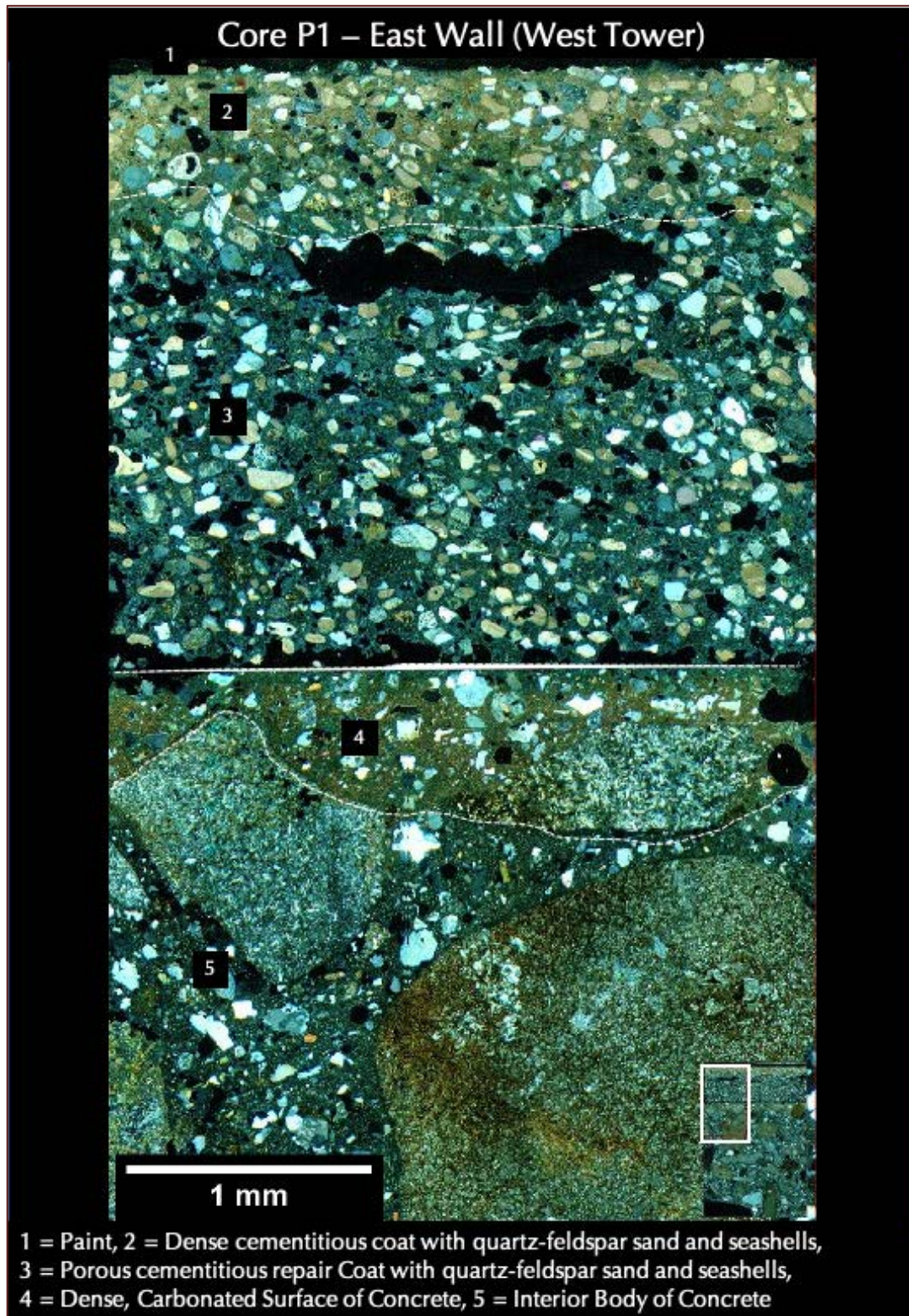


Figure 18: Blue dye-mixed epoxy-impregnated thin section of Core P-1 from West Wall seen in XPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The **paint coat** consisting of: a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which

has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

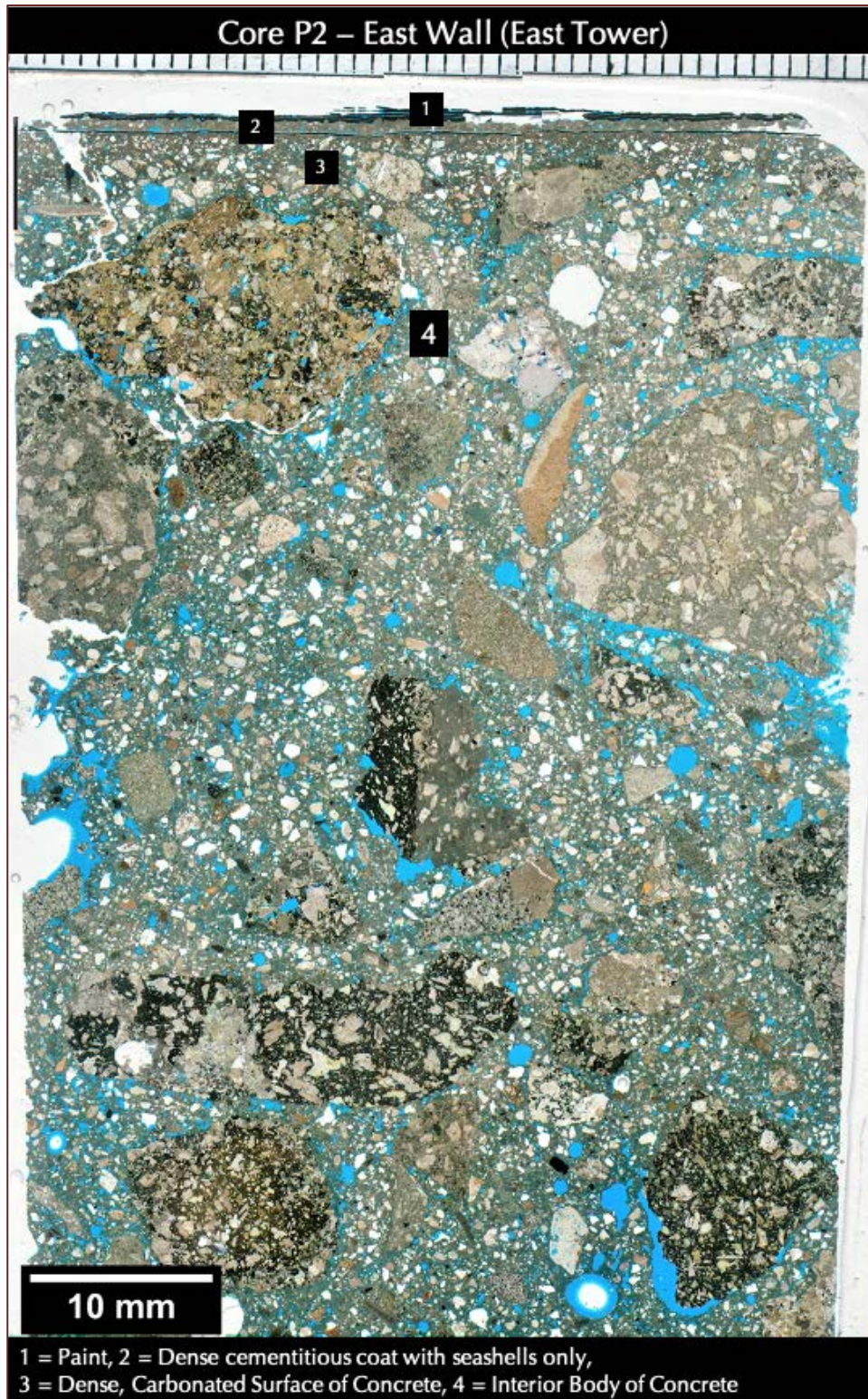


Figure 19: Blue dye-mixed epoxy-impregnated thin section of Core P-2 from East Wall seen in PPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and (A2) a middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats, altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar

topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

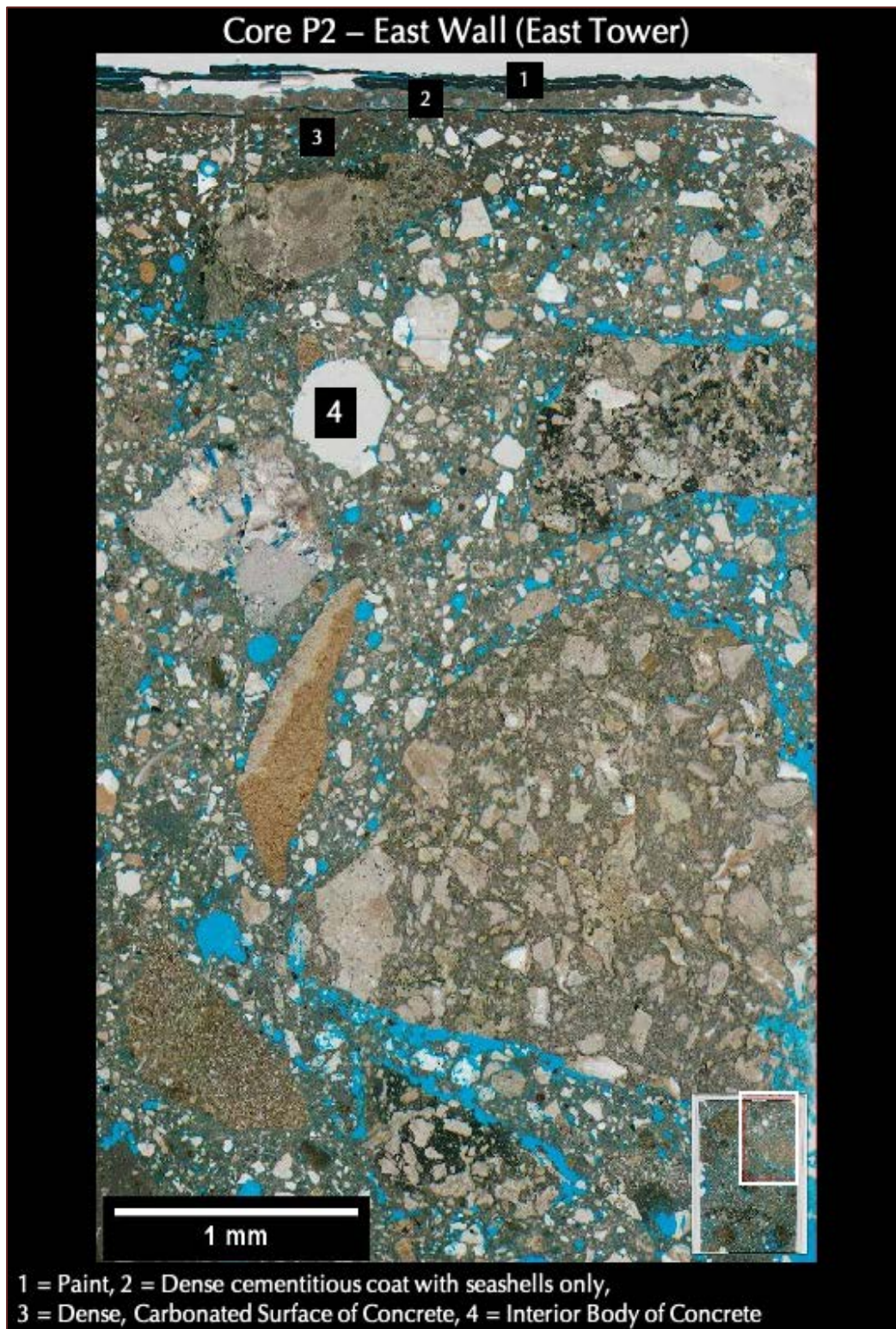


Figure 20: Blue dye-mixed epoxy-impregnated thin section of Core P-2 from East Wall seen in PPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and (A2) a middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats, altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall

dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

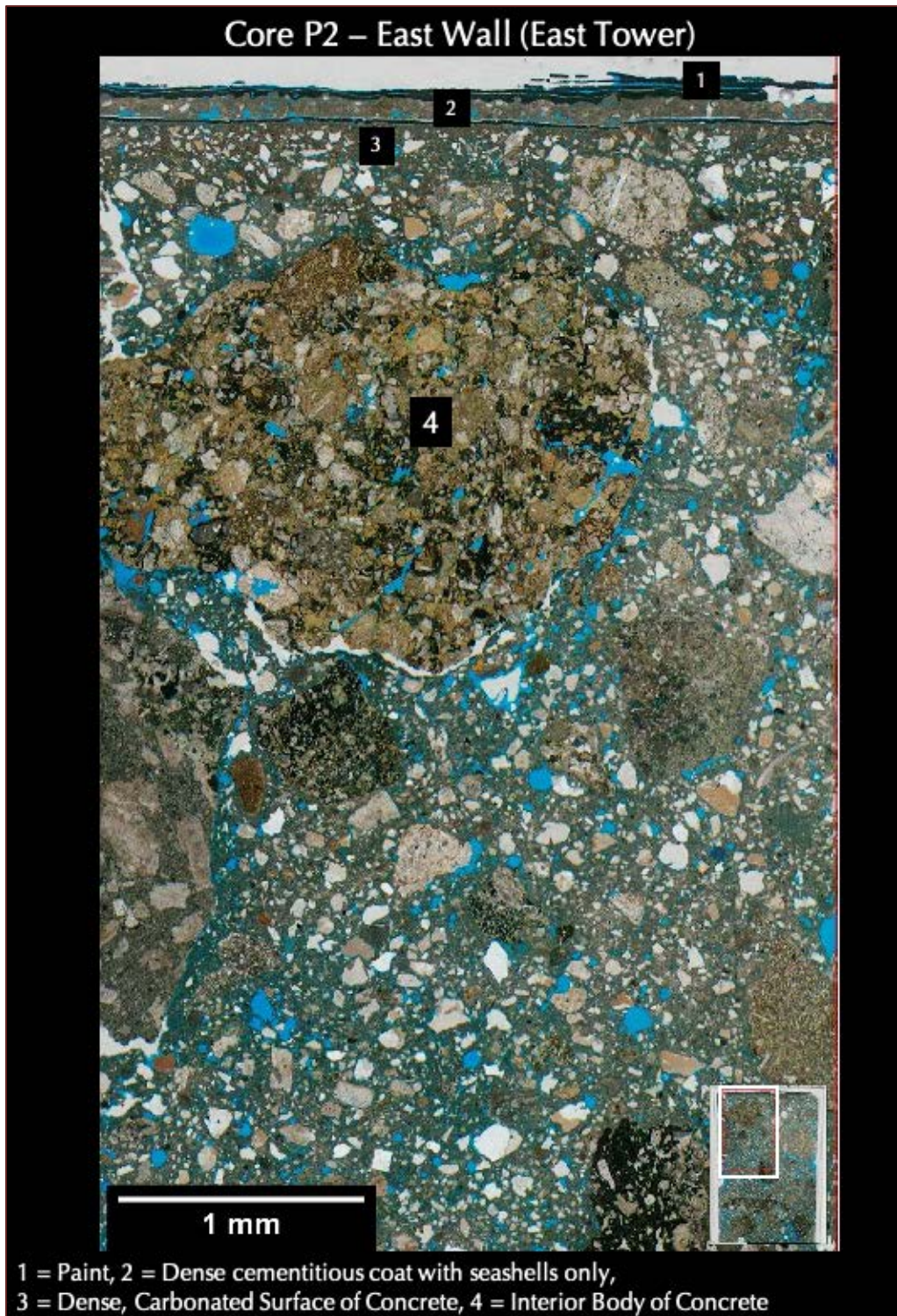


Figure 21: Blue dye-mixed epoxy-impregnated thin section of Core P-2 from East Wall seen in PPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and a (A2) middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats, altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall

dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

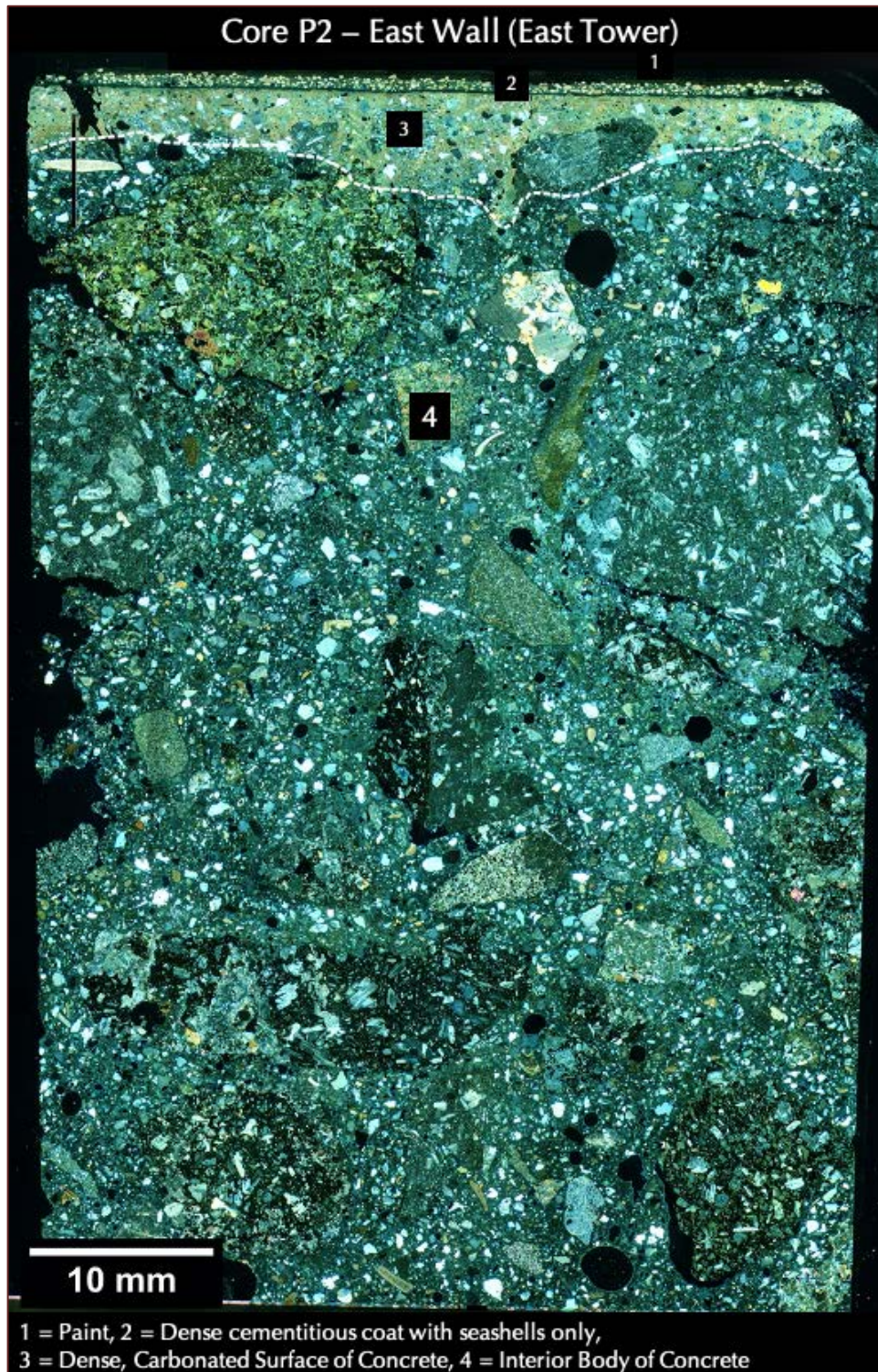


Figure 22: Blue dye-mixed epoxy-impregnated thin section of Core P-2 from East Wall seen in XPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and (A2) a middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats, altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-consolidated nature of

concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

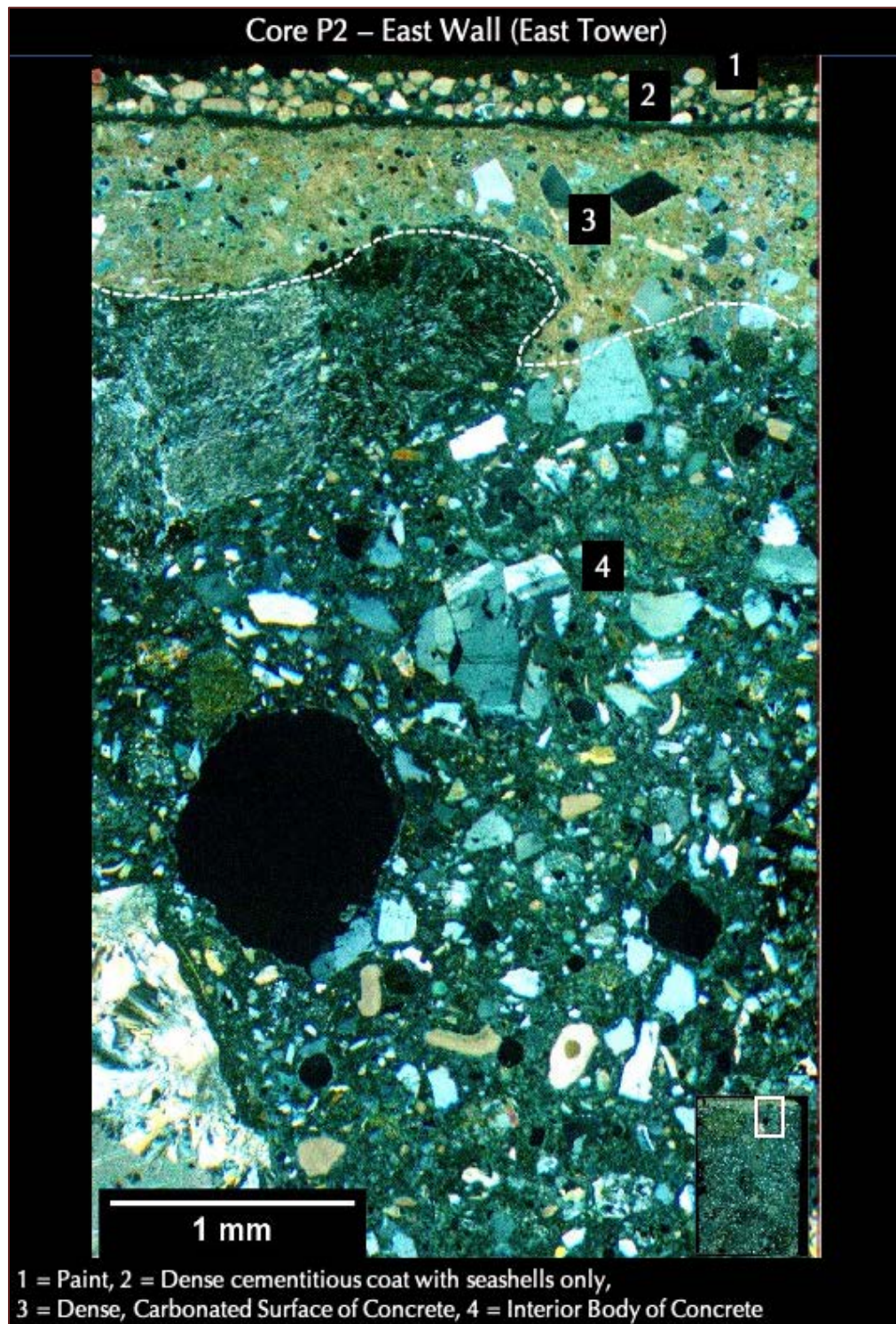


Figure 23: Blue dye-mixed epoxy-impregnated thin section of Core P-2 from East Wall seen in XPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and (A2) a middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats, altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to

non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

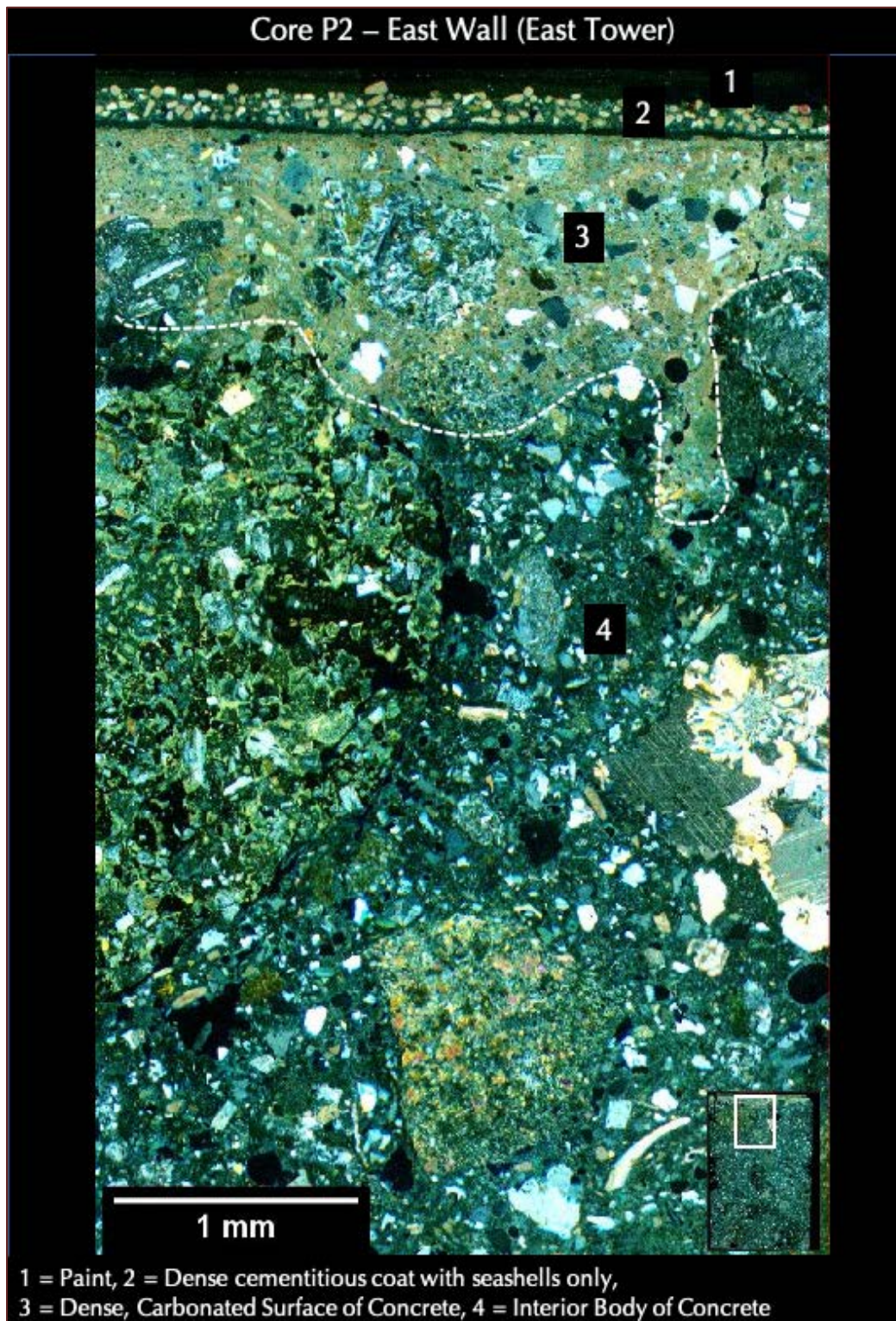


Figure 24: Blue dye-mixed epoxy-impregnated thin section of Core P-2 from East Wall seen in XPL mode scanned with a transmitted-light stereozoom microscope with polarizing light facilities showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and (A2) a middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats, altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to

non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

MICROGRAPHS OF THIN SECTIONS

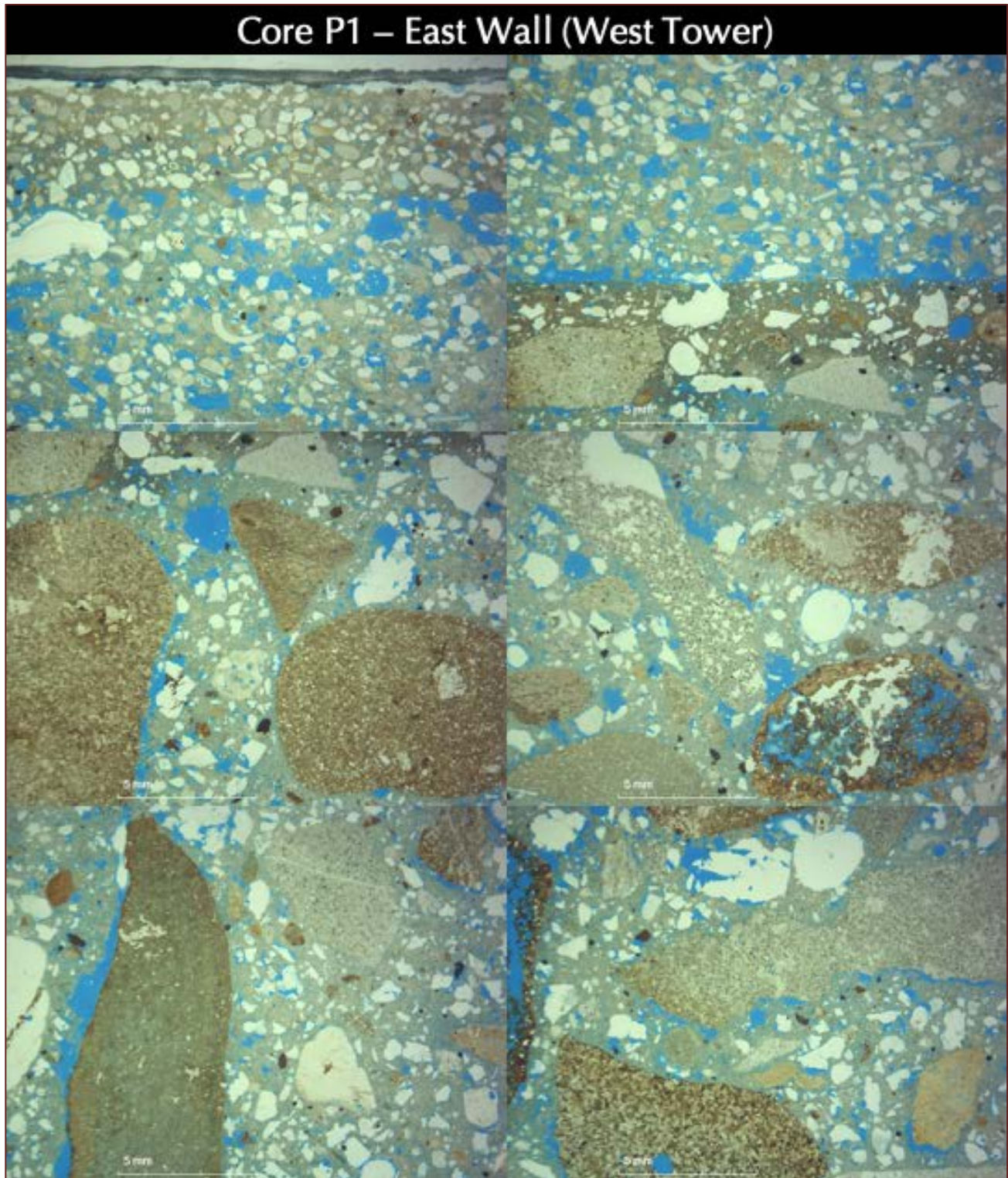


Figure 25: Micrographs of thin section of Core P-1 from West Wall showing the acrylic paint coat, the dense, cementitious coat, the porous repair mortar topping, the densified finished surface region of the main concrete body containing crushed gravel coarse aggregate particles, many of which show the typical volcanic texture and mineralogy of basalt-andesite-trachyte-dacite clan.

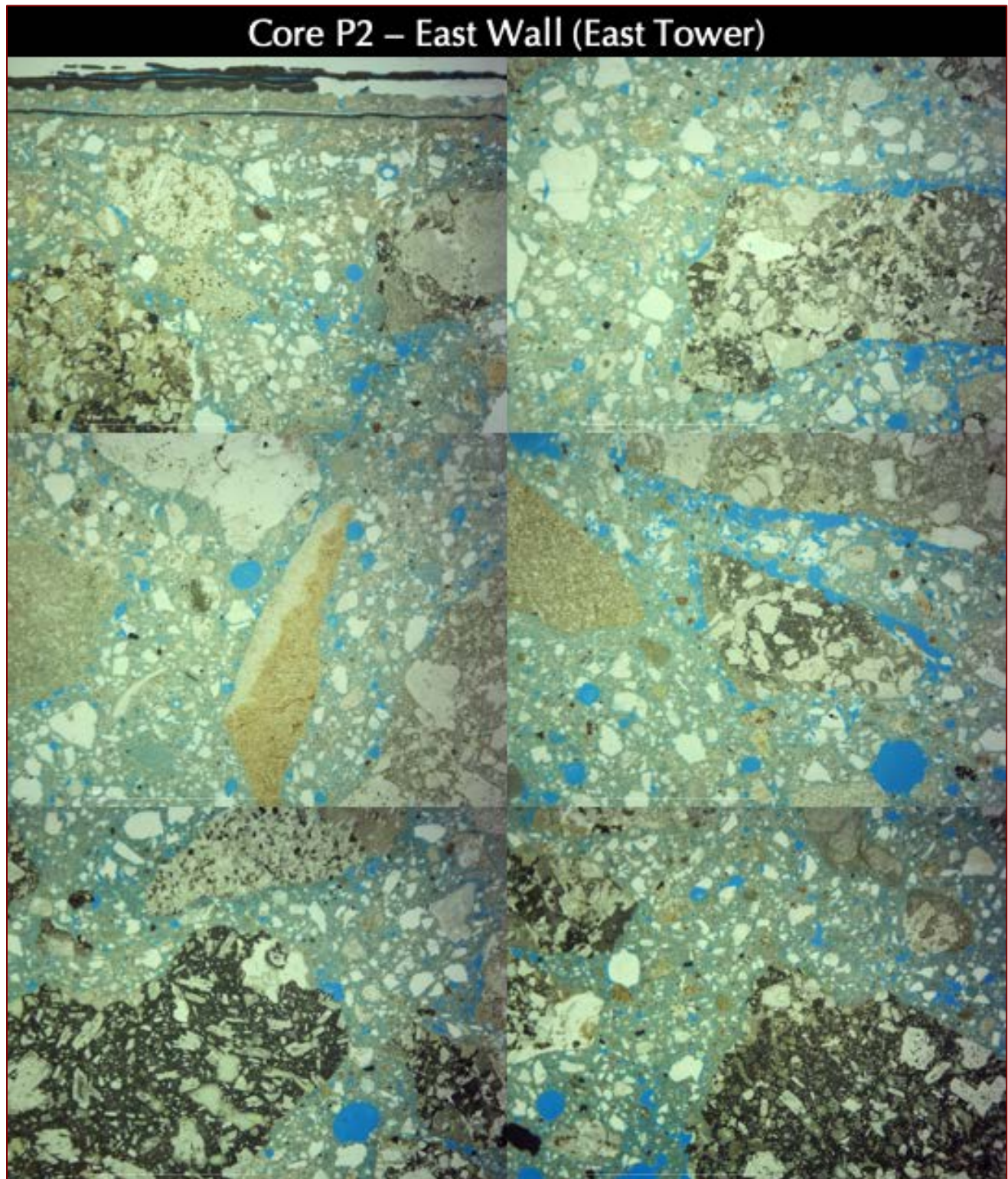


Figure 26: Micrographs of thin section of Core P-2 from East Wall showing the acrylic paint coat, the dense, cementitious coat, the densified finished surface region of the main concrete body containing crushed gravel coarse aggregate particles, many of which show the typical volcanic texture and mineralogy of basalt-andesite-trachyte-dacite clan.

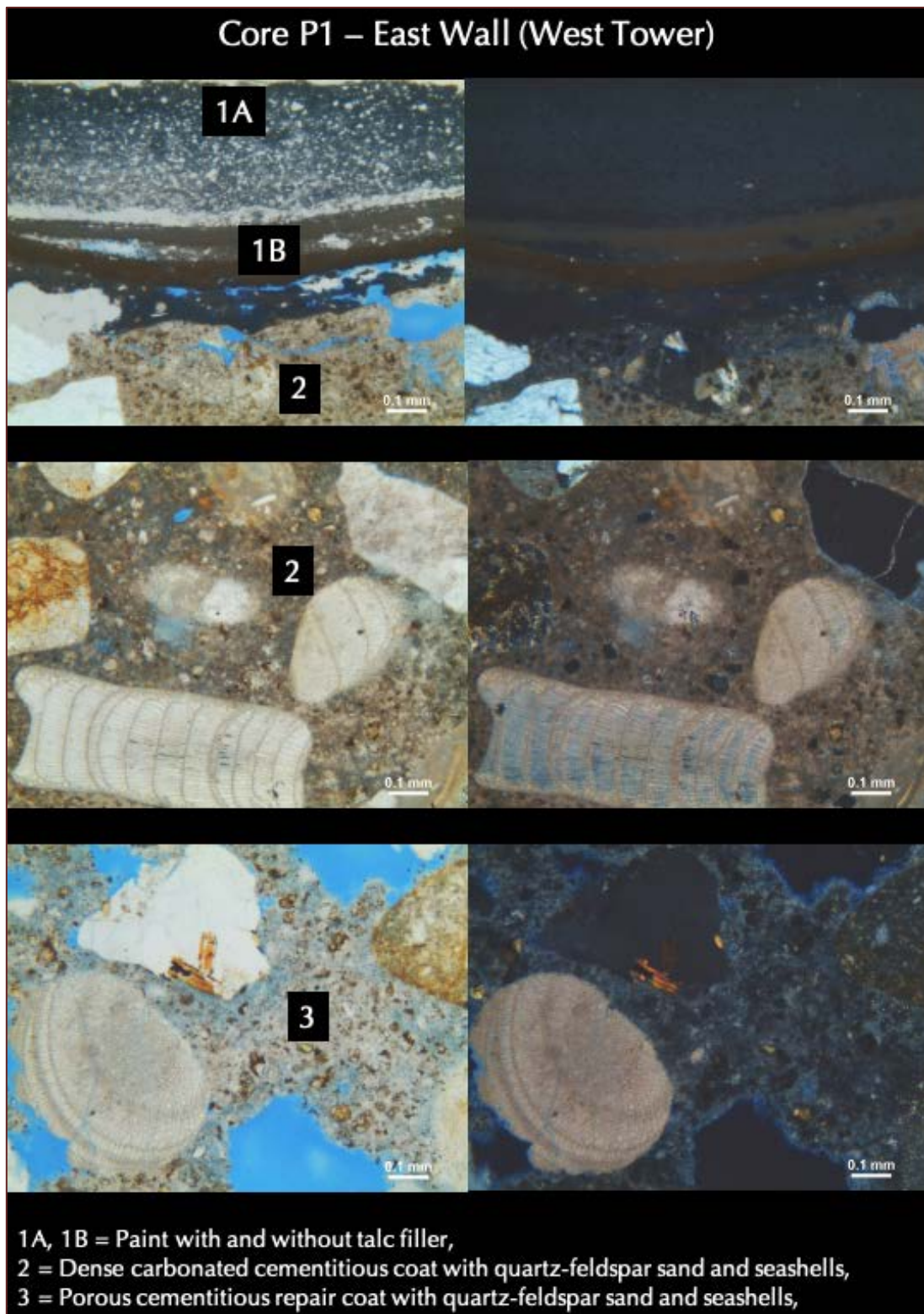


Figure 27:
Micrographs of thin section of Core P-1 from West Wall showing:

(A) The **paint coat** consisting of a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm, which comprises two different paint coats with (#1A) and without (#1B) talc filler; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has

(C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy. Left and right column photos were taken in PPL and corresponding XPL modes, respectively.

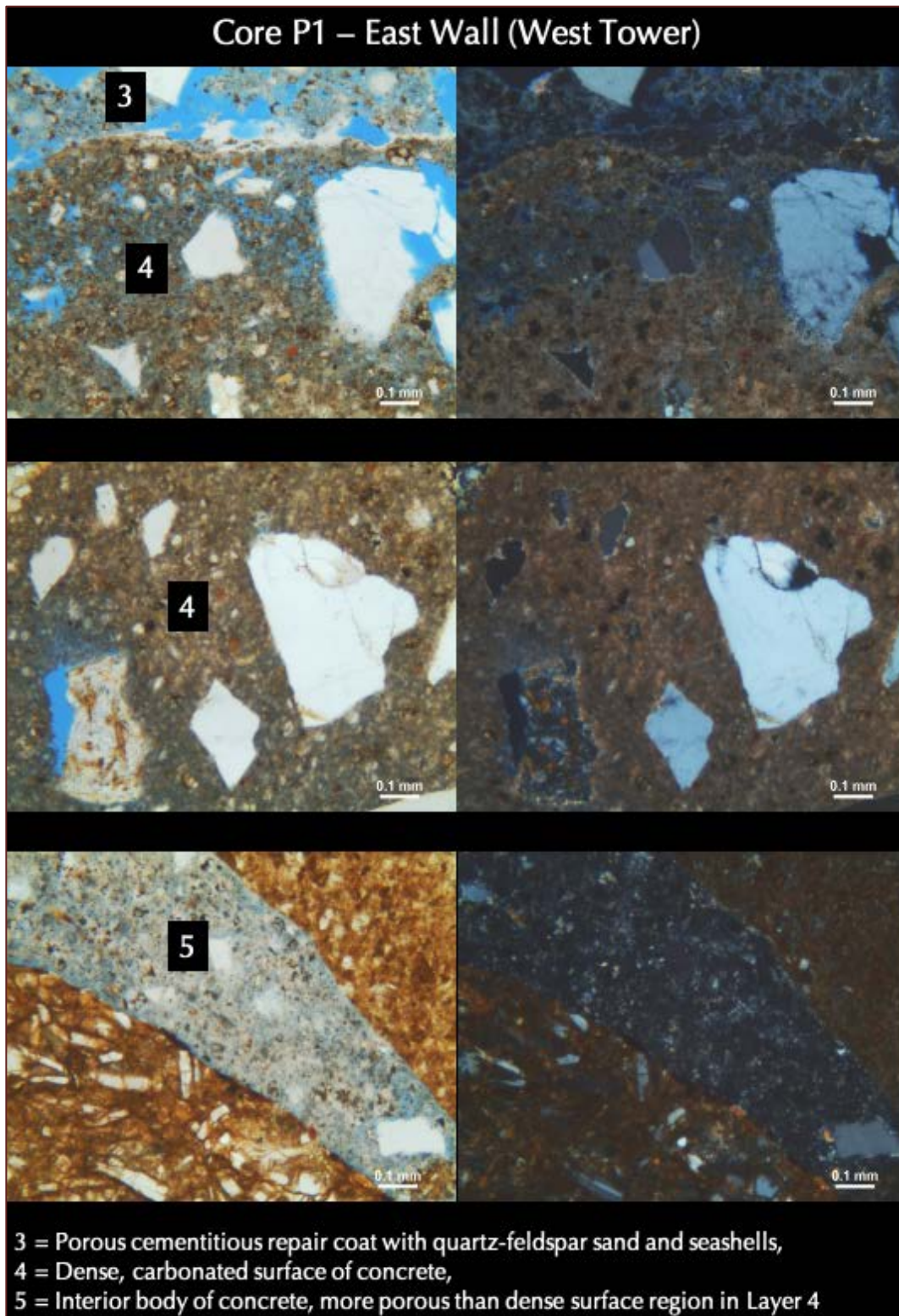


Figure 28: Micrographs of thin section of Core P-1 from West Wall showing:

(A) The **paint coat** consisting of a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm, which comprises two different paint coats with (#1A) and without (#1B) talc filler; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length,

containing crushed gravel coarse aggregate, which shows the typical volcanic texture and mineralogy of basalt-andesite-trachyte-dacite clan, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy. Left and right column photos were taken in PPL and corresponding XPL modes, respectively.

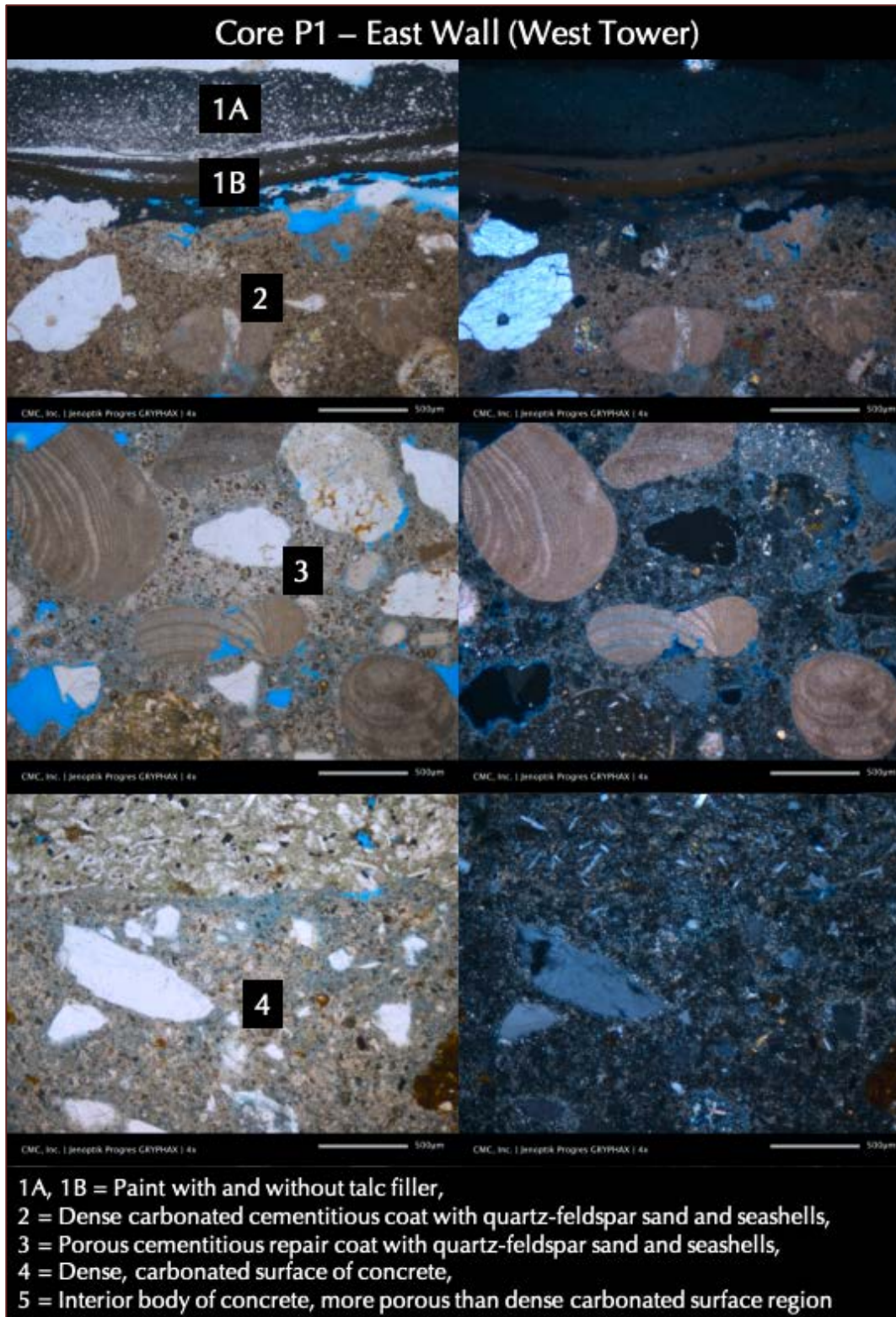


Figure 29: Micrographs of thin section of Core P-1 from West Wall showing:

(A) The **paint coat** consisting of a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm, which comprises two different paint coats with (#1A) and without (#1B) talc filler; and,

(B) The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer marked as #2 having a nominal thickness of 5 mm; and, (B2) the porous main body of the repair coat marked as #3 consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm;

(C) The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length,

containing crushed gravel coarse aggregate, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy. Left and right column photos were taken in PPL and corresponding XPL modes, respectively.

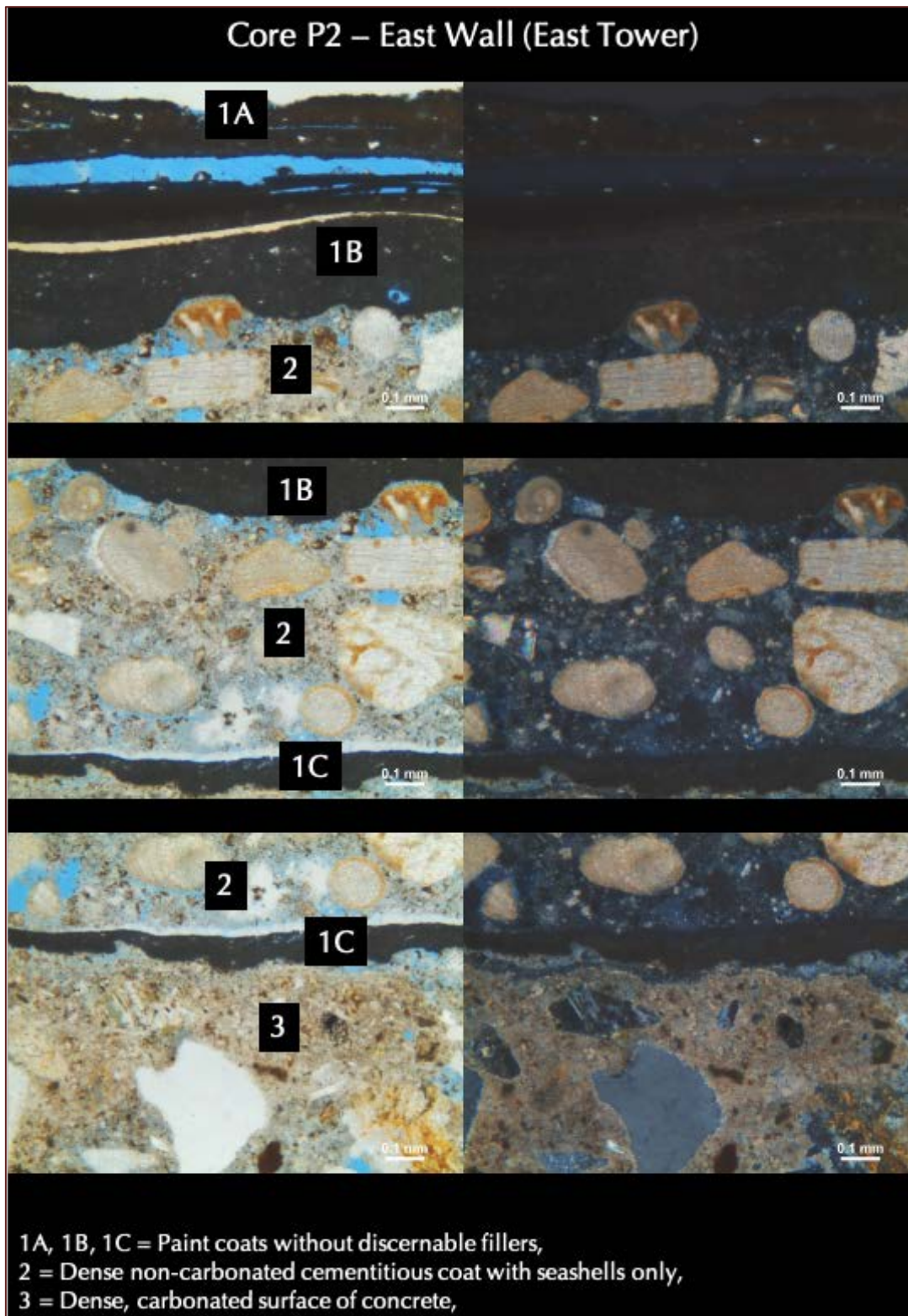


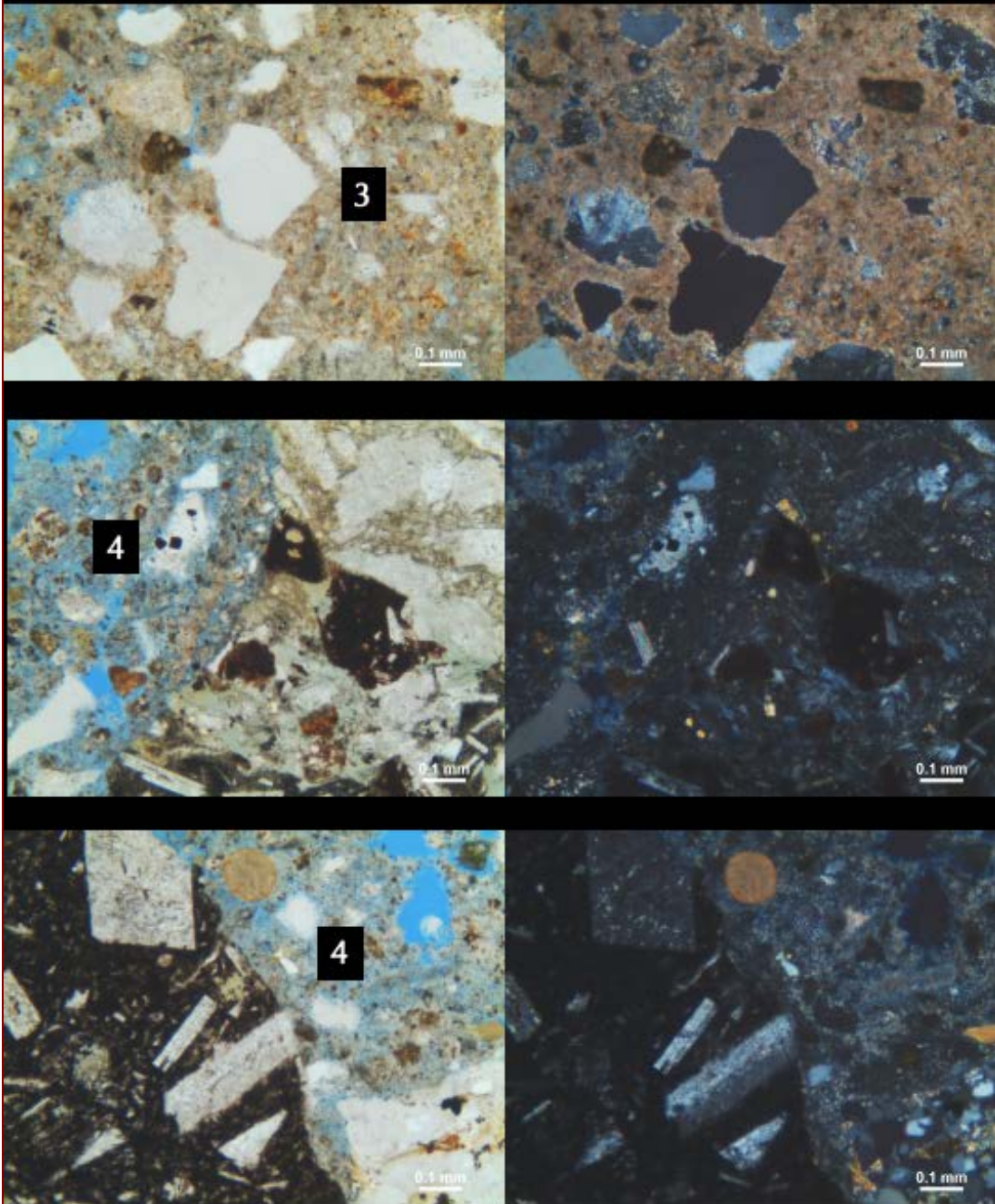
Figure 30:
Micrographs of thin section of Core P-2 from East Wall showing:

(A) The top **protective coating** consisting of alternating layers of: (A1) **paint coats** (marked as #1) and (A2) a middle dense, carbonated **cementitious coat** (marked as #2) of Portland cement paste and seashells (<1 mm size) where the cementitious seashell-cement paste coat is sandwiched between two paint coats (1B and 1C), altogether applied over

(B) The **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-

consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

Core P2 – East Wall (East Tower)



3 = Dense, carbonated surface of concrete,
4 = Interior body of concrete, more porous than dense carbonated surface in Layer 3

Figure 31: Micrographs of thin section of Core P-2 from East Wall showing:

(a) The dense, carbonated finished surface region (#3) of

(b) The main concrete body (#4) containing crushed gravel coarse aggregate particles many of which show the typical volcanic texture and mineralogy of basalt-andesite-trachyte-dacite clan.

Left and right column photos were taken in PPL and corresponding XPL modes, respectively.

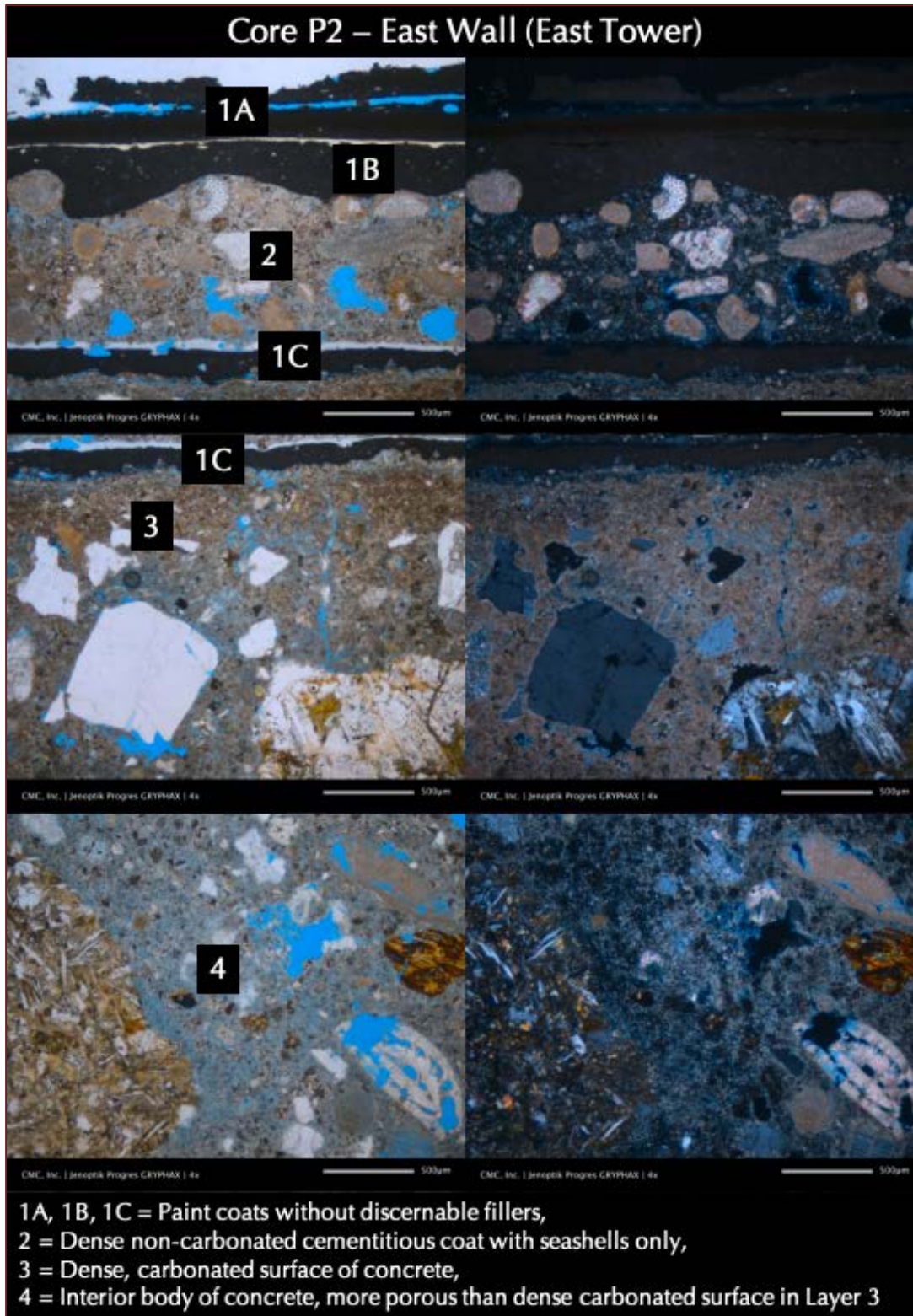


Figure 32:
Micrographs of thin
section of Core P-2
from East Wall
showing:

(a) Two paint coats
(#1A and #1B),

(b) A dense,
carbonated
cementitious coat
(#2) of only seashells
and Portland cement
paste sandwiched
between paint coats
1B and 1C,

(c) The dense,
carbonated finished
surface region (#3) of

(d) The main
concrete body (#4)
containing crushed
gravel coarse
aggregate particles
many of which shows
the typical volcanic
texture and
mineralogy of basalt-
andesite-trachyte-
dacite clan.

(e) Left and right
column photos were
taken in PPL and
corresponding XPL
modes, respectively.



PROTECTIVE COATINGS

Both cores P-1 and P-2 from West and East walls, respectively, have the following protective coatings applied on the main concrete body, which are shown in numerous micrographs from Figures 9 through 32.

For Core P-1 from West Wall, the concrete is protected by the following two successive layers of paint and mortar topping coats from the exposed end towards the concrete:

- a. The **paint coat** consisting of a thin, dark gray, acrylic paint coat at the very top marked as #1 having a nominal thickness of <0.5 mm, which comprises two different paint coats with (#1A) and without (#1B) talc filler; and,
- b. The **mortar topping** consisting of: (B1) a dense, carbonated cementitious coat of Portland cement and mixed seashells and silica sand of <1 mm size in a layer having a nominal thickness of 5 mm; and, (B2) the relatively porous main body of the mortar coat consisting of mixed seashells and silica sand and porous Portland cement paste, having a nominal thickness of 12 mm.

The paint and mortar topping protective layers were applied over the **main concrete body**, which has (C1) a thin dense dark gray, carbonated finished surface region, marked as #4 having a nominal thickness of 5 mm, above (C2) the main concrete body marked as #5, of 150 mm recovered length, containing crushed gravel coarse aggregate, which shows the typical volcanic texture and mineralogy of basalt-andesite-trachyte-dacite clan, natural siliceous sand fine aggregate, Portland cement paste, and many interstitial voids where pore spaces and voids are highlighted by blue epoxy.

These layers of paint coat (two layers) and mortar topping (two layers from dense carbonated to porous non-carbonated) are applied over the concrete, which has: (a) a densified finished surface region (#4) having a nominal thickness of 2 to 3 mm, and (b) the main concrete body, which is relatively more porous than the densified surface region (#5) having a recovered length of 150 mm.

For Core P-2 from East Wall, the concrete is protected by the following two successive layers of paint and mortar topping coats from the exposed end towards the concrete:

- a. The top **protective coating** consisting of alternating layers of: (A1) **paint coats**, and (A2) a middle dense, carbonated **cementitious coat** of Portland cement paste and seashells (<1 mm size, only seashells no silica sand) where the cementitious seashell-cement paste coat is sandwiched between two paint coats.

These protective layers were applied over the **main concrete body**. The concrete contains dark gray crushed stone coarse aggregate which is very different from crushed gravel found in Core P-1 from West Wall, natural siliceous sand fine aggregate, Portland cement paste, and some spherical entrained air voids highlighted by blue epoxy indicating marginally air-entrained nature as opposed to non-air-entrained nature of concrete in Core P-1 from West Wall, and overall dense and well-consolidated nature of concrete. Therefore, the concrete used in the East Wall at the core location is from a different mix having different crushed stone coarse aggregate and some air-entraining



agent compared to the concrete used in the West Wall at the location of Core P-1. Notice no mortar topping as seen in P-1 at this P-2 location, but a dense dark gray, carbonated finished top surface region of concrete (marked as #3) as also seen in Core P-1 of the main concrete body (#4).

COARSE AGGREGATES IN CONCRETE

Coarse aggregates are all volcanic rocks in both cores, but in Core P-1 from West Wall they are crushed gravel of andesite-dacite-rhyolite clan from light to dark brown ferruginous volcanic rocks to altered green volcanic rocks, whereas in Core P-2 from East Wall they are dark gray crushed stone of andesite-trachyte clan all having nominal maximum sizes of $\frac{3}{4}$ in. (19 mm). Particles are variably colored in P-1 but dark gray in P-2, dense and hard, subangular to subrounded in P-1 to angular in P-2, equidimensional to elongated, unaltered, uncoated, and uncracked. Particles are well-distributed throughout the lengths of the cores and well-graded. There is no evidence of any potentially deleterious physical or chemical deterioration of coarse aggregate particles found in the cores during service.

FINE AGGREGATES IN CONCRETE

Fine aggregates are compositionally similar mixtures of fine-grained volcanic rocks (basalt-andesite-trachyte-rhyolite) of coarse aggregates, natural siliceous sands of quartz, quartzite, feldspar, chert, etc., and a minor amount of seashells in both cores having nominal maximum sizes of $\frac{3}{8}$ in. (9.5 mm). Particles are subangular to subrounded, dense, hard, variably colored from colorless to light gray to brown to pink, 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.

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

Properties and Compositions of Aggregates	P-1 West Wall	P-2 East Wall
Coarse Aggregates		
Types	Volcanic rocks in both cores, but in Core P-1 from West Wall they are crushed gravel of andesite-dacite-rhyolite clan from light to dark brown ferruginous volcanic rocks to altered green volcanic rocks, whereas in Core P-2 from East Wall they are dark gray crushed stone of andesite-trachyte clan	
Nominal maximum size (in.)	$\frac{3}{4}$ in. (19 mm)	$\frac{3}{4}$ in. (19 mm)
Rock Types	In Core P-1 from West Wall they are crushed gravel of andesite-dacite-rhyolite clan from light to dark brown ferruginous volcanic rocks to altered green volcanic rocks, whereas in Core P-2 from East Wall they are dark gray crushed stone of andesite-trachyte clan	
Angularity, Density, Hardness, Color, Texture, Sphericity	Variably colored in P-1 but dark gray in P-2, dense and hard, subangular to subrounded in P-1 to angular in P-2, equidimensional to elongated	
Cracking, Alteration, Coating	Unaltered, uncoated, uncracked	



Properties and Compositions of Aggregates	P-1 West Wall	P-2 East Wall
Grading & Distribution	Particles are well-graded and well-distributed	
Soundness	Sound; no evidence of any cracking	
Alkali-Aggregate Reactivity	None	None
Fine Aggregates		
Types	Compositionally similar mixtures of fine-grained volcanic rocks (basalt-andesite-trachyte-rhyolite) of coarse aggregates, natural siliceous sands of quartz, quartzite, feldspar, chert, etc., and a minor amount of seashells	
Nominal maximum size	³ / ₈ in. (9.5 mm)	³ / ₈ in. (9.5 mm)
Rock Types	Fine-grained volcanic rocks (basalt-andesite-trachyte-rhyolite) of coarse aggregates, natural siliceous sands of quartz, quartzite, feldspar, chert, etc., and a minor amount of seashells	
Cracking, Alteration, Coating	Particles are variably colored (colorless, light gray, brown, pink), subangular to subrounded, dense, hard, equidimensional to elongated	
Grading & Distribution	Well-graded and Well-distributed	
Soundness	Sound	
Alkali-Aggregate Reactivity	None	None

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

PASTE IN CONCRETE

Concretes in both cores contain Portland cement pastes, which are moderately gray, hard, and dense. Freshly fractured surfaces have subvitreous lusters and subconchoidal textures. Residual and relict Portland cement particles are present in the sound interior bodies and estimated to constitute 6 to 8 percent of the paste volumes. The calcium hydroxide component of cement hydration occurs as small, platy, patchy units in the sound interior bodies and is estimated to constitute 8 to 10 percent of the paste volume. Hydration of Portland cement is normal. The textural and compositional features of the pastes are indicative of Portland cement contents similar in both cores and estimated to be approximately 5½ to 6 bags per cubic yard; and water-cement ratios uniform throughout the bodies of the cores and estimated to be 0.40 to 0.45. There is no evidence of deleterious secondary deposits in either core. Carbonation of pastes extended to nominal depths of 5 to 6 mm at the densified finished surface regions in both cores. Bonds between the coarse and fine aggregate particles and pastes are tight. There is no evidence of any deleterious micro or macro-cracking of concrete in the sound interior bodies of the cores.

Properties and Compositions of Paste	P-1 West Wall	P-2 East Wall
Color, Hardness, Porosity, Luster	Gray, hard, and dense, freshly fractured surfaces have subvitreous lusters and subconchoidal textures	
Residual Portland Cement Particles	Normal, 6 to 8 percent by paste volume in the sound interior concretes	
Calcium hydroxide from cement hydration	Normal, 8 to 10 percent by paste volume in the sound interior concretes	
Pozzolans, Slag, etc.	None	
Water-cementitious materials ratio (w/cm), estimated	0.40 to 0.45, uniform throughout the sound interior bodies of cores	



Properties and Compositions of Paste	P-1 West Wall	P-2 East Wall
Cementitious materials contents, estimated (equivalent to bags of Portland cement per cubic yard)	5 ¹ / ₂ to 6	5 ¹ / ₂ to 6
Secondary Deposits	None	
Depth of Carbonation, mm	Carbonation of pastes extended to nominal depths of 5 to 6 mm at the densified finished surface regions in both cores	
Microcracking	There is no evidence of any deleterious micro or macro-cracking of concrete in the sound interior bodies of the cores	
Aggregate-paste Bond	Tight in the sound interior concretes	
Bleeding, Tempering	None	
Chemical deterioration	None in the interior concretes	

Table 2: Properties and composition of hardened cement pastes.

There is no evidence of deleterious secondary deposits in either core. Bonds between the coarse and fine aggregate particles and pastes are tight. There is no evidence of any deleterious micro or macro-cracking of concrete in the sound interior bodies of the cores.

AIR IN CONCRETE

Air occurs as: (a) very fine (less than 100 microns) to fine (less than 500 microns), discrete, spherical and near-spherical voids having sizes up to 1 mm in Core P-2 from East Wall, but not in Core P-1 from West Wall; and (b) coarse, near-spherical and irregularly shaped voids having sizes up to 4 mm. The former voids are characteristic of entrained air and the latter voids are characteristic of entrapped air. Concrete in the West Wall core is non-air-entrained, having an estimated air content of less than 1 to 2 percent. However, the concrete from the East Wall is marginally air-entrained having an estimated air content of 3 to 4 percent.

Air	P-1 West Wall	P-2 East Wall
Estimated Air Content	Less than 1 to 2 percent	3 to 4 percent
Air Entrainment	Non-air-entrained	Marginally air-entrained
Air-Void System	Poor	Moderate
Micrographs showing air void systems	Figure 10	Figure 12

Table 3: Air contents and air entrainments in the cores.

**CHLORIDE PROFILES**

Results of water-soluble chloride contents determined from potentiometric titration on pulverized concrete samples collected from the top exposed ends, the mid-depth locations, and the bottom ends as shown in Figure 33 and tested according to the procedures of ASTM C 1218 are given below:

Sample		Chloride Contents from Potentiometric Titration		
		% Chloride by mass of concrete	Cement Content assuming 15 percent	Chloride as percent by mass of <i>cement</i> (assuming 15 percent cement in concrete)
P-1 West Wall	Top (Including Mortar Topping)	0.2599	0.15	1.73
	Mid-Depth	0.0753	0.15	0.50
	Bottom	0.0147	0.15	0.09
P-2 East Wall	Top	0.1964	0.15	1.31
	Mid-Depth	0.0120	0.15	0.08
	Bottom	0.0108	0.15	0.07

Table 4: Water-soluble chloride contents from the exposed, mid-depth, and bottom ends of Cores P-1 and P-2 from West and East Walls, respectively. Values in red indicate higher 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.

Both cores showed high chloride contents at their exposed ends, which are anticipated from their reported locations in close proximity to the ocean. For the West Wall, the chloride content is high at least to the mid-depth location i.e. to a depth of 90 mm from the exposed end, where 0.5 percent chloride by mass of cement exceeds the industry-recommended maximum chloride limit of 0.2 percent by mass of cement for corrosion of steel to occur in the presence of oxygen and moisture. However, these chloride values may indicate residual chloride in concrete before installation of the protective systems, which may have reduced the chloride ingress from the environment. The top high chloride in Core P-1, however, included the entire thickness of the mortar topping along with 0.5 in. thick portion of concrete, which may indicate interaction of high chloride in the moist air adjacent to the coatings.

For the Core P-2 from the East Wall, the chloride content at the exposed end of concrete immediately beneath the paint coat is high but the chloride level has dropped down to below the maximum threshold chloride limit at the mid-depth location i.e. to a depth of 50 mm from the painted exposed surface.

Incorporation of seashells as sand particles may have introduced some chloride into the concrete especially if seashells were not washed to remove chloride contaminated in the shells. However, lower-than-threshold chloride levels in the interior of both cores indicate no such contribution of chloride from the seashells at least to exceed the chloride levels beyond the threshold chloride for corrosion of steel. Therefore, the interior bodies of concrete in

both cores beyond the exposed surface regions in the mid-depth locations and inside are found to be free of any chloride-induced corrosion especially in the East Wall core.

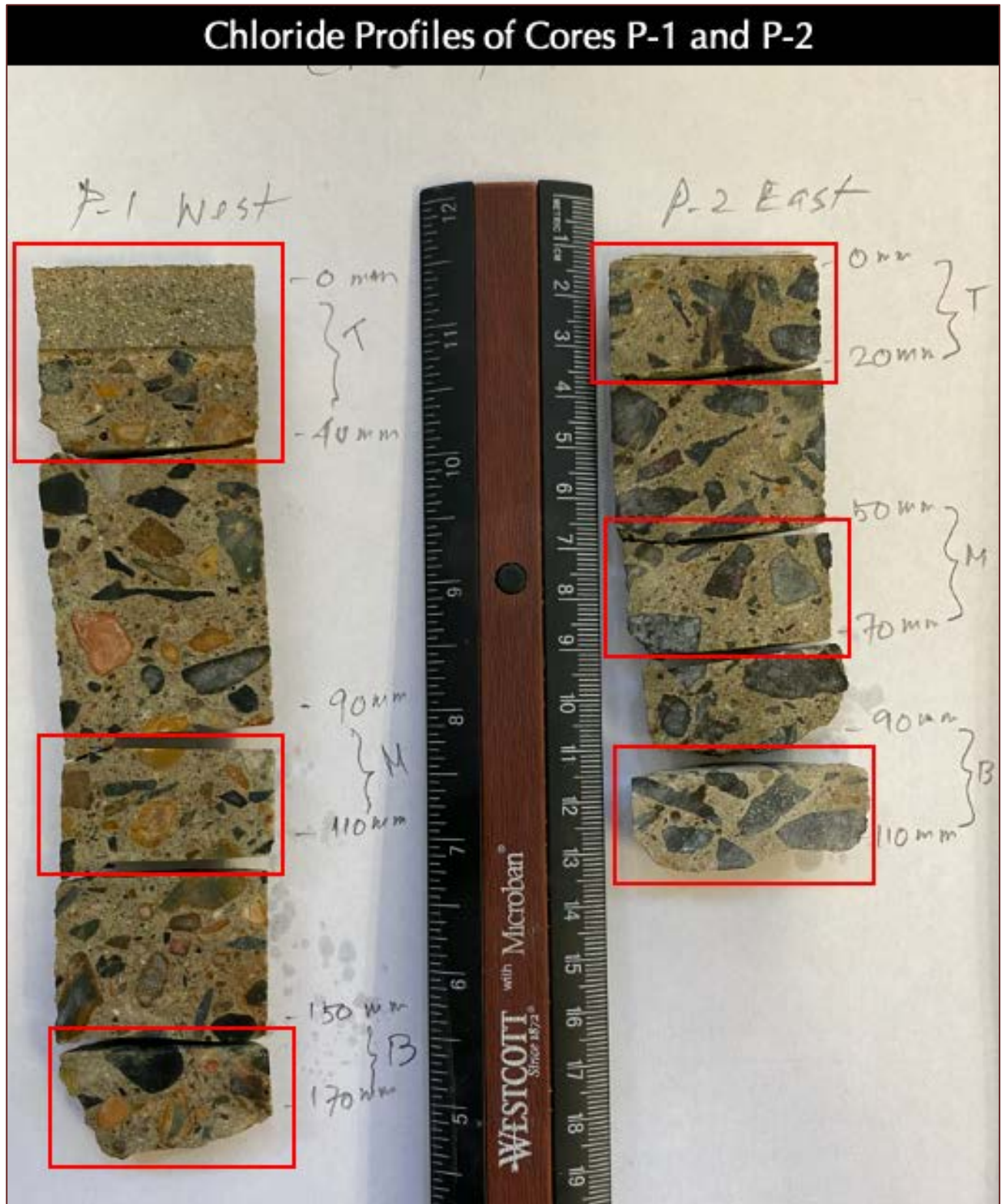


Figure 33: Sections from each core selected for chloride analysis.



DISCUSSIONS

Both cores from both West and East Walls showed protective measures taken to combat penetration of potentially corrosive agents (chloride, carbon dioxide) from the oceanfront environment into the concrete.

As a result of these protective measures, the main concrete body at the locations of both cores showed minimum atmospheric carbonation, which is judged to have occurred during the service prior to the application of protective coatings. Depth of carbonation is measured to be only 5 to 6 mm mostly within the densified finished surface region of the main concrete body beyond which the concrete is not carbonated.

Water-soluble chloride analyses at the top exposed surface regions, at the mid-depth locations, and at the bottom ends of two cores showed very high chloride at the exposed surface regions of both cores, as anticipated in an ocean front environment, where high chloride at the exposed surface regions within the top $\frac{1}{2}$ inch of the concrete are judged to have occurred from penetration of chloride and moisture from the air into the concrete prior to the application of the protective coatings. The mid-depth locations, as well as the bottom ends of cores have chloride levels mostly below the maximum threshold chloride level of 0.2 percent chloride by mass of cementitious materials to initiate corrosion of steel in concrete in the presence of oxygen and moisture. Therefore, the chloride-induced corrosion potential of steel in concrete is found to be prominent at the surface regions of concrete, i.e., beneath the protective coatings, where such levels were already established prior to the applications of coating and were not stripped away before the coatings were installed. Due to only three depths of chloride measurements requested from top, mid-depth, and bottom ends of cores, the actual depth of high chloride (i.e. higher-than-threshold 0.2% chloride) beyond the top $\frac{1}{2}$ in. depth could not be measured, except seeing some still high chloride at the mid-depth location of Core P-1 from the West Wall (0.5 percent as opposed to maximum 0.2 percent chloride threshold by mass of cement to initiate corrosion) but not such level at the mid-depth of Core P-2 from the East Wall. Therefore, after the initial chloride ingress prior to the installation of protective measures, the interior concrete probably did not receive as high chloride as it did before the coatings were installed. Protective coatings are definitively helping the interior concrete from continued penetration of corrosive agents of chloride, moisture, and carbon dioxide from the air.

Therefore, durability of the interior concrete in both walls depend very much on the serviceability of the protective coatings in this marine environment where importance of having a coating of impermeable paint, dense low water-cementitious materials ratio cementitious coat, etc. as seen in this case in the two cores examined is paramount. The overall qualities and conditions of concretes in the main bodies of both cores are judged to be sound with no evidence of any physical or chemical deterioration. The interior concretes are dense, well-consolidated, and should be serviceable in their intended environment as long as they are well-protected by the protective coatings to prevent penetration of moisture, chloride, and other corrosive agents to cause further corrosion of steel, and corrosion-related spalling. Due to the high chloride level found at the surface regions further protection from moisture is



essential since moisture in the presence of inherent chloride at the surface region can trigger corrosion of steel if present at the surface region.

REFERENCES

ASTM C 856 "Standard Practice for Petrographic Examination of Hardened Concrete," Vol. 4.02, ASTM International, West Conshohocken, PA, 2016.

Jana, D., "Sample Preparation Techniques in Petrographic Examinations of Construction Materials: A State-of-the-art Review," *Proceedings of the 28th Conference on Cement Microscopy*, International Cement Microcopy Association, Denver, Colorado, pp. 23-70, 2006.

ASTM C 1218, "Standard Test Method for Water-Soluble Chloride in Mortar and Concrete," Vol. 4.02, ASTM International, West Conshohocken, PA, 2010.

★ ★ ★ END OF TEXT ★ ★ ★

The above conclusions are based solely on the information and samples provided at the time of this investigation. The conclusion may expand or modify upon receipt of further information, field evidence, or samples. Samples will be disposed after submission of the report as requested. All reports are the confidential property of clients, and information contained herein may not be published or reproduced pending our written approval. Neither CMC nor its employees assume any obligation or liability for damages, including, but not limited to, consequential damages arising out of, or, in conjunction with the use, or inability to use this resulting information.



END OF REPORT¹

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.