

Laboratory Studies of a Mortar Coating Sample From a Prestressed Concrete Cylinder Pipe



Englewood 24-inch Transmission Main
Dean Street, Englewood, New Jersey



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EXECUTIVE SUMMARY

Reported herein are the results of detailed laboratory studies of multiple pieces of a mortar-coating sample of a prestressed concrete cylinder pipe (PCCP) from the Englewood 24-inch Transmission Main located in Englewood, New Jersey. The prestressed concrete cylinder pipe sample was taken from buried pipeline reportedly laid in October 1974. Prestressed concrete cylinder pipe failed on 12/14/18 while in service. No indication pipe was going to fail until it did, which was catastrophic to the pipe. Pipe was buried approximately 5 feet underground. After the failure, the pipe was stored outside in a utility yard for one month before samples were collected.

The mortar coating shows rough, convex, severely weathered, carbonated, and altered exposed outside surface that contains numerous fine parallel cracks to depths of 2 to 5 mm from the exposed scaled/exfoliated surface indicating continuing scaling or exfoliation of pipe from the exposed surface downwards with progressive deterioration that has eventually led to the reported failure. These exposed surface-parallel microcracks have reduced the overall thickness of the pipe to the point of failure. Nominal thickness of individual pieces varied from 20 mm down to 10 mm.

As opposed to the top half of the pipe thickness, the bottom half i.e. from the interior body down to the wire cast surface region is relative sound and free of any cracking. There are, however, many fine to coarse voids and interstitial spaces between aggregate particles that are best seen in microstructures.

The mortar coating contains natural sand aggregates having major amounts of rounded to subrounded shale and other argillaceous rocks, subordinate amounts of siliceous particles of quartz, quartzite, feldspar, and minor amount of calcareous (limestone) particles all having nominal maximum sizes of 2 mm. All sand particles are well-graded, well-distributed, and have been sound during their service in the coating. Presence of major amount of shale in the sand, however, indicates potential physical unsoundness of coating from potential absorption of moisture by shale and subsequent expansion.

The interior portions of the coating contains Portland cement paste, which is variably porous, severely carbonated at the top 2 to 5 mm of the exposed surface region, moderately soft to soft at the top 2 to 5 mm to moderately hard to hard at the bottom half, light gray to beige at the top 2 to 5 mm to medium gray at the bottom half, well-consolidated in the portion beneath the altered and cracked surface region. Water-cement ratio of coating in the sound portion is judged to be from 0.40 to 0.45 and less than 0.40 in the $\frac{1}{16}$ in. thick neat pastes at the wire cast surfaces.

The inside wire cast surfaces show impressions of $\frac{1}{8}$ in. diameter prestressing wires at $1\frac{1}{4}$ -in. center-to-center distances, and have $\frac{1}{16}$ in. thick neat pastes at the wire cast surfaces. The wire cast surfaces are smooth, shiny, medium gray, and have lower water-cement ratio (w/c) than that in the body (w/c is estimated to be less than 0.40 in the $\frac{1}{16}$ in. of the neat pastes of wire cast surfaces as opposed to 0.40 to 0.45 in the body).

Air occurs as irregularly shaped voids having nominal sizes up to 3 mm that are characteristic of entrapped voids including interstitial voids in between the sand particles. The mortar coating is non-air-entrained having an air content estimated to be 6 to 8 percent, which are all entrapped air voids in between the sand particles.

Wire cast surfaces show occasional reddish-brown corrosion products of prestressing wires, which from severe carbonation of paste at the top 2 to 6 mm as seen in thin section photomicrographs along with high chloride content determined later are judged to be carbonation-induced loss of alkalinity of the coating and subsequent carbonation of prestressing wires as well as chloride-induced corrosion of prestressing wires.

Results show negligible chloride content (0.04% by mass of cement) at the top exposed surface region due to leaching of chloride but high chloride content (1.32 to 1.99% by mass of cement) in the mid-depth and wire cast surface region respectively indicating penetration of chloride from the environment, which has caused corrosion of prestressing wires and resultant corrosion products seen in the failed portion of pipe in field photos.

The cold and boiling water absorptions as well as the volume of permeable voids are all consistent with an overall porous nature of coating that has facilitated chloride penetration down to the depth of prestressing wires to cause corrosion of wires. Additionally, alteration and exfoliated cracking of coating at the top 2 to 5 mm of the exposed surface region as seen in petrographic examinations has caused loss of thickness of coating down to the point of failure.

Microstructural, chemical (chloride), and physical (absorption) tests showed an inherently porous coating that was contaminated with chloride from the environment during service to cause corrosion of prestressing wires, and has caused alteration and severe parallel microcracking and exfoliation at the top 2 to 5 mm of the exposed surface region to cause loss of the coating thickness down to the point of failure.

INTRODUCTION

Reported herein are the results of detailed laboratory studies of a mortar-coating sample of a prestressed concrete cylinder pipe (PCCP) from the Englewood 24-inch Transmission Main located in Englewood, New Jersey, which has experienced a catastrophic failure on December of 2018 while in service.

BACKGROUND INFORMATION

The prestressed concrete cylinder pipe sample was taken from buried pipeline reportedly laid in October 1974. Prestressed concrete cylinder pipe failed on 12/14/18 while in service. No indication pipe was going to fail until it did, which was catastrophic to the pipe. Pipe was buried approximately 5 feet underground. After the failure, the pipe was stored outside in a utility yard for one month before samples were collected. Figure 1 shows portion of the failed pipe, particularly brown corrosion products at the failed portion.

METHODOLOGIES

The mortar-coating sample was tested by using the following ASTM methods (a brief description of each method is provided; detailed procedures can be found in the ASTM):



Figure 1: Shown are the failed pipe in the field (top), and the removed failed portion of pipe (bottom). Notice severe brown corrosion products at the failed portion of the pipe.

1. Petrographic Examinations, by using the methods of ASTM C 856, "Standard Practice for Petrographic Examination of Hardened Concrete." Steps followed in Petrographic Examinations include:

- Detailed visual examinations of the sample, as received;
- Collecting conditions of as-received photographs with a digital camera and/or a flat-bed scanner;
- Low-power stereomicroscopic examinations of saw-cut and freshly fractured sections of the mortar for evaluation of texture, composition, and air-void system;
- Examinations of oil immersion mounts for special features and materials from the mortar in a petrographic microscope;
- Examinations of blue dye-mixed epoxy-impregnated thin section of mortar in a petrographic microscope for detailed compositional and microstructural analyses (details of sample preparation techniques are given in Jana, 2006);
- Photographing sample, as received and at various stages of preparation with a digital camera and a flatbed scanner;
- Photomicrographs of lapped sections and thin sections of samples taken from stereomicroscope and petrographic microscope, respectively to provide detailed compositional and mineralogical information.
- A Nikon Eclipse 600 POL petrographic microscope attached to a Jenoptik Progres GRYPHAX high-resolution digital camera were used for petrographic examinations and collecting photomicrographs of thin sections of samples (Figure 2). A Nikon SMZ-10A stereomicroscope (Figure 2) and an Olympus SZH stereomicroscope were used for examinations of fresh fractured and lapped sections and transmitted-light examinations of thin section, respectively.

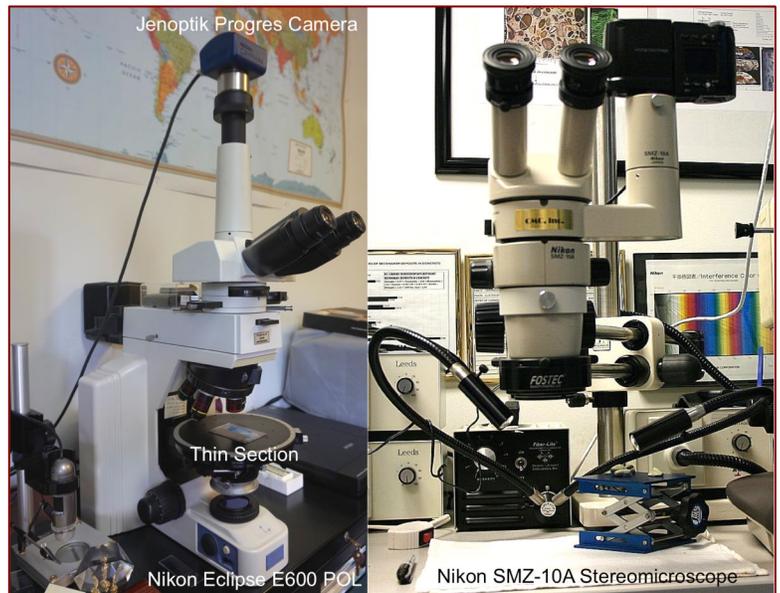


Figure 2: Nikon Eclipse E600POL Petrographic Microscope with Jenoptik Gryphax Camera and Nikon SMZ-10A Stereomicroscope used for petrographic examinations.

2. Acid-Soluble Chloride Contents, by using the methods of ASTM C 1152, "Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete." Steps followed in chloride analysis include:

- Sample Selection and Sectioning – A representative portion of the mortar coating was selected from each sample, and, cross-sectioned to expose a through-depth sectioned interior of the pipe. Approximately one-third portions of the total thickness of the coating was marked from the exposed end, mid-depth location, and bottom end (i.e. the prestressing wire side) on the crossed section to be further slice into the top, middle, and bottom slices of the pipe section, each representing one-third the thickness of the pipe. Chloride contents were thus determined from the top, mid-depth, and bottom ends after crushing and pulverizing the sectioned slices in a tungsten carbide ring & puck within a vibratory mixer/mill (shatterbox) for a few seconds to pulverize the mass down to pass US No. 20 sieve.
- Acid Digestion – About 10±0.01 gm. of powdered sample was measured and dispersed with 75-mL water in a 250-mL beaker; immediately 25 mL dilute (1+1) nitric acid (HNO₃) was slowly added, stirring and breaking up any lumps with a glass rod. In case of hydrogen sulfide smell, a 3 mL of H₂O₂ (30%) was added. Then 3 drops of methyl orange indicator was added to the beaker and stirred.
- Further Digestion in Boiling Acid – Covered the beaker from previous step with a watch glass, allowed to stand for 1-2 min. Then a few drops of HNO₃ (1+1) were added until a faint pink or red color persisted in the solution above the settled solid. Then 10 additional drops of nitric acid was added and stirred. Then the covered mixture in the beaker was heated rapidly to boiling, but not more than a few seconds. Removed from hot plate.

- Filtration – Filtered the sample solution, under suction, through a washed No. 41 coarse-textured filter paper fitted to a Buchner funnel in a 500-mL filtration flask. Transferred the filtrate from the flask to the original beaker, which was already rinsed twice with water, along with the flask. Cooled the filtrate to room temperature. The volume was < 175-mL.

- Preparation for Titration – To the cooled filtrate, carefully pipetted 2-mL standard 0.05N NaCl. The solution was transferred from the beaker to the sample cup for automated titration. Each sample cup either contained a magnetic stirring rod for stirring, or, received a stirrer from the auto-sample-changer/holder during titration. A Metrohm DMS 751

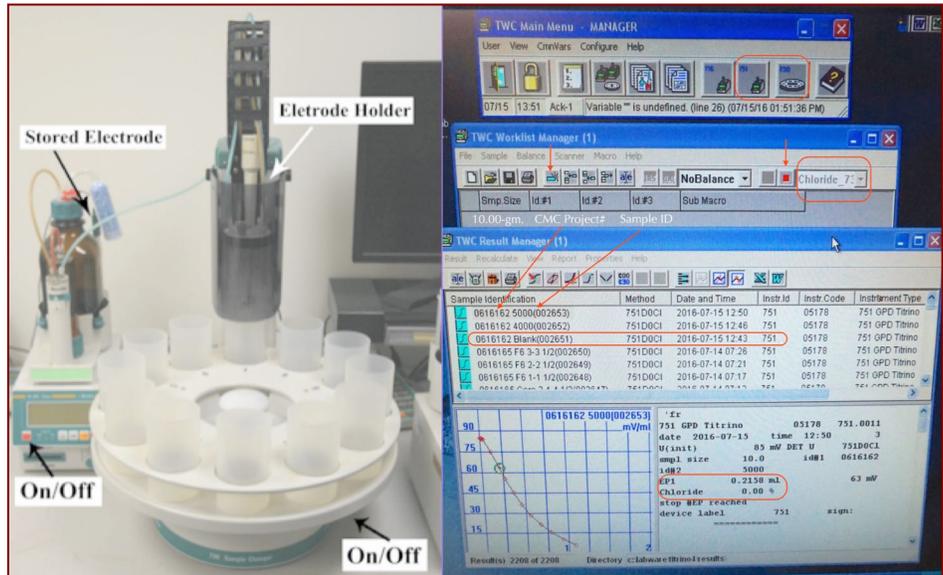


Figure 3: Determination of chloride contents by automated titration with Metrohm DMS 751 Titrino and attached Titrino 730 auto-sample changer (left). Results are displayed in Brinkmann Metrohm Titrino Workshell software (right).

Titrino Automated Titrator equipped with a Titrino 730 Auto-sample-changer was used for simultaneous titration of three sections per sample of mortar coating. The chloride combination electrode was immersed into the sample solution, along with the stirrer, and delivery tip of the AgNO₃ dispenser (to dispense 0.05N standard AgNO₃ solution) all from the 730 auto-sampler to each sample solution.

- Automatic titration was monitored by Brinkman Metrohm Titrino Workshell software running in Windows PC attached to the DMS 751 Titrino to accurately record the equivalent point of titration. Blank samples having known chloride contents were run before and after running the samples.
 - Percent chloride by mass of mortar coating to the nearest 0.001% is determined from CL, % = 3.545 [(V1-V2)N]/W, where V1 = milliliters of 0.05 N AgNO₃ solution used for sample titration (equivalent point), V2 = Milliliters of 0.05N AgNO₃ solution used for blank titration (equivalent point); N = exact normality of 0.05 N AgNO₃ solution, and W = mass of sample in grams. This equation is equivalent to % chloride = (equivalent point from titration times 0.177) divided by sample weight in grams.
3. Density, Absorption, Specific Gravity, and Volumes of Permeable Voids, by using the methods of ASTM C 642, "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." Steps followed include:
- Selection of a representative portion of the mortar coating and sectioning into 3 to 4 small 1-in. cube-size pieces.
 - Obtaining oven-dry constant mass after drying the samples for 24 hours at 100-110°C in a laboratory oven, then cooling it down to the ambient temperature, and recording the oven-dried weight, A;
 - Obtaining saturated weight after immersing the samples in approximately 21°C water, overnight, followed by surface drying, and recording saturated surface dry (SSD) weight, B;
 - Obtaining saturated weight after boiling for five (5) hours; removing surface moisture with a towel; and recording saturated weight after boiling, C;
 - Obtaining immersed weight of sample while completely immersed in water, D;
 - From the above four weights, A through D, Calculating the following
 - a. Absorption After Immersion, % = 100×[(B-A)/A]
 - b. Absorption After Immersion & Boiling, %=100×[(C-A)/A]
 - c. Bulk Specific Gravity, Dry =A/(C-D)=G₁
 - d. Bulk Specific Gravity, After Immersion = B/(C-D)
 - e. Bulk Specific Gravity, After Immersion & Boiling = C/(C-D)
 - f. Apparent Specific Gravity = A/(A-D)=G₂
 - g. Volume of Permeable Pore Space (Voids) % =100× [(G₂-G₁)/G₂] = 100× [(C-A)/(C-D)]



SAMPLE

Figure 4 shows condition of the mortar coating sample, as received in multiple pieces. The largest piece measures $13\frac{1}{2}$ in. \times 11 in. \times $\frac{9}{16}$ in. (350 mm \times 280 mm \times 14 mm). Nominal thickness of individual pieces varies from 10 to 20 mm.

The mortar coating shows rough, convex, severely weathered, carbonated, and altered exposed outside surface that contains numerous fine parallel cracks to depths of 2 to 5 mm from the exposed scaled/exfoliated surface indicating continuing scaling or exfoliation of pipe from the exposed surface downwards with progressive deterioration that has eventually led to the reported failure.

These exposed surface-parallel microcracks are best seen on the as received and lapped cross sections of pipe pieces in Figures 5 and 8, respectively. These parallel microcracks have reduced the overall thickness of the pipe to the point of failure.

As opposed to the top half of the pipe thickness, the bottom half i.e. from the interior body down to the wire cast surface region is relative sound and free of any cracking (Figures 7 and 9). There are, however, many fine to coarse voids and interstitial spaces between aggregate particles that are best seen in microstructures in Figures 9, 13, and 14.

The inside of the wire cast surfaces are concave, fresh fractured, having partial impressions of prestressing wires as parallel wire cast surfaces showing trace remains of reddish-brown corrosion products (Figures 4 and 6).

The inside wire cast surfaces (Figures 4 and 6) show impressions of $\frac{1}{8}$ in. diameter prestressing wires at $1\frac{1}{4}$ -in. center-to-center distances (Figures 4 and 6), and have $\frac{1}{16}$ in. thick neat pastes at the wire cast surfaces.

The wire cast surfaces are smooth, shiny, medium gray, and have lower water-cement ratio (w/c) than that in the body (w/c is estimated to be less than 0.40 in the $\frac{1}{16}$ in. of the neat pastes of wire cast surfaces as opposed to 0.40 to 0.45 in the body, discussed later).



Figure 4: The mortar coating sample, as received in multiple pieces, showing: (i) the severely weathered exposed surfaces in the top and middle left photos, (ii) the fresh fractured interior surfaces having impressions of the prestressing wires in the top and middle right photos, and (iii) side views of the coating in the bottom photos.

PETROGRAPHIC EXAMINATIONS

EXPOSED SURFACE



Figure 5: Rough, convex, severely weathered, carbonated, and altered exposed outside surface that contains numerous fine parallel cracks to depths of 2 to 5 mm from the exposed scaled/exfoliated surface indicating continuing scaling or exfoliation of pipe from the exposed surface downwards with progressive deterioration that has eventually led to the reported failure. Arrows show incipient scales that have reduced the overall thickness of the pipe.

WIRE CAST SURFACES

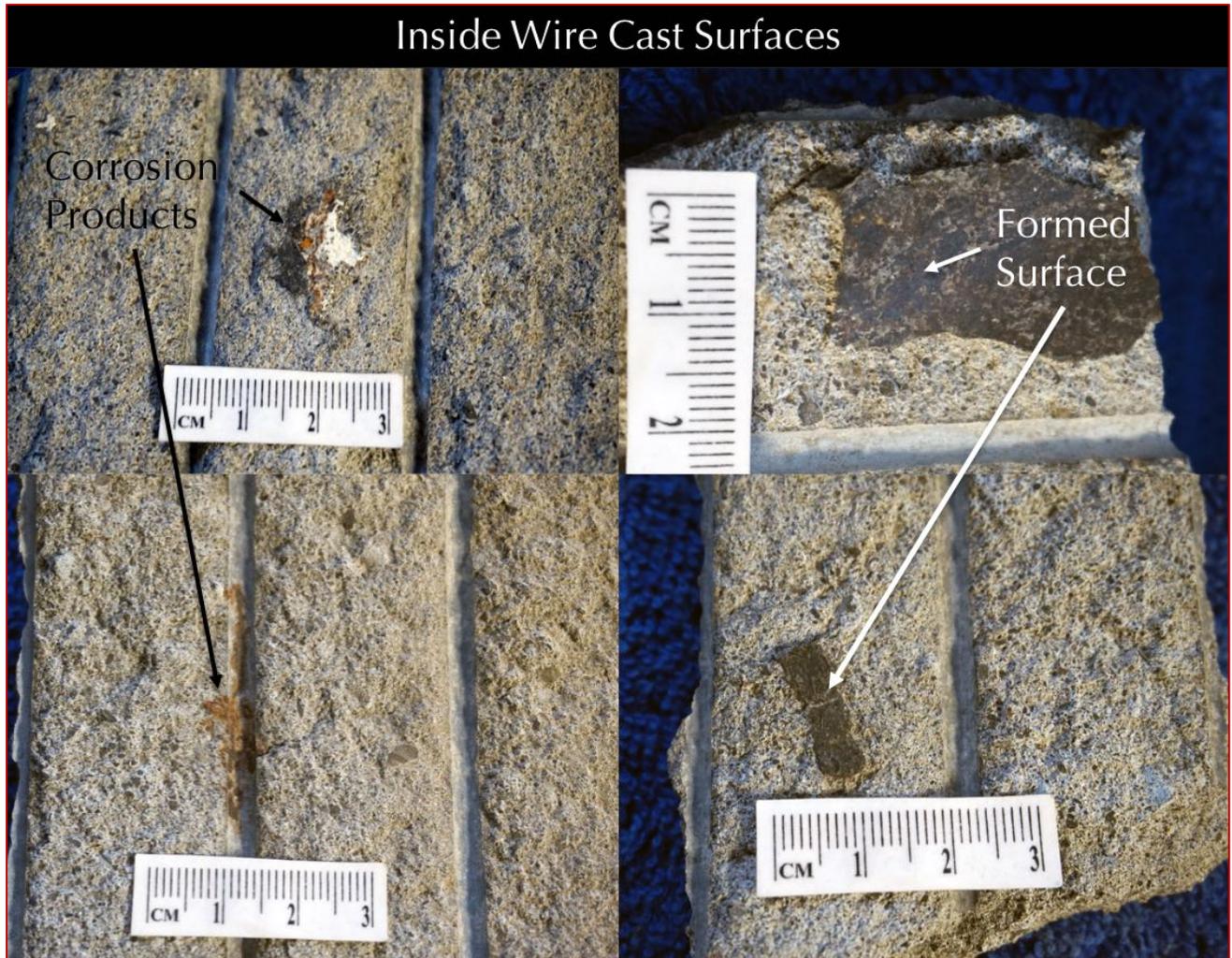


Figure 6: Fresh fractured interior and parallel wire cast surface of pipe showing corrosion products of prestressing wires. The inside wire cast surfaces showing impressions of $\frac{1}{8}$ in. diameter prestressing wires at $1\frac{1}{4}$ -in. center-to-center distances, and have $\frac{1}{16}$ in. thick neat pastes at the wire cast surfaces. The wire cast surfaces are smooth, shiny, medium gray, and have lower water-cement ratios (w/c is estimated to be less than 0.40 to 0.45 in the $\frac{1}{16}$ in. of the neat pastes of wire cast surfaces).

LAPPED CROSS SECTIONS

Figure 7 shows lapped cross sections of mortar coating where the leftmost figure shows two long coating and middle and right photos show enlarged portions of the lapped cross section from the left photo.

All photos show natural siliceous-argillaceous-calcareous sand aggregates, well-graded, well-distributed, Portland cement paste, altered cracked nature of the exposed surface region and sound nature of interior fresh fractured surface region, wire cast surfaces (boxed in middle and right photos).

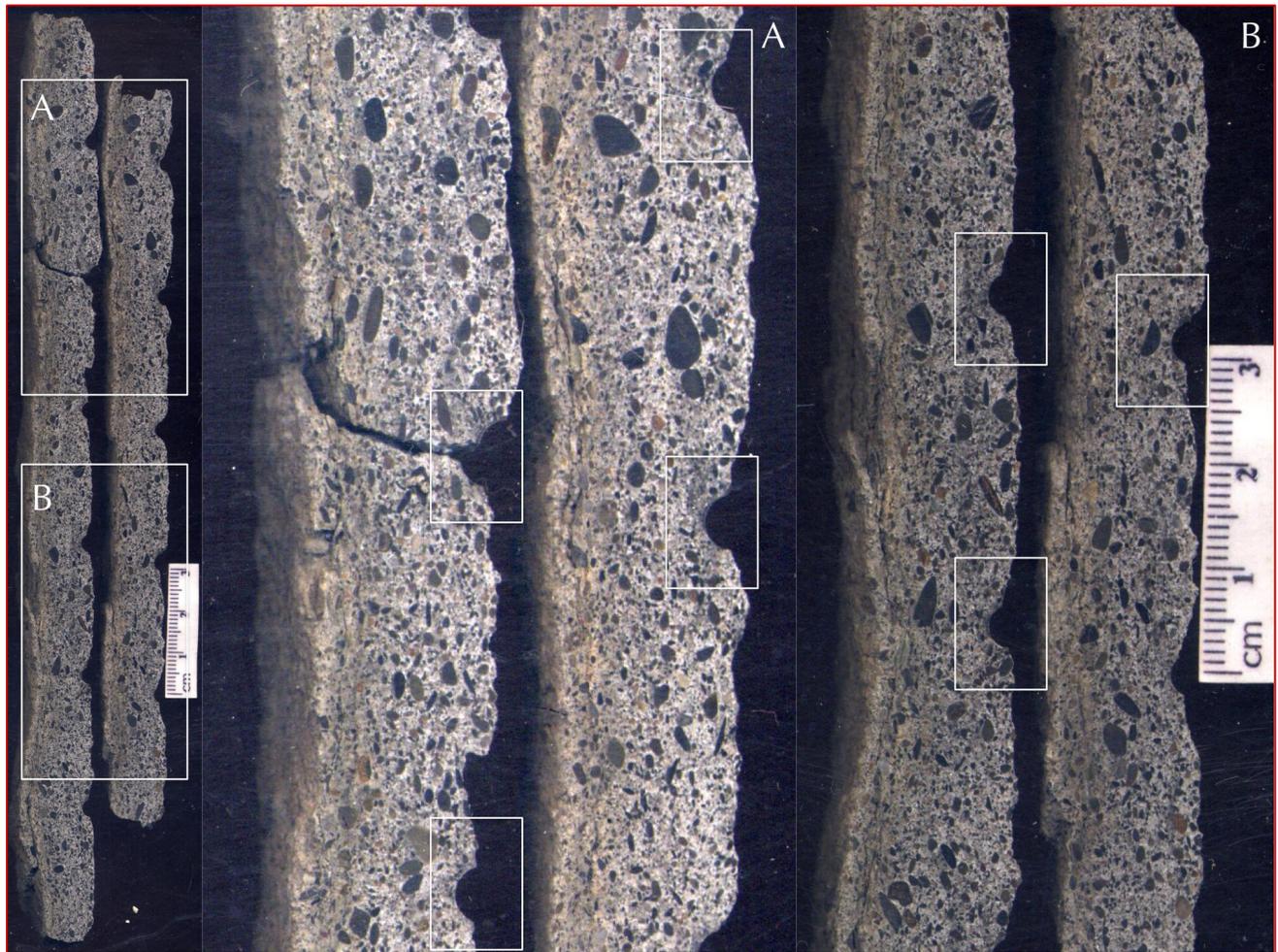


Figure 7: Lapped cross sections of pipe showing natural siliceous-argillaceous-calcareous sand aggregates, well-graded, well-distributed, Portland cement paste, altered cracked nature of the exposed surface region and sound nature of interior fresh fractured surface region, wire cast surfaces.

PHOTOMICROGRAPHS OF LAPPED CROSS SECTIONS

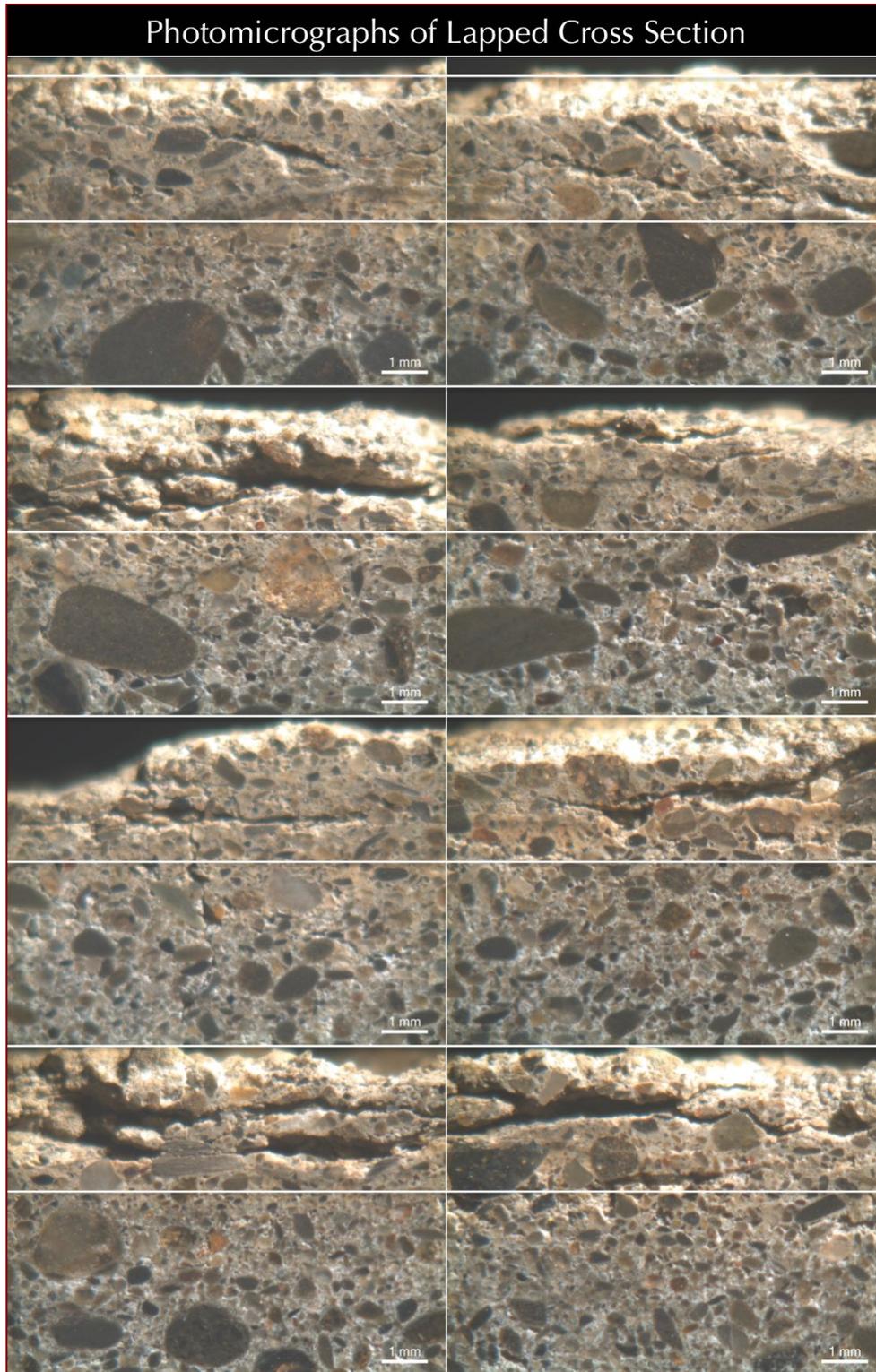


Figure 8: Photomicrographs of lapped cross section of mortar coating showing the deteriorated soft, fragile, leached light-toned and cracked paste at the exposed surface region having parallel cracks (boxed) at the top 2 to 5 mm depth from the exposed surface and relatively sound coating beneath the deteriorated portion in the boxed areas.

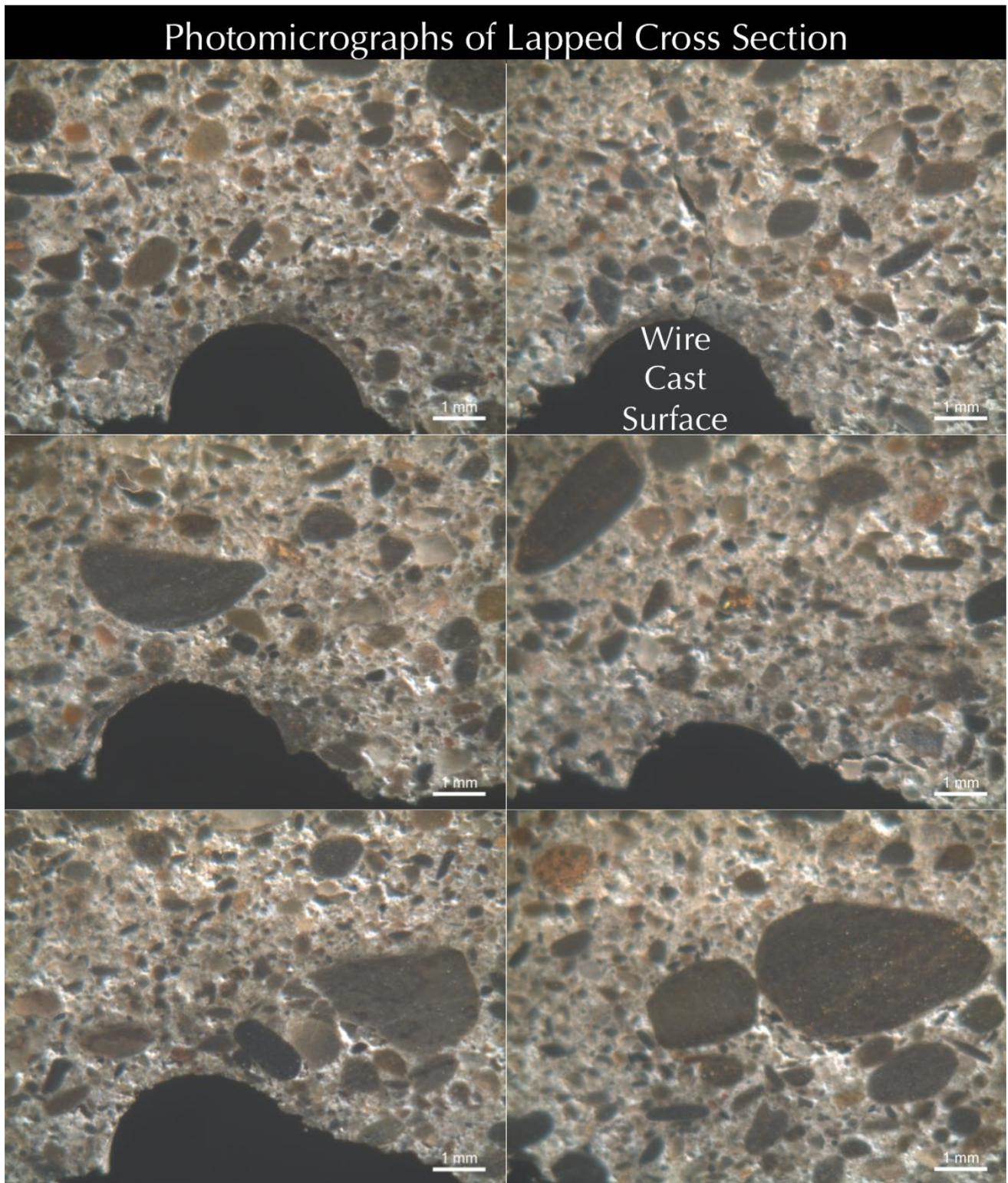


Figure 9: Photomicrographs of lapped cross section of mortar coating from the mid-depth to bottom fresh fractured and wire cast surface region showing relatively sound condition of coating that is free of any cracking as seen at the exposed surface region. Notice neat paste darker gray in color than the body in the wire cast surface region.

THIN SECTIONS

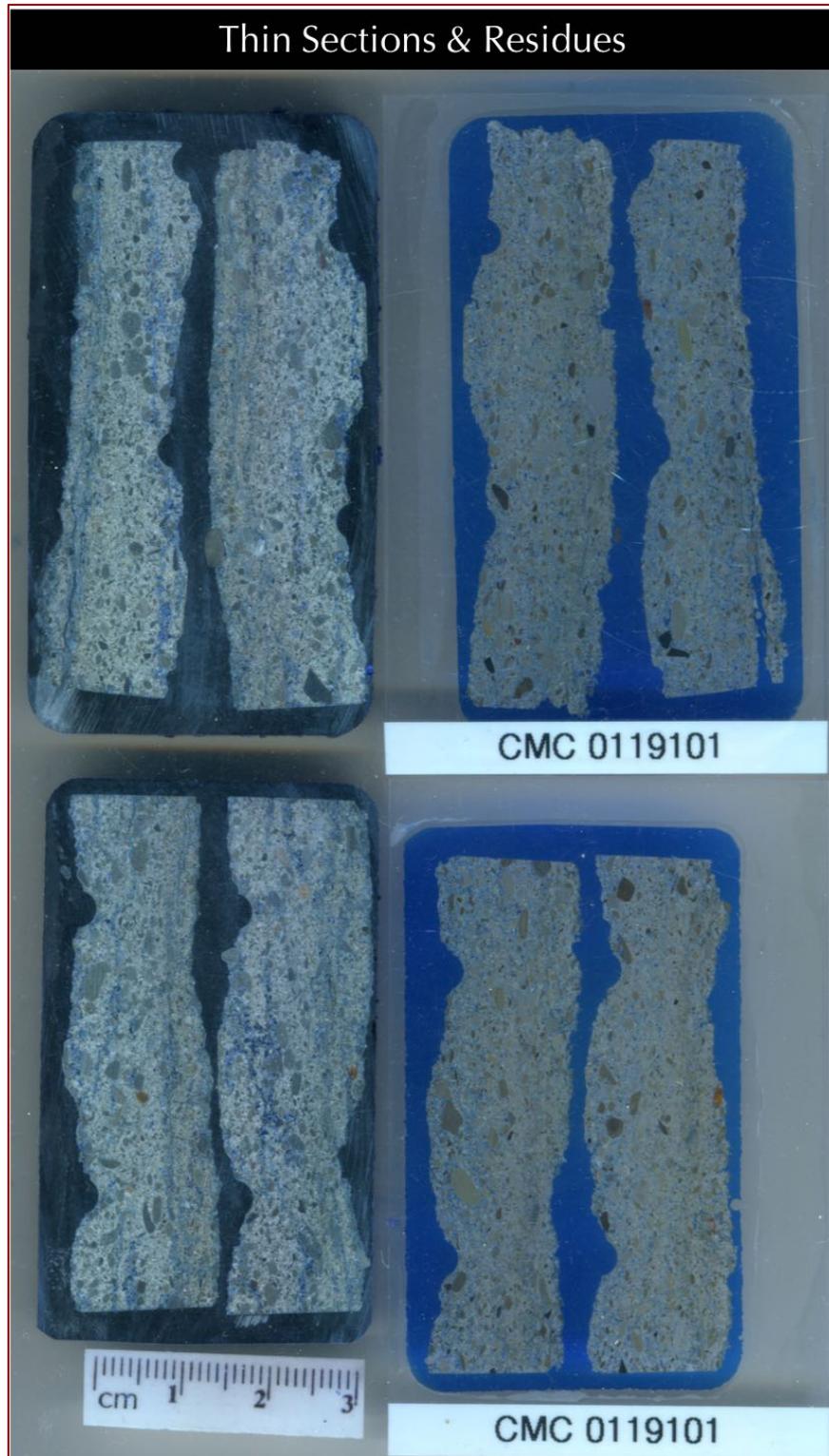


Figure 10: Blue dye-mixed epoxy-impregnated thin sections of mortar coating and corresponding residues from thin section preparation. Thin sections show deep absorption of blue epoxy due to high inherent porosities from interstitial voids and paste.

MICROSTRUCTURES OF PCCP

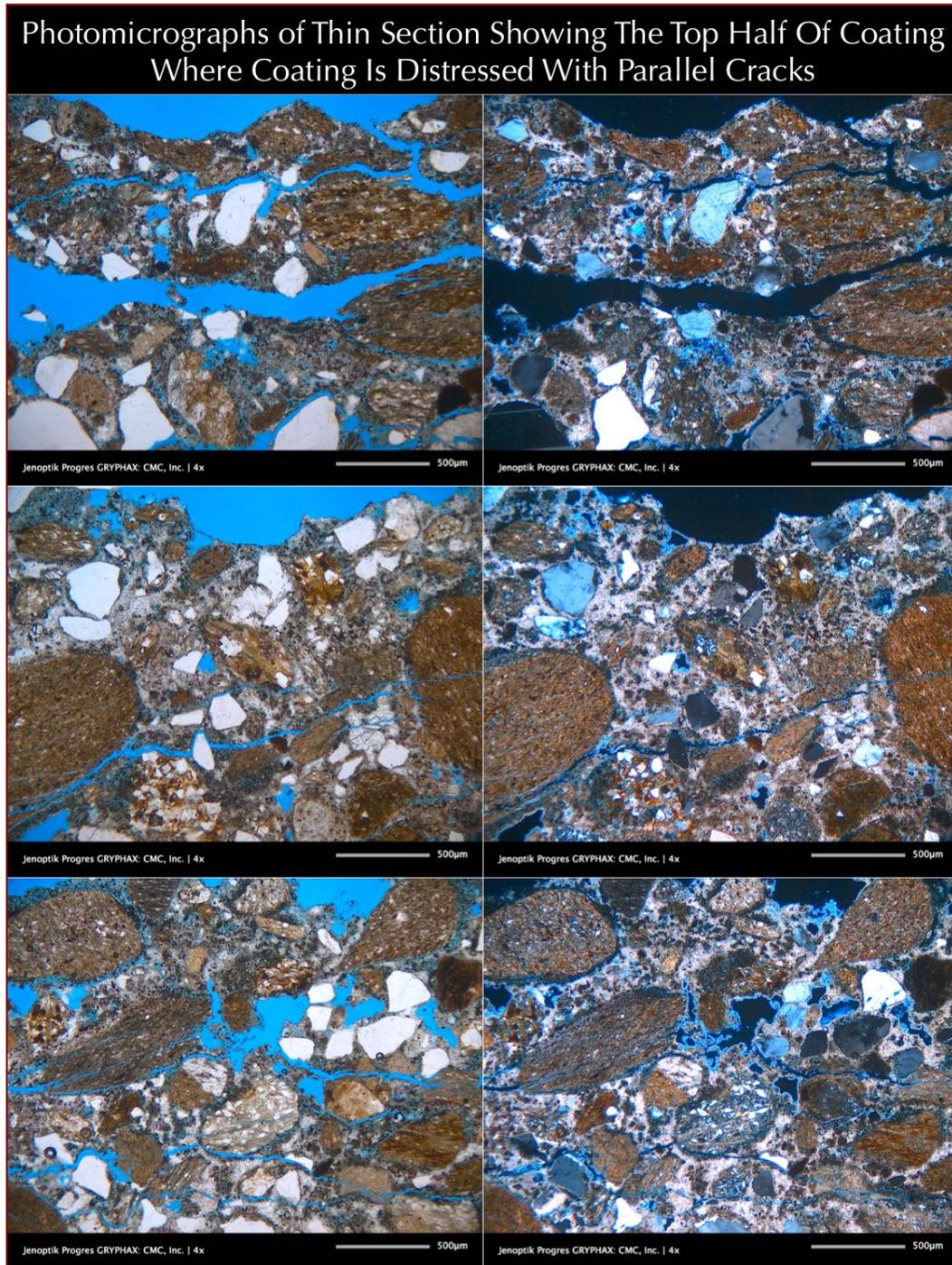


Figure 11: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of mortar coating showing: (a) severe cracking and deterioration of exposed surface region where parallel cracks are highlighted by blue epoxy; (b) natural argillaceous-siliceous-calcareous sand consisting of major amounts of rounded and subrounded shale and other argillaceous rocks, and subordinate amounts of rounded and subrounded quartz, quartzite, and minor amounts of carbonates (limestone); (c) overall porous and carbonated nature of paste from the altered exposed surface region at the top 2 to 5 mm where interstitial void spaces are filled with secondary calcium carbonate deposits.

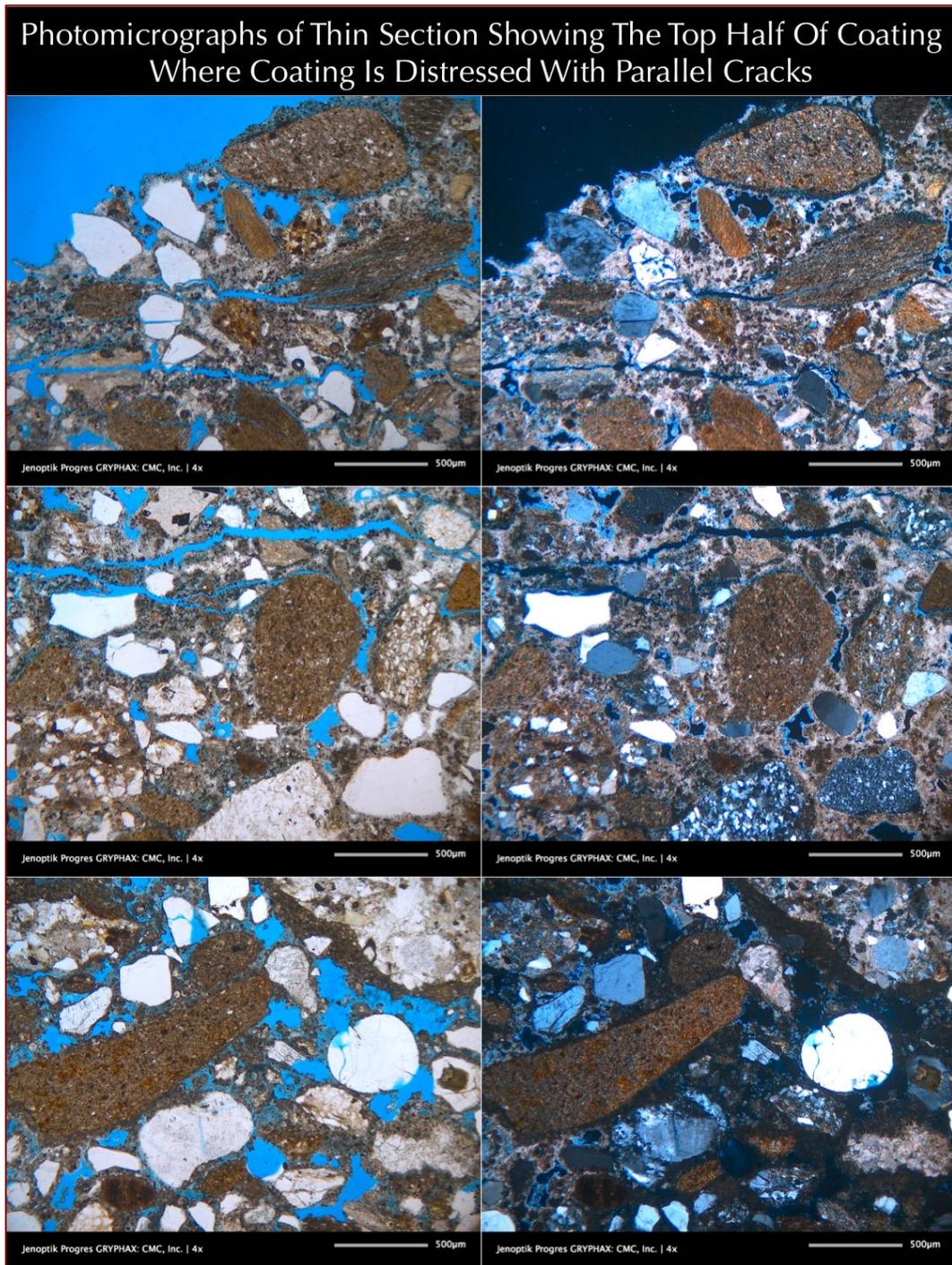


Figure 12: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of mortar coating showing: (a) severe cracking and deterioration of exposed surface region where parallel cracks are highlighted by blue epoxy; (b) natural argillaceous-siliceous-calcareous sand consisting of major amounts of rounded and subrounded shale and other argillaceous rocks, and subordinate amounts of rounded and subrounded quartz, quartzite, and minor amounts of carbonates (limestone); (c) overall porous and carbonated nature of paste from the altered exposed surface region at the top 2 to 5 mm where interstitial void spaces are filled with secondary calcium carbonate deposits. The bottom row shows interior coating beneath the cracked and carbonated surface region, where paste is not carbonated but porous due to the presence of many void spaces highlighted by blue epoxy.

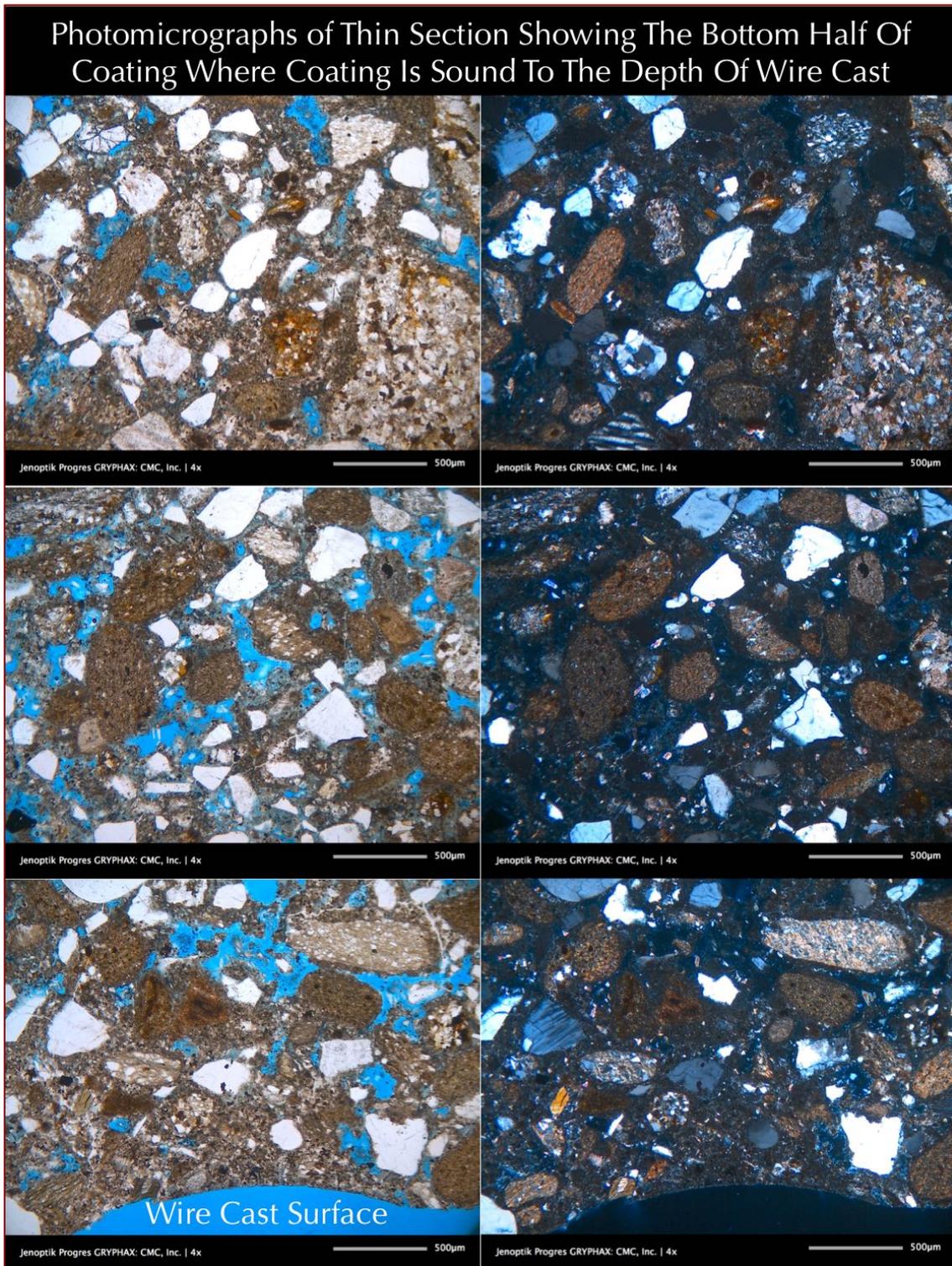


Figure 13: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of mortar coating from the interior down to the fresh fractured and wire cast surface region showing many pore and void spaces between sand particles highlighted by blue epoxy, natural sand having major amount of shale and other argillaceous rocks, dense neat paste at the wire cast surface region (bottom row) and lack of carbonation of paste in the bottom half of the coating that is so prominent at the top 5 mm of the exposed surface region seen in Figures 11 and 12.

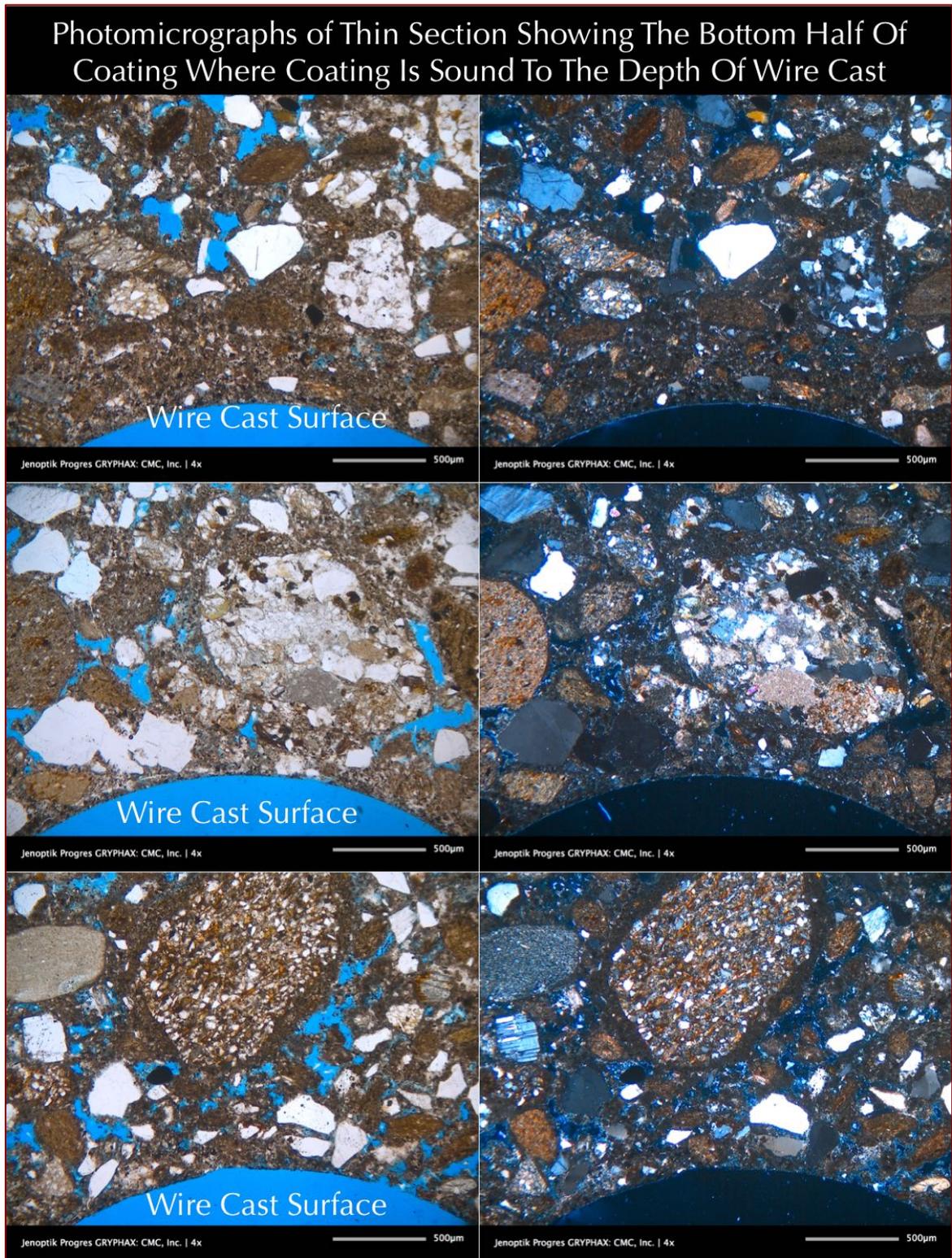


Figure 14: Photomicrographs of blue dye-mixed epoxy-impregnated thin section of mortar coating from the interior down to the fresh fractured and wire cast surface region showing many pore and void spaces between sand particles highlighted by blue epoxy, natural sand having major amount of shale and other argillaceous rocks, dense neat paste at the wire cast surface region (bottom row) and lack of carbonation of paste in the bottom half of the coating that is so prominent at the top 5 mm of the exposed surface region seen in Figures 11 and 12.



AGGREGATES

The mortar coating contains natural sand aggregates having major amounts of rounded to subrounded shale and other argillaceous rocks, subordinate amounts of siliceous particles of quartz, quartzite, feldspar, and minor amount of calcareous (limestone) particles all having nominal maximum sizes of 2 mm. All sand particles are well-graded, well-distributed, and have been sound during their service in the coating. Presence of major amount of shale in the sand (Figures 11 to 14), however, indicates potential physical unsoundness of coating from potential absorption of moisture by shale and subsequent expansion.

PASTE

The interior portions of the coating contains Portland cement paste, which is variably porous, severely carbonated at the top 2 to 5 mm of the exposed surface region, moderately soft to soft at the top 2 to 5 mm to moderately hard to hard at the bottom half, light gray to beige at the top 2 to 5 mm to medium gray at the bottom half, well-consolidated in the portion beneath the altered and cracked surface region. Water-cement ratio of coating in the sound portion is judged to be from 0.40 to 0.45 and less than 0.40 in the $\frac{1}{16}$ in. thick neat pastes at the wire cast surfaces.

AIR

Air occurs as irregularly shaped voids having nominal sizes up to 3 mm that are characteristic of entrapped voids including interstitial voids in between the sand particles. The mortar coating is non-air-entrained having air content estimated to be 6 to 8 percent, which are all entrapped air voids in between the sand particles.

CONDITION OF WIRE CAST SURFACES

Wire cast surfaces show occasional reddish-brown corrosion products of prestressing wires, which from severe carbonation of paste at the top 2 to 6 mm as seen in thin section photomicrographs along with high chloride content determined later are judged to be carbonation-induced loss of alkalinity of the coating and subsequent carbonation of prestressing wires as well as chloride-induced corrosion of prestressing wires.

CHLORIDE ANALYSES

Portions of the coating sample were sectioned from top exposed surface region, interior mid-depth region, and wire cast surface region, oven-dried, pulverized, and used for chloride analyses by following the methods described in the Methodology section (*a la* ASTM C 1152). Results of bulk chloride contents (acid-soluble) at the top, middle, and bottom sections of coating are given in the following Table 2 and in Figures 15 and 16.



Location (inches from top)	Percent Chloride by Mass of Sample	Percent Chloride by Mass of Cement (% Chloride by Mass of Sample/0.15)	% Chloride PPM (% Chloride by Mass of Sample x 10000)	Equivalent Flake Calcium Chloride (% Chloride by Mass of Cement x 2.07)
Top Exposed Surface Region	0.006	0.043	65	0.01
Interior Mid-depth location	0.199	1.328	1992	0.41
Wire cast bottom surface region	0.299	1.994	2991	0.62

Table 1: Acid-soluble chloride contents of mortar coating samples from the altered top exposed surface end, the mid-depth location, and, the bottom prestressing wire end. Percent chloride by mass of cement in the 2nd column is determined by assuming a 15 percent cement content in the coating, which would change depending on the actual cement content in the mortar [percent chloride by mass of cement = percent chloride in the coating divided by 0.15, if mortar contains 15 percent cement, and so on].

Results show negligible chloride content at the top exposed surface region due to leaching of chloride but high chloride content in the mid-depth and wire cast surface region indicating penetration of chloride from the environment, which has caused corrosion of prestressing wires and resultant corrosion products seen in the failed portion of pipe in field photos.

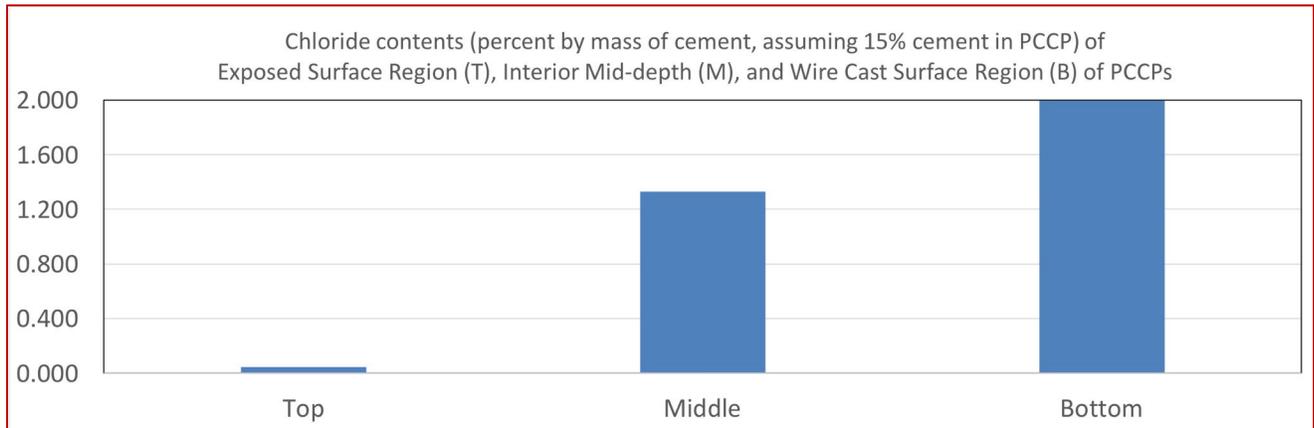


Figure 15: Acid-soluble chloride contents of coatings in relation to threshold chloride level of 0.2 percent needed to initiate chloride-induced corrosion of prestressing wires in the presence of oxygen and moisture. Top exposed surface region showed negligible chloride due to leaching whereas mid-depth and wire cast surface region showed high chloride contents indicating potential chloride-induced corrosion of prestressing wires.

The minimum threshold chloride content to initiate corrosion of prestressing wires in the presence of oxygen and moisture is somewhere in the range of 0.15 to 0.20 percent chloride i.e. by mass of cement. Chloride contents at the mid-depth and wire cast surface region are significantly higher than this threshold limit of corrosion. Therefore, chloride content is determined to be higher than the minimum chloride needed to trigger the corrosion of wires in the presence of both oxygen and moisture.

Figure 16 shows plots of millivolts versus milliliters of silver nitrate solutions during potentiometric titration of acid-soluble chloride from coatings in Metrohm DMS Titrino 751 and the equivalence points of titration (circled on the



plots in the graphs) at the steepest slope that was used in calculations of chloride contents of coating [% chloride = (Equivalent point times 0.177) divided by sample weight in grams].

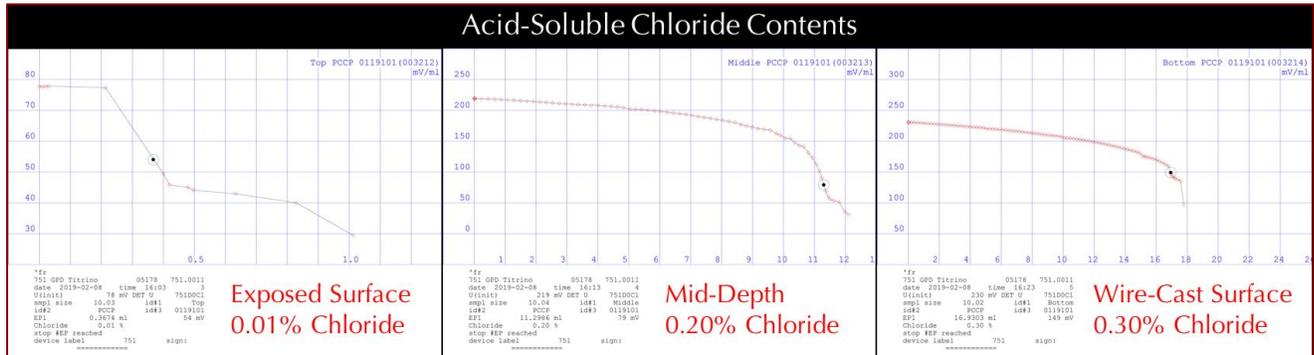


Figure 16: Plots of millivolts versus milliliters of silver nitrate solutions during titration in Metrohm DMS Titrino 751 and the equivalence points of titration (circled on the plots in the graphs) at the steepest slope that was used in calculations of chloride contents of coating [% chloride = (Equivalent point times 0.177) divided by sample weight in grams].

ABSORPTION, DENSITY, VOLUME OF PERMEABLE VOIDS

Sample	Absorption After Immersion (%)	Absorption After Boil (%)	Bulk Specific Gravity Dry	Bulk Specific Gravity After Immersion	Bulk Specific Gravity After Boil	Apparent Specific Gravity	Volume Permeable Voids (%)
1	7.77	6.80	2.21	2.38	2.36	2.60	15.03
2	10.10	9.70	2.21	2.44	2.43	2.82	21.48
3	16.74	14.93	2.08	2.43	2.39	3.02	31.07
Average	11.54	10.47	2.17	2.42	2.39	2.81	22.53
St. Dev.	4.66	4.12	0.08	0.03	0.03	0.21	8.07

Table 2: Absorptions after immersion in cold and boiling waters, bulk specific gravity in dry condition and while immersed in water, apparent specific gravity, and volumes of permeable voids in the mortar coating. Methods of calculations of data in each column are described in the ‘Methodology’ section.

Contrary to average cold-water absorption values of 11.5 percent, boiling-water absorption is low due to loss of paste during boiling water immersion of coating indicating the inherently deteriorated condition. Volume of permeable voids is high indicating deep penetration of elements as seen in chloride contents. The cold and boiling water absorptions as well as the volume of permeable voids are all consistent with an overall porous nature of coating that has facilitated chloride penetration down to the depth of prestressing wires to cause corrosion of wires. Additionally, alteration and exfoliated cracking of coating at the top 2 to 5 mm of the exposed surface region as seen in petrographic examinations has caused loss of thickness of coating down to the point of failure.



CONCLUSIONS

Microstructural, chemical (chloride), and physical (absorption) tests showed an inherently porous coating that was contaminated with chloride from the environment during service to cause corrosion of prestressing wires, and has caused alteration and severe parallel microcracking and exfoliation at the top 2 to 5 mm of the exposed surface region to cause loss of the coating thickness down to the point of failure.

REFERENCES

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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.