Investigation of the Long Term Effects of Magnesium Chloride and Other Concentrated Salt Solutions on Pavement and Structural Portland Cement Concrete

Project Number: SD2002-01

Submitted by:

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Quarterly Report

Overview

This Quarterly Report is submitted to outline the work accomplished during the reporting period 1-15-05 to 4-15-07, identify problems (current and anticipated), and to describe any deviations from the agreed Work Plan. This Quarterly Report is arranged by the Tasks described in the project Work Plan. Tasks not listed have been completed and the details of each can be found in previous reports. The following is a summary of results for this reporting period.

- Examination of field samples has been completed including chloride profiling.
- Analytical methods to evaluate deterioration of laboratory specimens (other than microscopy) have been examined.
- Chloride profiling of laboratory specimens continues.
- Work at the University of Toronto measuring diffusivity, sorptivity, and permeability of specimens from Task 6 has been completed.

Task Report

Task 5: Characterization of Field Specimens

The analysis of field cores has been completed and the results are presented below. An important part of this process was the determination of the effective water/cement ratio and determination of the chloride profiles for these pavements. A brief description of the analytical methods used to determine these properties is provided prior to the discussion of the individual sites. This work completes Task 5.

Brief description of w/c ratio determination methodology

A set of three mortar cylinders were cast with w/c ratios of 0.40, 0.50, and 0.60, and moist cured for 28 days. The cylinders were cut into billets, and the billets impregnated with epoxy resin spiked with a fluorescent dye (DayGlo Tigris Yellow D-043 solvent yellow 43 added at a dosage of 0.5 wt% to Epoxy Technologies EPO-TEK 301 resin). The impregnated billets were prepared in thin section, and images collected in epifluorescent mode with an Olympus BX-60 System Microscope equipped with an Optronics DEI-750 CCD video camera. The G-band was extracted from each 640 x 480 pixel, 2.612 x 1.959 mm, 24 bit, RGB image, and the fine aggregate and air voids manually masked to isolate fluorescence due to the uptake of the dyed resin into the capillary pores of the hardened cement paste. Figures A-1 through A-6 show images collected from each of the standards both before and after the masking operation. Figure A-7 compares histograms of cement paste fluorescence from the standards. The average intensity from each masked image was used as measurement of cement paste fluorescence, as summarized in Table A-1, and used to develop the calibration curve shown in Figure A-8. This calibration curve was applied to measurements collected from field concrete samples to yield equivalent w/c values as compared to the 28 day moist cured mortar standards. For more detailed treatments of epifluorescent microscopy and its application to w/c estimation, the following references are suggested:

Walker, H. N., and Marshall, B. F., "Methods and Equipment Used in Preparing and Examining Fluorescent Ultrathin Sections of Portland Cement Concrete" *Cement, Concrete, and Aggregates*, Vol. 1, No. 1, 1979, pp. 3-9.

J. Elsen, N. Lens, T. Aarre, D. Quenard, V. Smolej, "Determination of the w/c ratio of hardened cement paste and concrete samples on thin sections using automated image analysis techniques" *Cement and Concrete Research*, Vol. 25, No. 4, 1995, pp. 827-834.

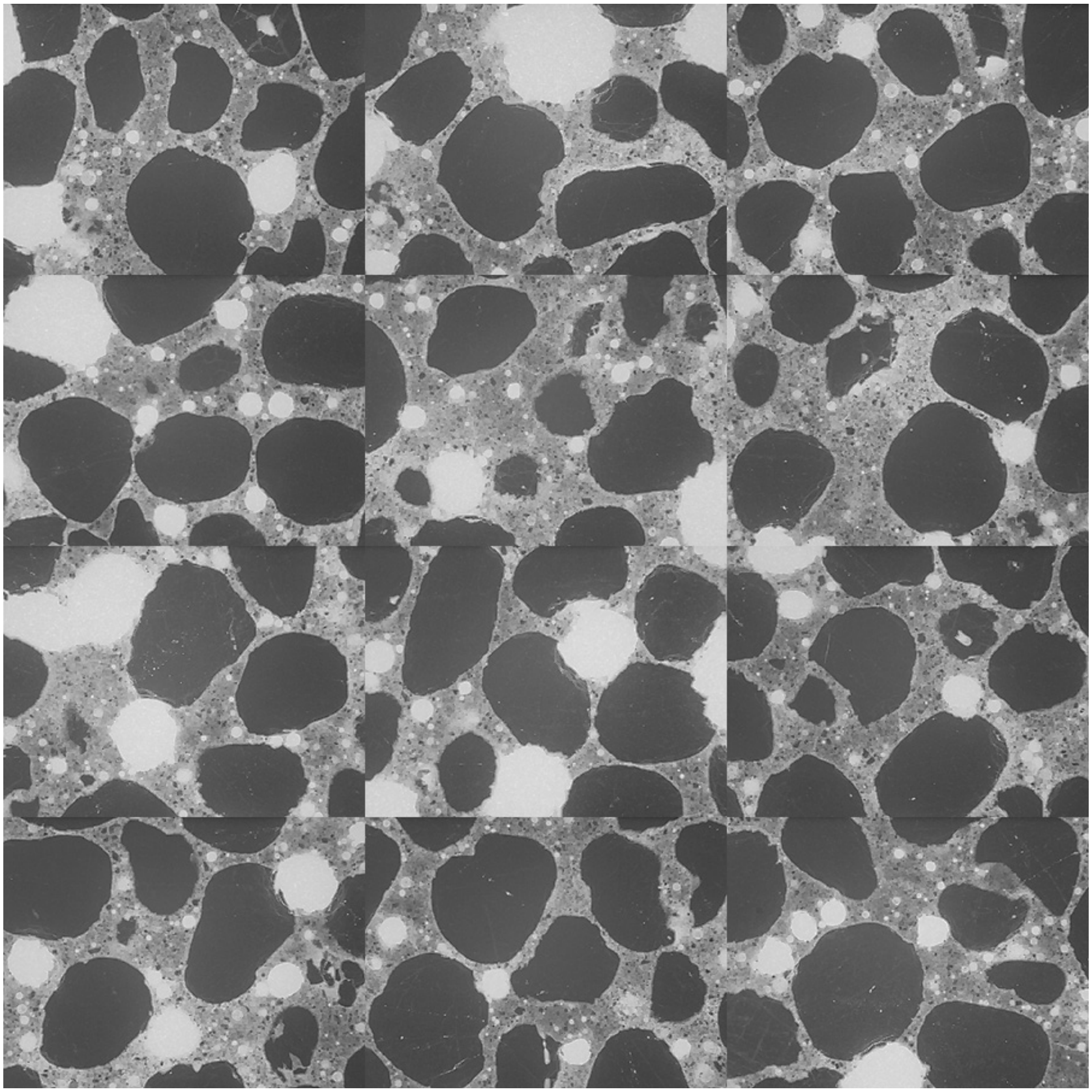

Figure A-1: Mosaic of 12 frames collected from 0.40 w/c 28 day moist cured mortar standards (each individual frame measures 2.612 x 1.959 mm).

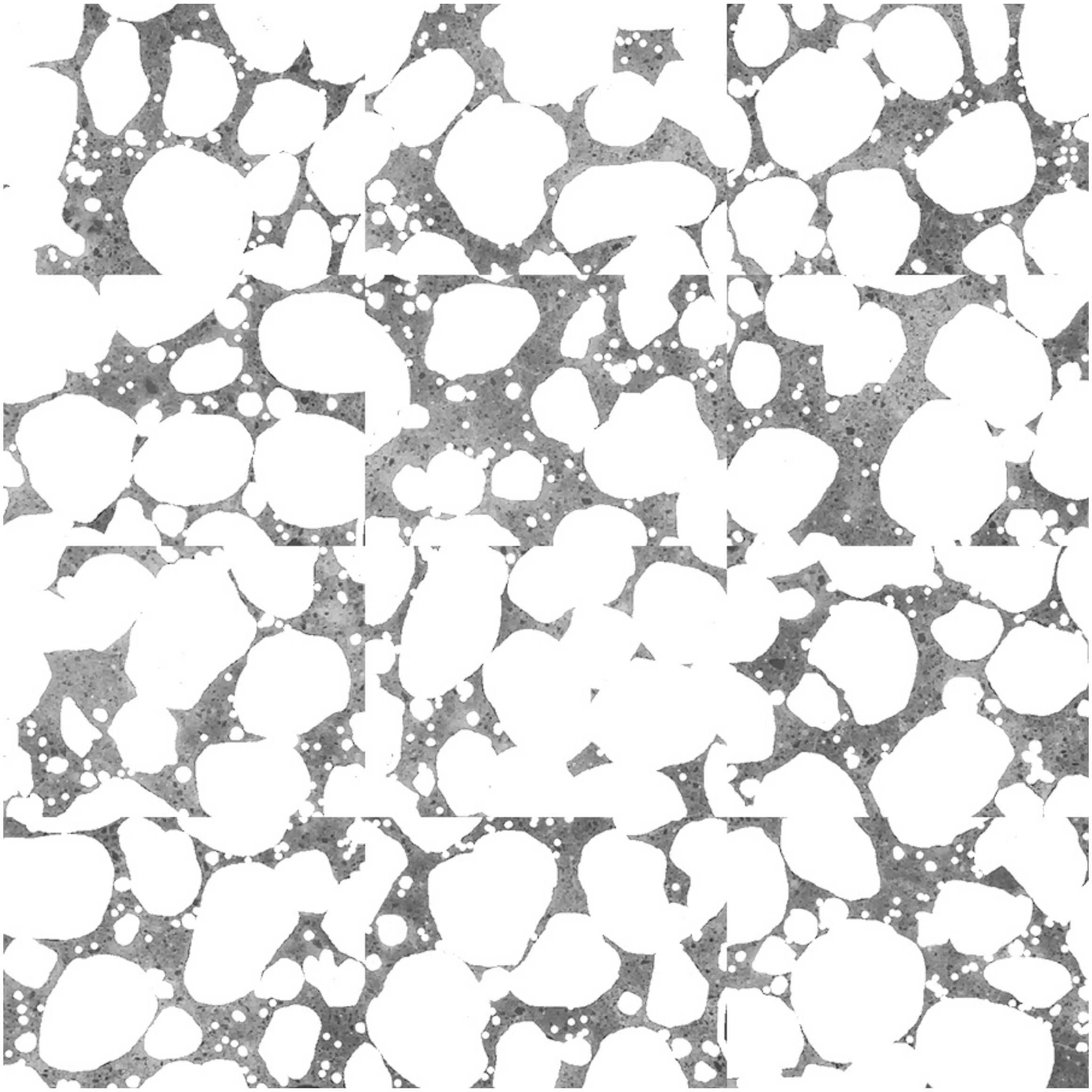

Figure A-2: Mosaic of 12 frames collected from 0.40 w/c 28 day moist cured mortar standards after masking out air voids and fine aggregate to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

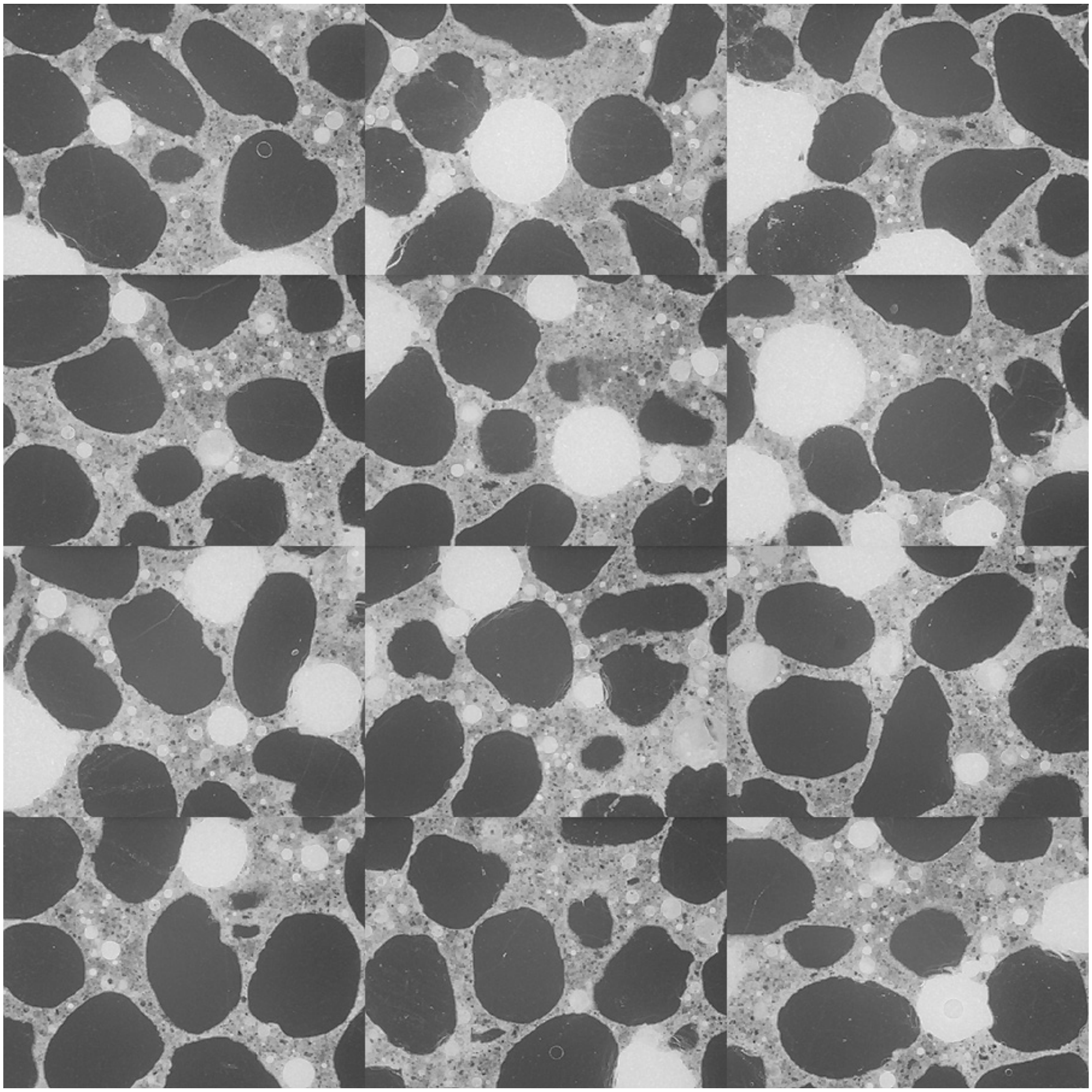
Figure A-3: Mosaic of 12 frames collected from 0.50 w/c 28 day moist cured mortar standards (each individual frame measures 2.612 x 1.959 mm).

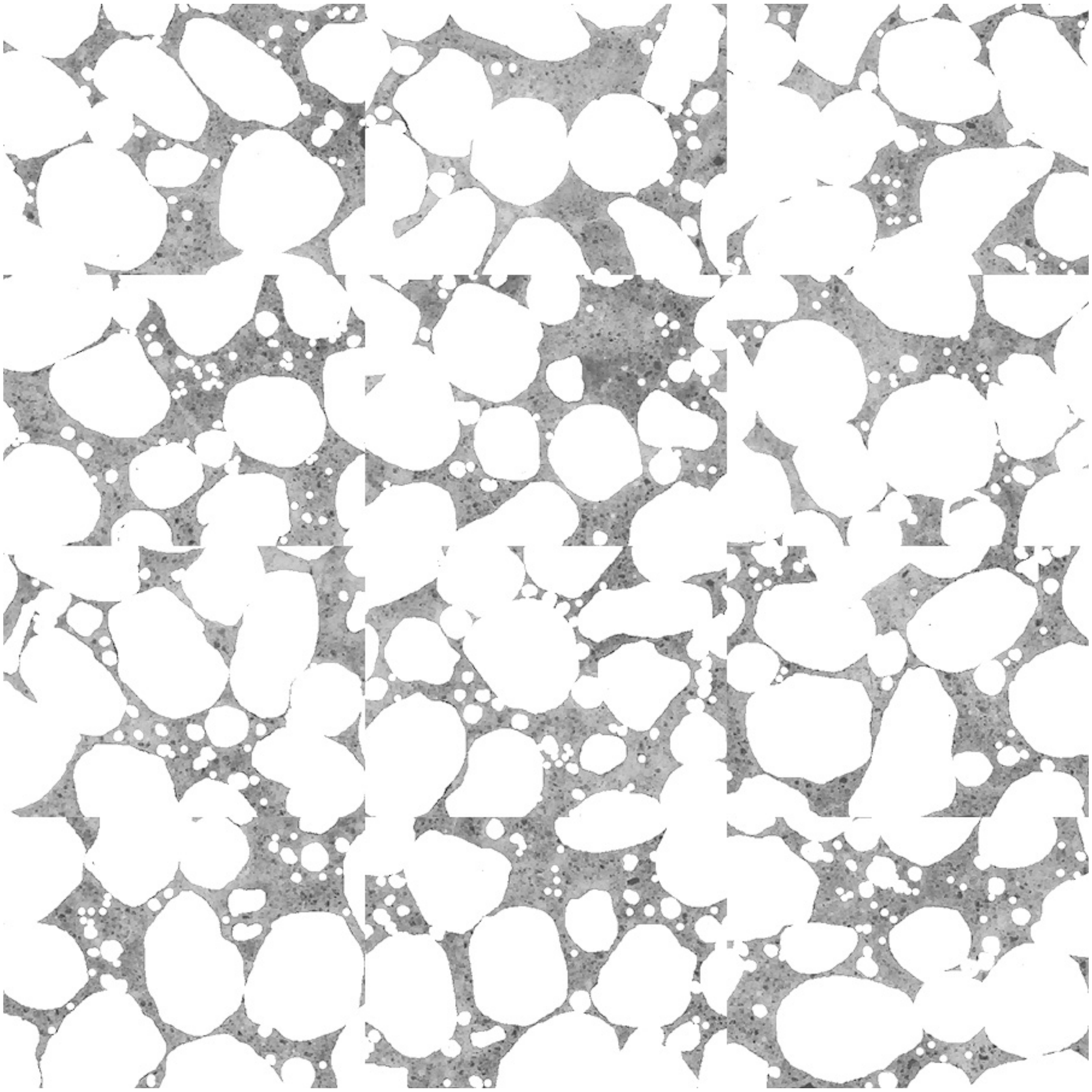

Figure A-4: Mosaic of 12 frames collected from 0.50 w/c 28 day moist cured mortar standards after masking out air voids and fine aggregate to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

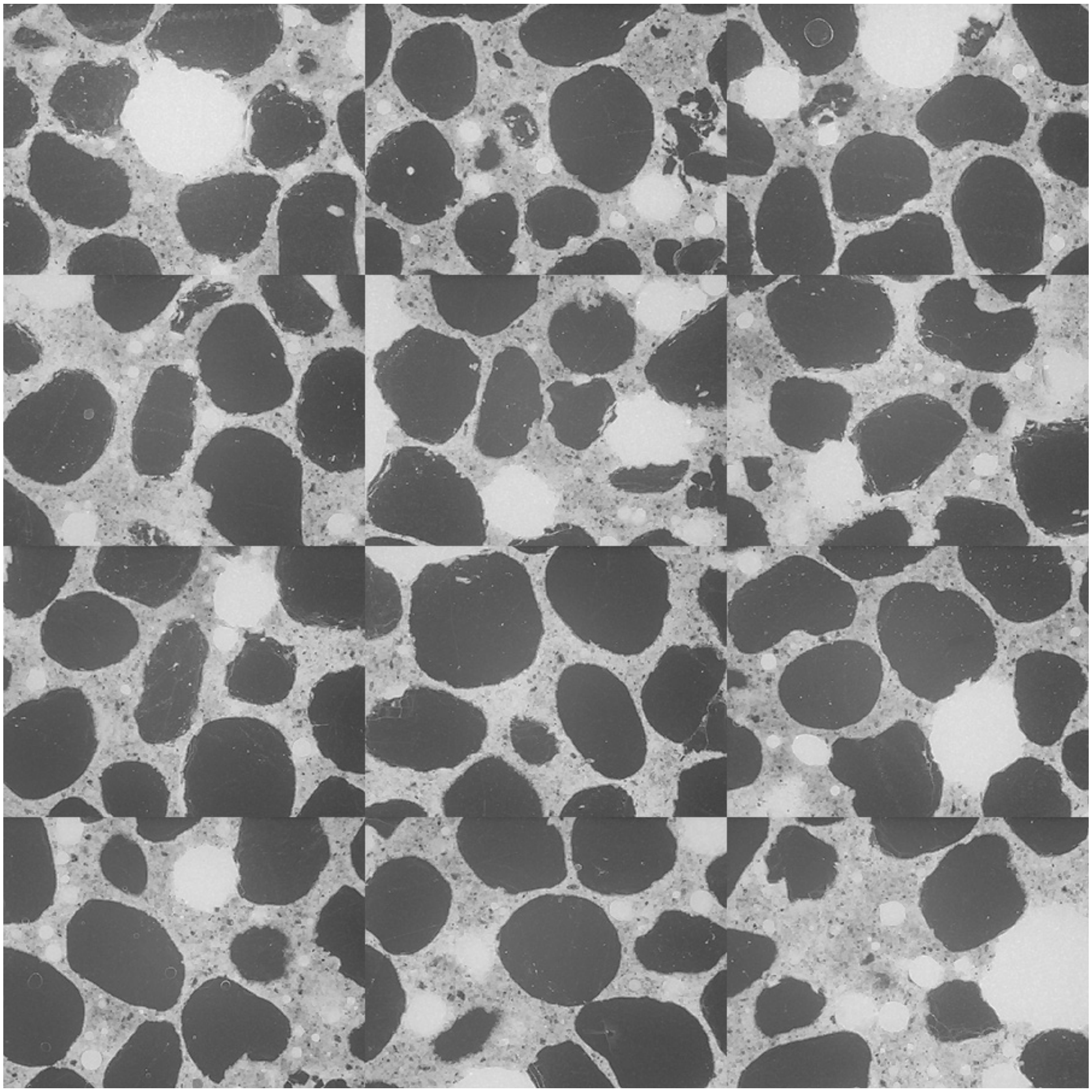

Figure A-5: Mosaic of 12 frames collected from 0.60 w/c 28 day moist cured mortar standards (each individual frame measures 2.612 x 1.959 mm).

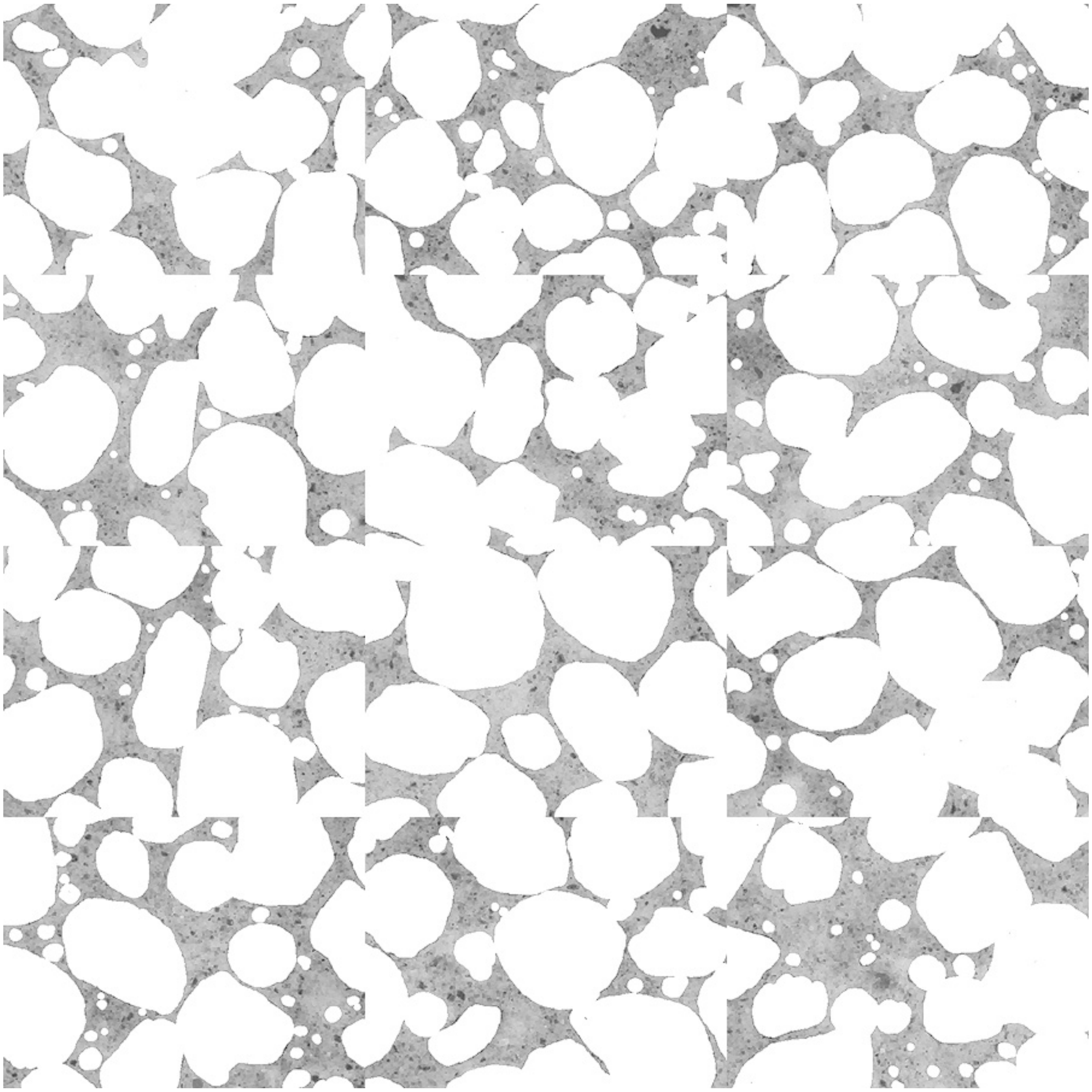

Figure A-6: Mosaic of 12 frames collected from 0.60 w/c 28 day moist cured mortar standards after masking out air voids and fine aggregate to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

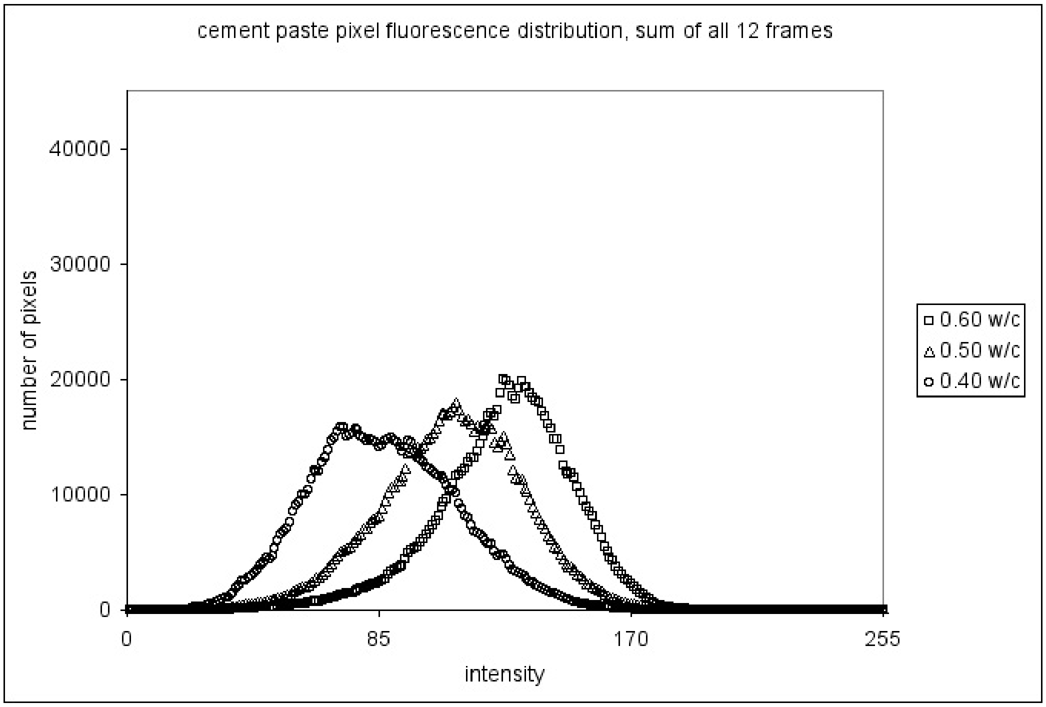

Figure A-7: Histogram plotting cement paste pixel intensities using all 12 frames collected from each of the 28 day moist cured mortar standards.

Table A-1: Average cement paste pixel intensities per frame collected from w/c standards.

w/c	cement paste pixel fluorescence measurements (average intensity per frame)			
0.6	130	118	122	132
	123	132	127	134
	119	121	124	134
0.5	106	118	110	106
	103	114	114	113
	106	106	103	108
0.4	80	94	79	87
	93	86	99	93
	78	86	77	77

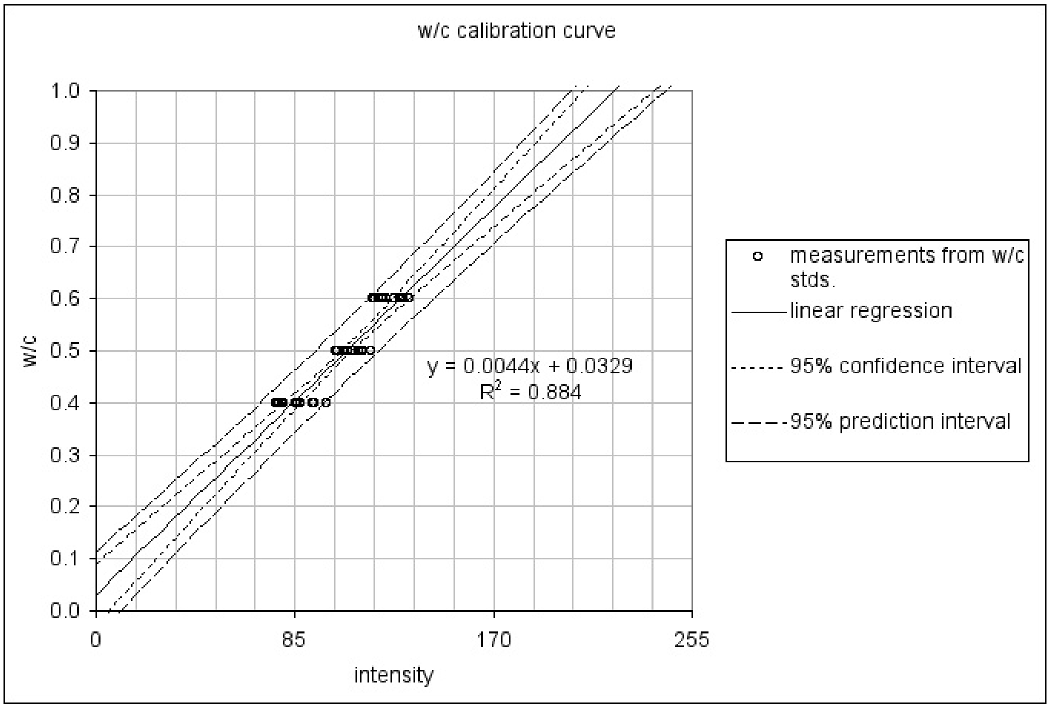

Figure A-8: Calibration curve plotting average cement paste pixel fluorescence intensity per frame versus w/c.

Brief description of chloride profile methodology

A series of 0.45 and 0.55 w/c ratio mortar cylinders were cast and moist cured for 28 days. The cylinders were spiked with known concentrations of $CaCl_2$. A Horiba/Oxford XGT-2000W X-ray Analytical Microscope was used to collect characteristic Cl Ka radiation (2.51 - 2.76 KeV) from regions of cement paste by placing diamond ground cross-sections cut from the cylinders beneath the 300 micrometer diameter x-ray beam. Figures B-1 and B-2 plot the calibration curves from the 0.55 and 0.45 w/c mortar samples. The slopes and intercepts of the regression lines are very similar. During July of 2006, researchers from the University of Florida interested in chloride profiling visited the lab. They brought a series of 0.35 w/c neat paste samples that had been spiked with known concentrations of Cl. Figure B-3 plots the calibration curve from the 0.35 w/c samples. The slope of the regression line from the 0.35 w/c samples was noticeably lower than the slopes from the 0.45 and 0.55 w/c samples. The observation showed that it is necessary to take the density of the cement paste into account when predicting chloride concentrations. Figure B-4 plots calibration curves for various w/c values as interpolated from the calibration curves from the 0.45, 0.55, and 0.35 w/c standards.

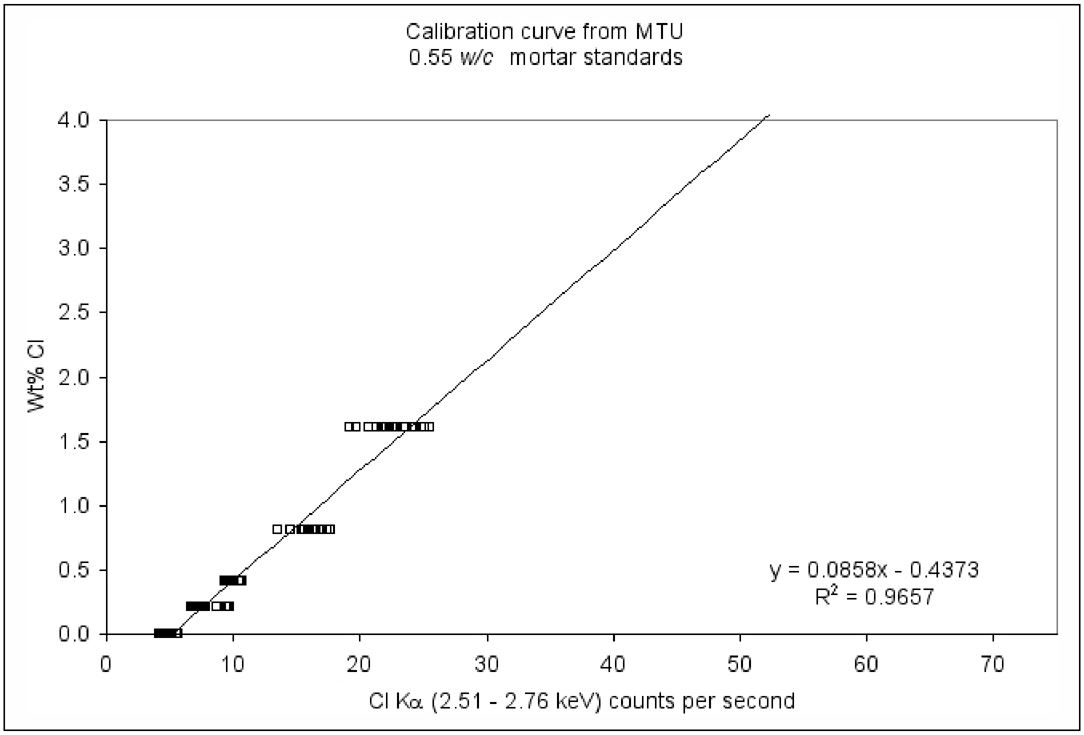

Figure B-1: Calibration curve plotting Cl Ka counts per second versus wt% Cl from cement paste of 0.55 w/c mortar standards.

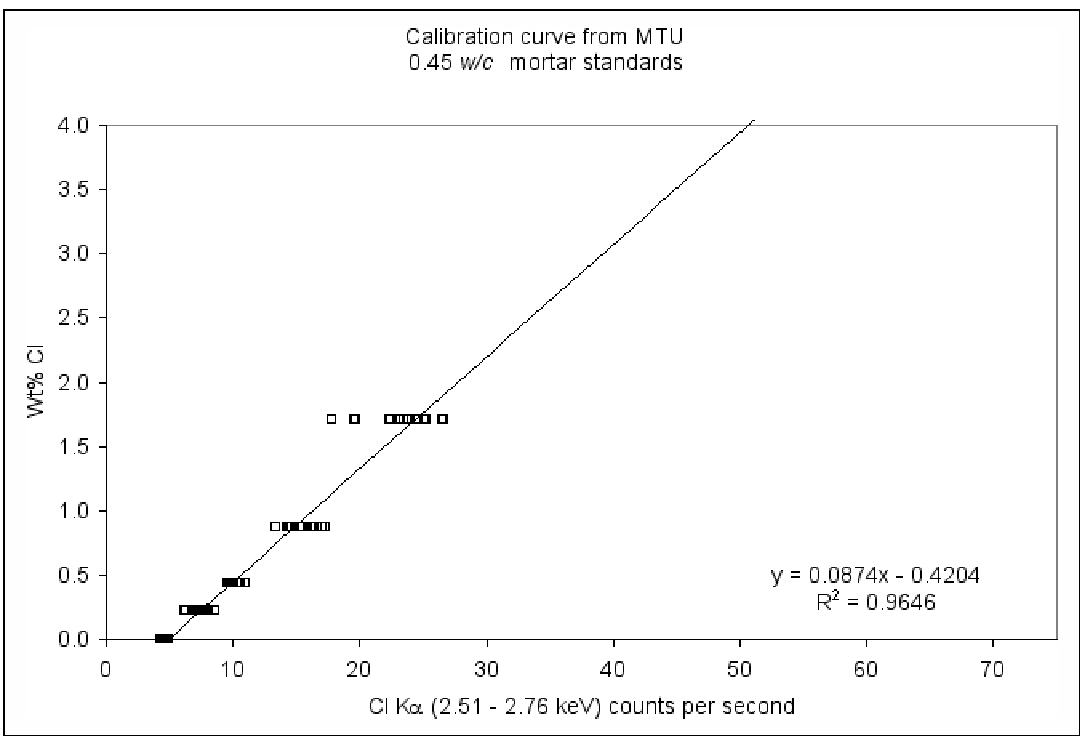

Figure B-2: Calibration curve plotting Cl Ka counts per second versus wt% Cl from cement paste of 0.45 w/c mortar standards.

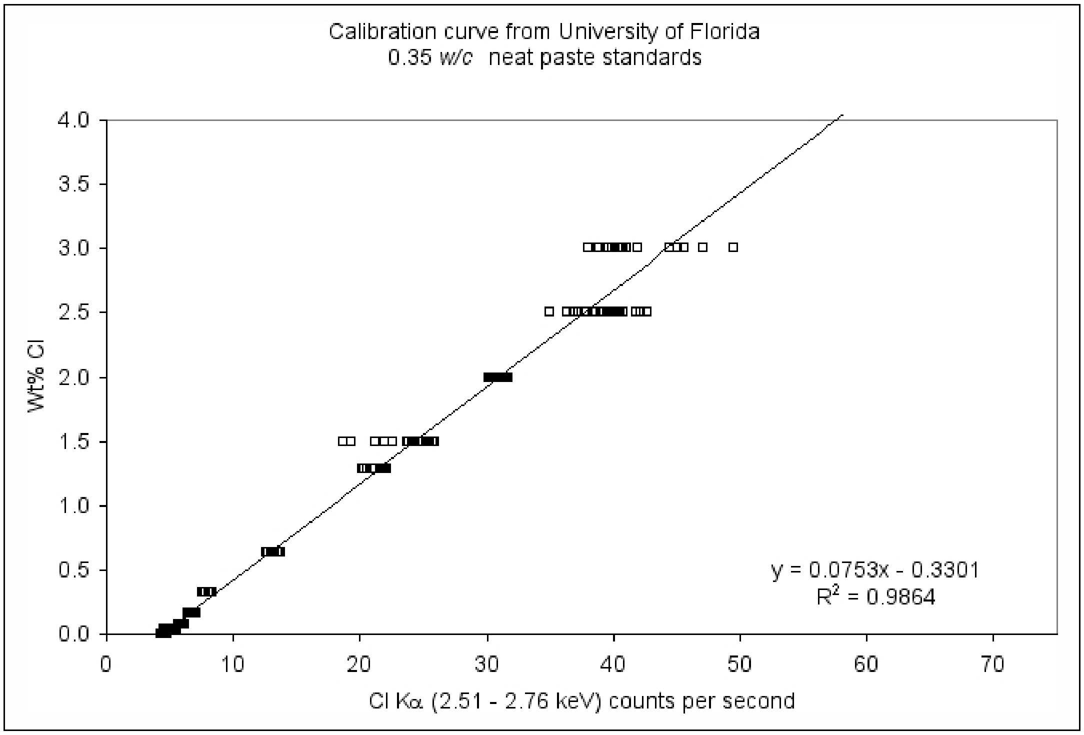

Figure B-3: Calibration curve plotting Cl Ka counts per second versus wt% Cl from cement paste of 0.35 w/c neat cement standards.

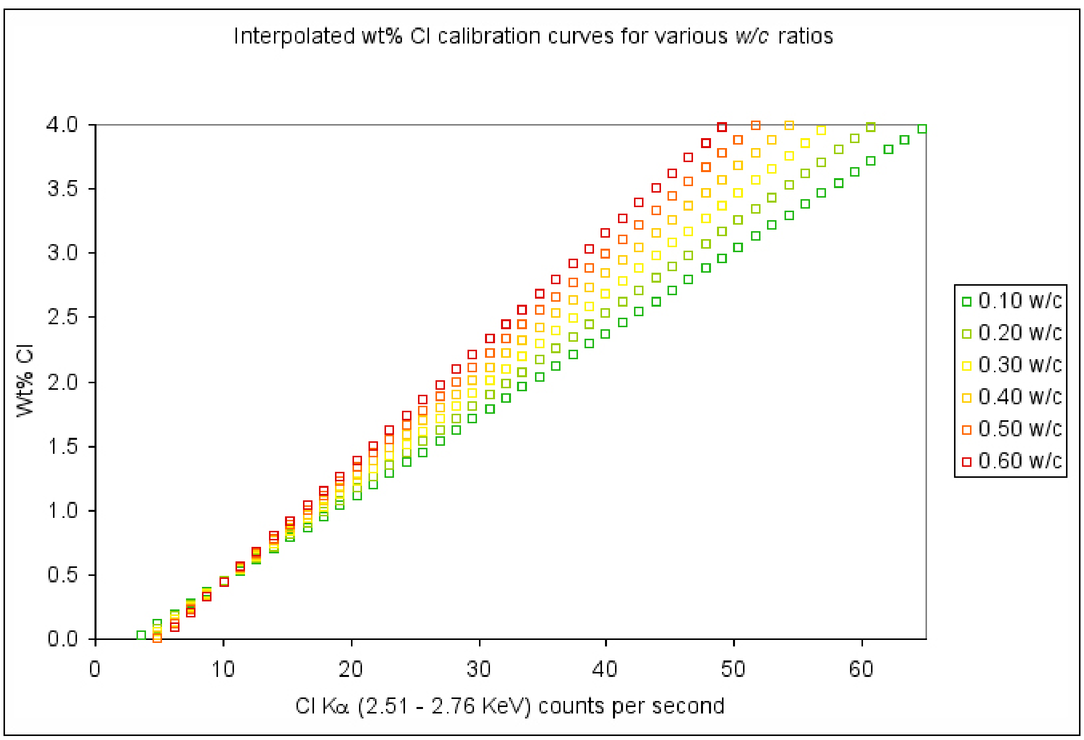

Figure B-4: Interpolated calibration curves plotting Cl Ka counts per second versus wt% Cl for cement pastes at various w/c levels.

Colorado, State Highway 83, south of Denver near milepost 57

This pavement, constructed 1996, exhibited visible signs of deterioration. Figure CO-1 shows the type of cracking observed in the field. The pavement has been exposed primarily to NaCl deicer. Figure CO-2 shows where the cores were taken, and Figures CO-3 and CO-4 show photographs of the individual cores. Two of the cores were cut into slabs and polished: core CO-1 (near a joint), and core CO-5 (mid-panel). Figures CO-5 through CO-8 show the slabs as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation depths. The black and white treatment did not reveal any macro-cracking in either of the cores. Table CO-1 summarizes the air void parameters. Both sets of slabs showed adequate entrained air, with spacing factors of 0.182 mm and 0.175 mm for cores CO-1 and CO-5 respectively. Figure CO-9 shows an example stereomicroscope image of the air void structure. Some alkali silica reactivity was observed with minor gel production and cracking, as illustrated in Figure CO-10. A w/c ratio estimation was performed on a thin section prepared from the top of core CO-6. Figures CO-11 and CO-12 show the images used to make the measurements. The results of the w/c estimation are summarized in Table CO-2, with an average w/c value of 0.47 as compared to the 28-day moist cured mortar sample standards. Figures CO-13 through CO-16 show chloride profiles from cores CO-6 and CO-8. Figure CO-17 shows fly ash particles present in the concrete.

Figure CO-1: Photograph of cracks in pavement.

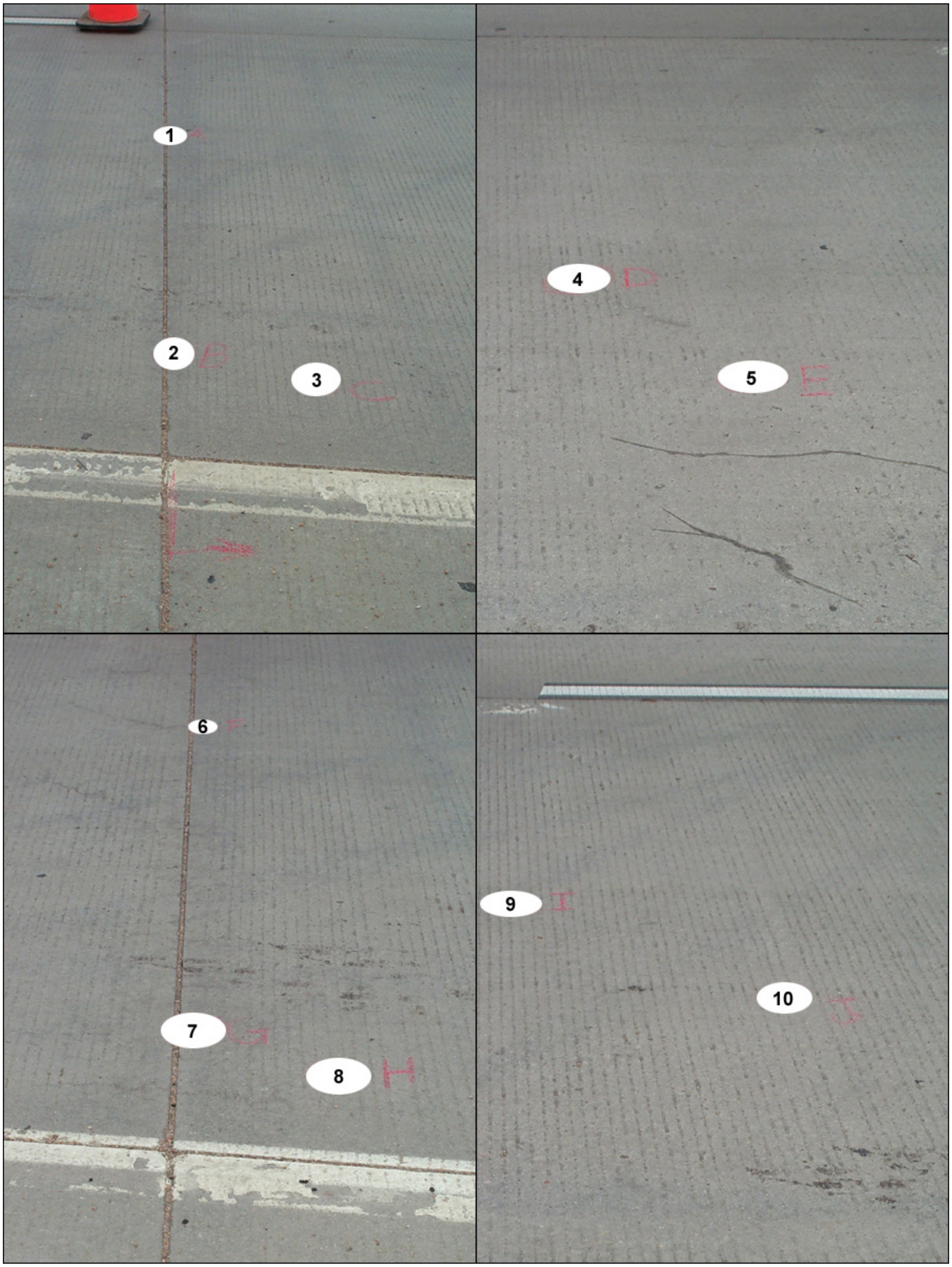

Figure CO-2: Photographs to show core locations.

Figure CO-3: Cores taken at joint.

Figure CO-4: Cores taken away from joint.

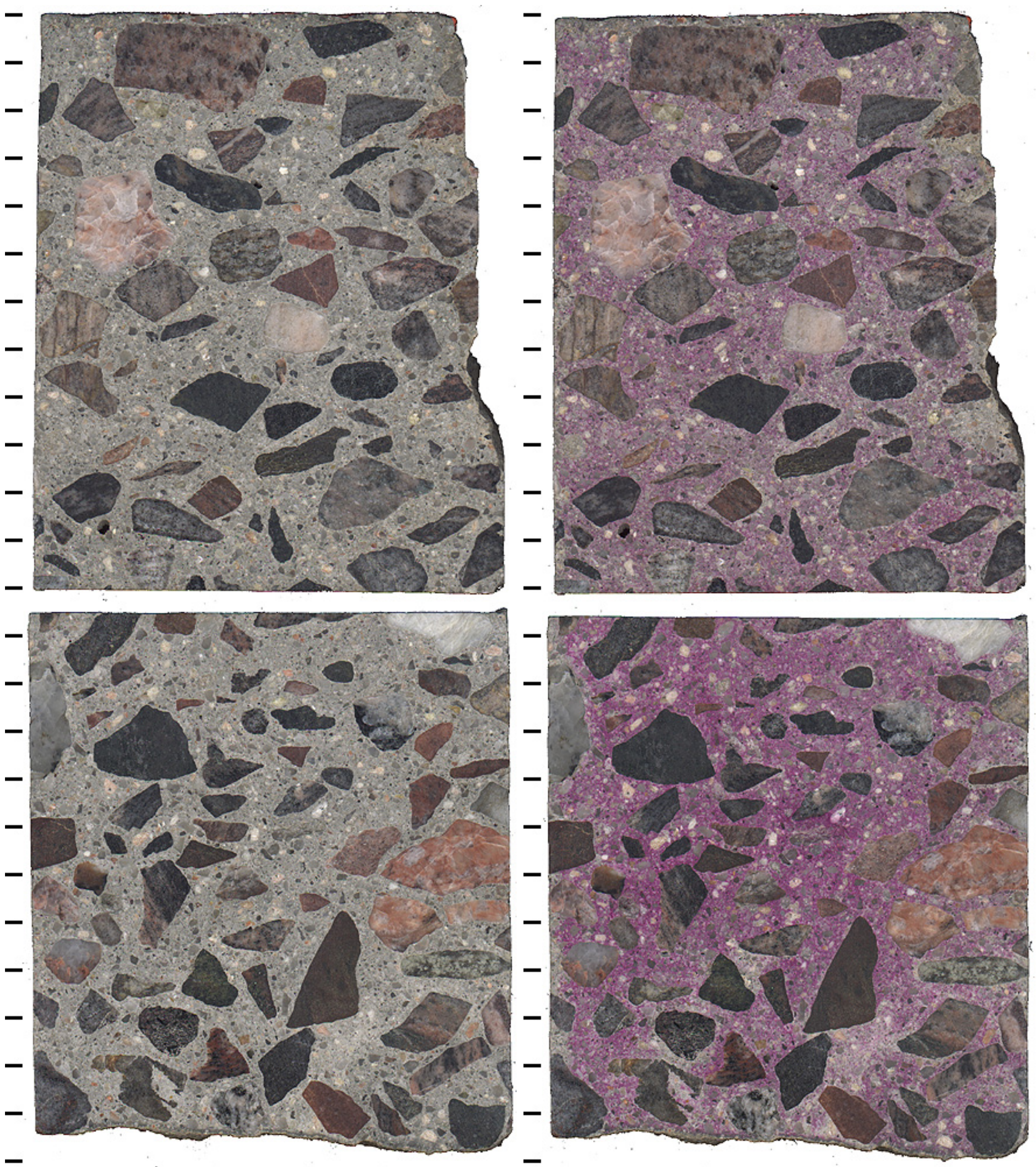

Figure CO-5: Polished slabs to show complete cross-section through core CO-1 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

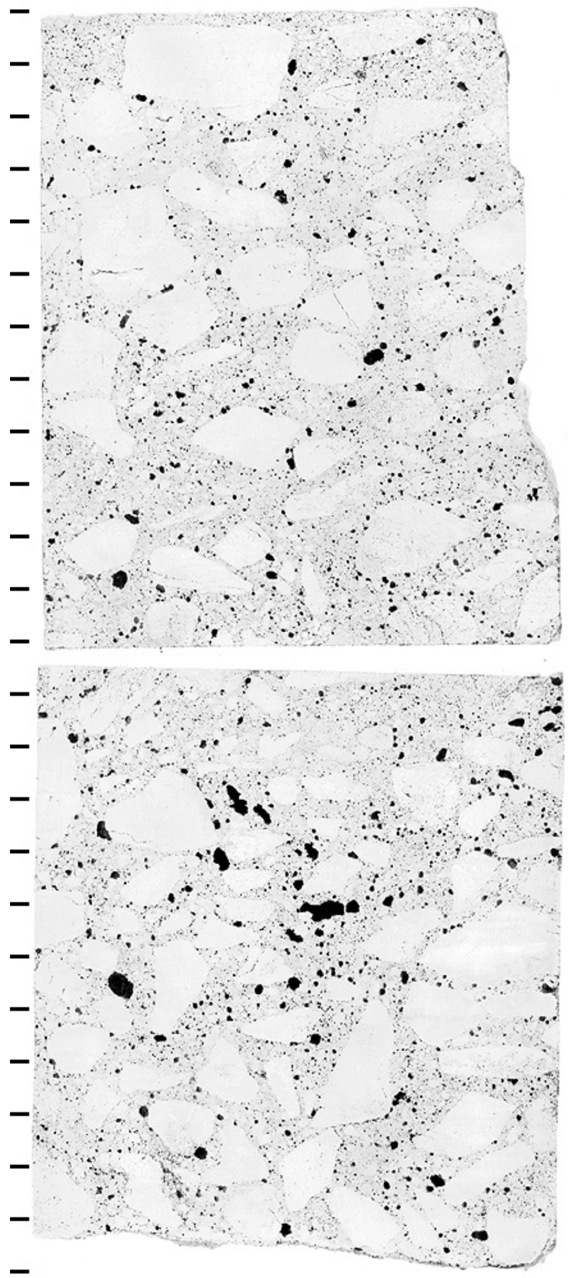

Figure CO-6: Polished slabs to show complete cross-section through core CO-1 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

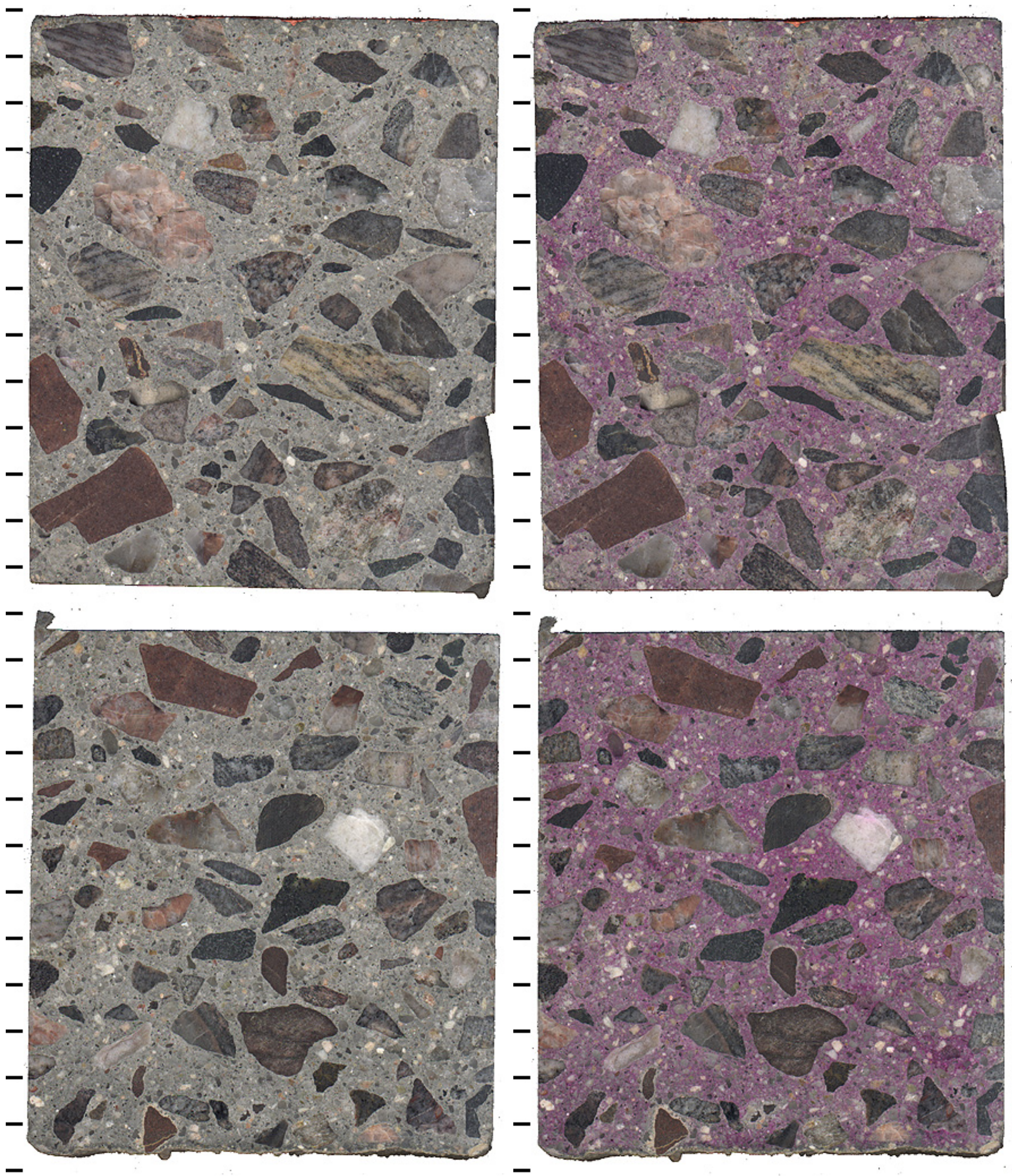

Figure CO-7: Polished slabs to show complete cross-section through core CO-5 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

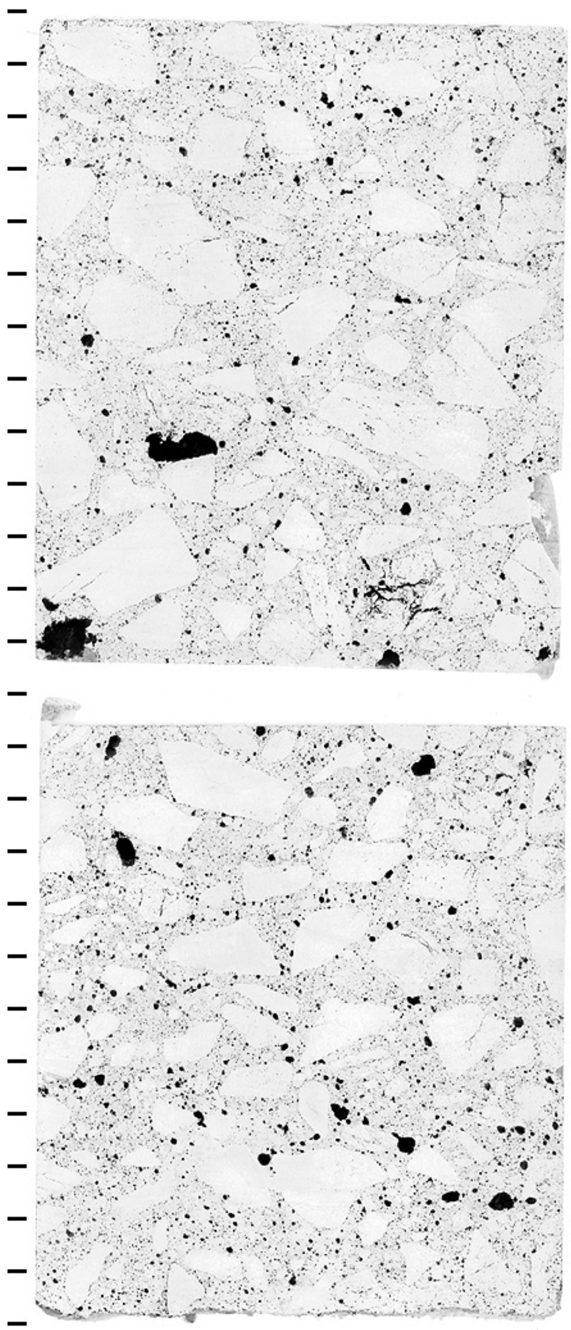

Figure CO-8: Polished slabs to show complete cross-section through core CO-5 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

Table CO-1: Air void parameters.

Sample ID	CO_01	CO_05
Location	at joint	away from joint
Raw data		
Total traverse length (mm)	3625.456	3625.456
Area analyzed (cm^2)	71.0	71.0
Air stops	79	83
Paste stops	300	282
Aggregate stops	1009	1023
Secondary deposit stops	0	0
Total stops	1388	1388
Number of air intercepts	1072	1051
Number of filled void intercepts	3	0
Results		
Air vol%	5.7	6.0
Paste vol%	21.6	20.3
Aggregate vol%	72.7	73.7
Secondary deposit vol%	0.0	0.0
Existing average chord length (mm)	0.192	0.206
Existing paste/air ratio	3.8	3.4
Existing air void specific surface (mm^{-1})	20.8	19.4
Existing air void frequency (voids/m)	296	290
Existing spacing factor (mm)	0.183	0.175
Original average chord length (mm)	0.192	0.206
Original paste/air ratio	3.8	3.4
Original air void specific surface (mm^{-1})	20.8	19.4
Original air void frequency (voids/m)	297	290
Original spacing factor (mm)	0.182	0.175

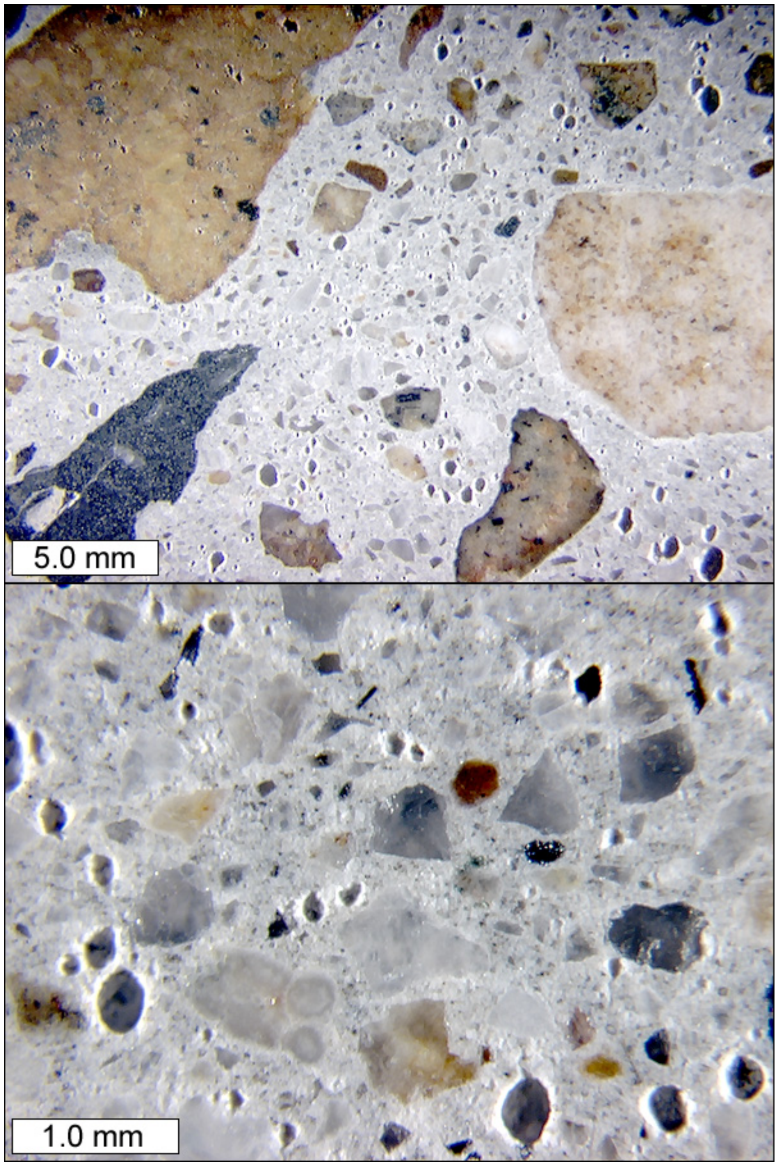

Figure CO-9: Stereo microscope images to show air void structure on polished slab from core CO-1.

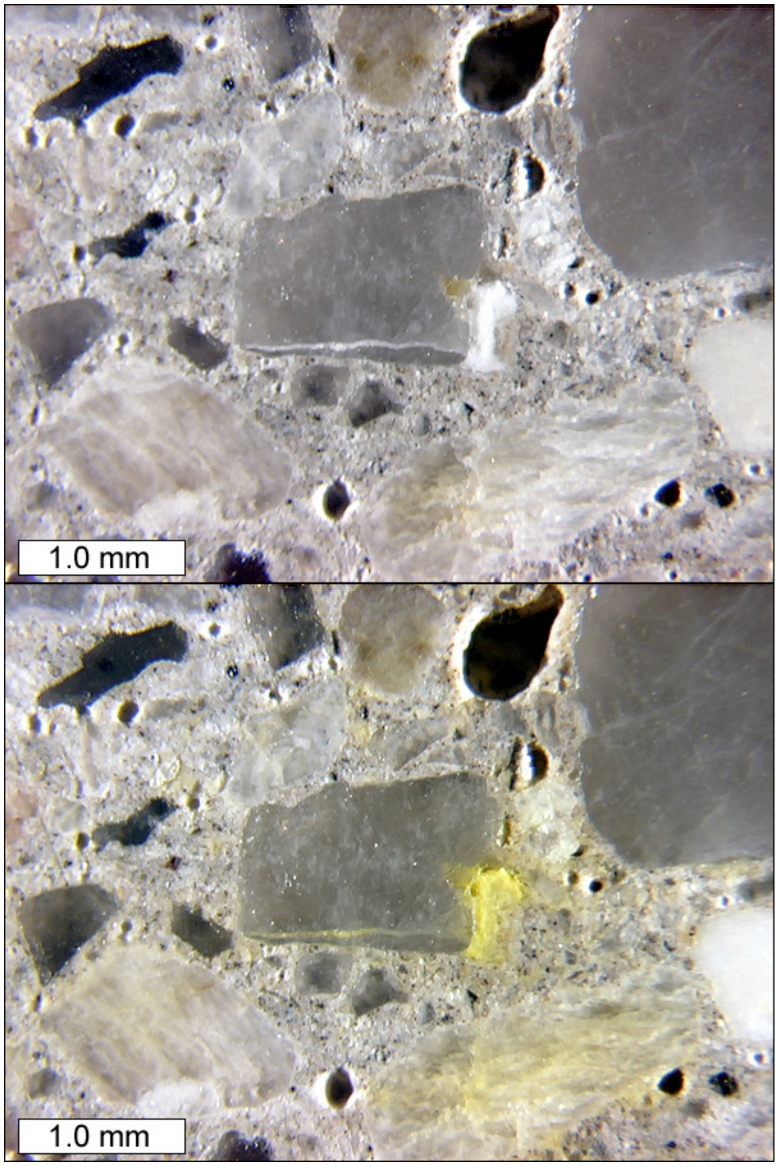

Figure CO-10: Stereo microscope images to show reactive aggregate particle both before (top) and after (bottom) treatment with sodium cobaltinitrite stain (sample CO-5).

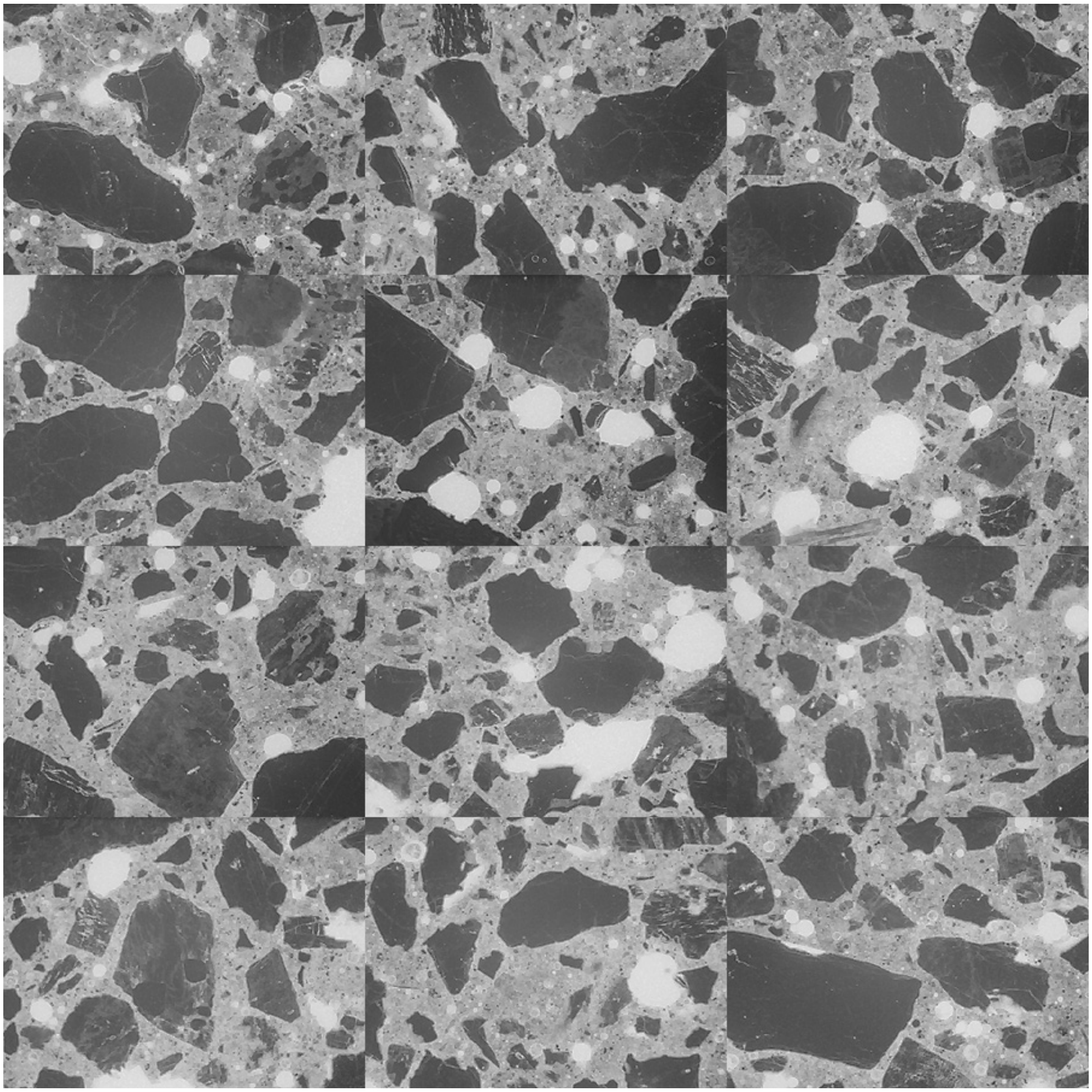

Figure CO-11: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core CO-6 (each individual frame measures 2.612 x 1.959 mm).

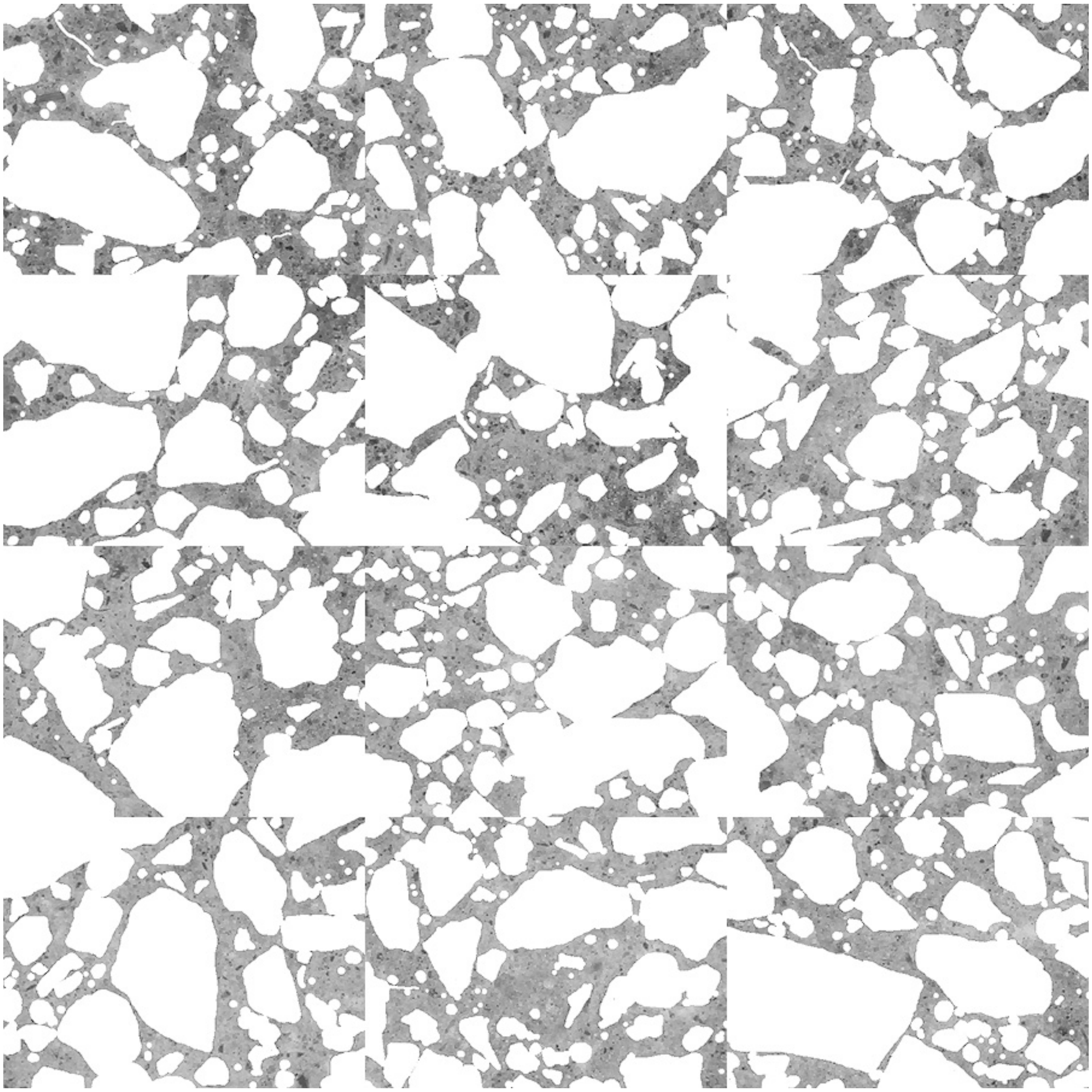

Figure CO-12: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core CO-6 after masking out air voids and fine aggregate to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table CO-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples).

cement paste pixel fluorescence measurements (average intensity per frame)			
88	96	90	93
87	108	102	115
110	116	115	113
equivalent w/c (y = 0.0044x + 0.0329)			
0.42	0.45	0.43	0.44
0.41	0.50	0.48	0.53
0.51	0.54	0.54	0.53

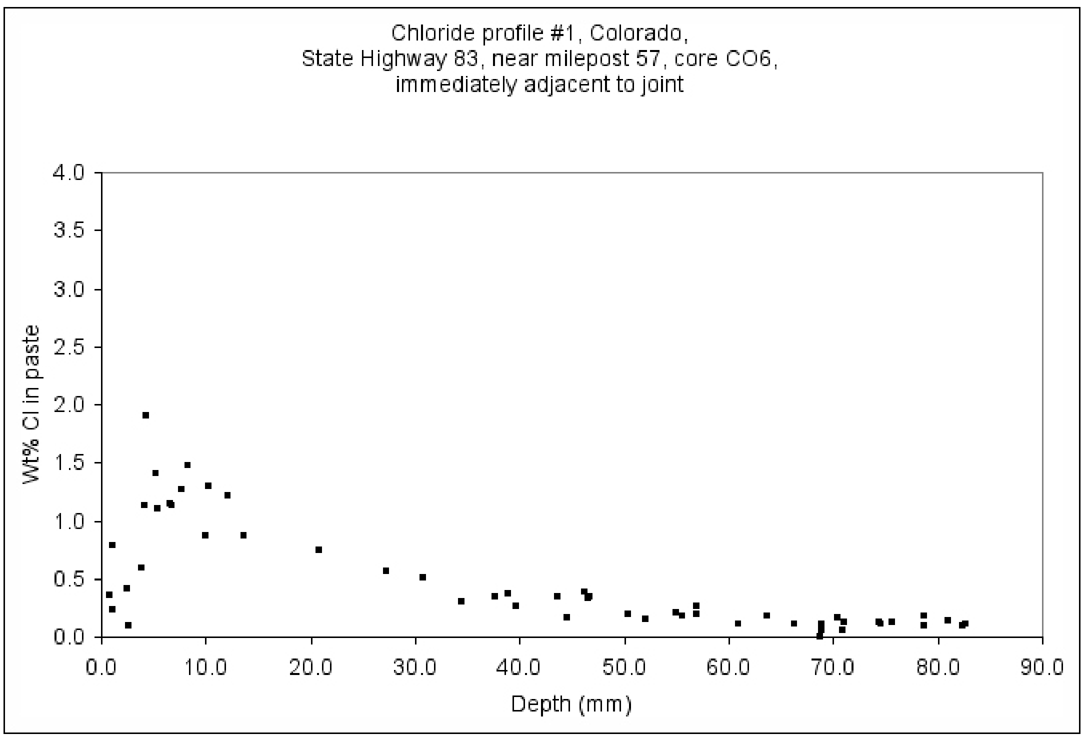

Figure CO-13: Chloride profile through cement paste, from billet prepared from core CO-6.

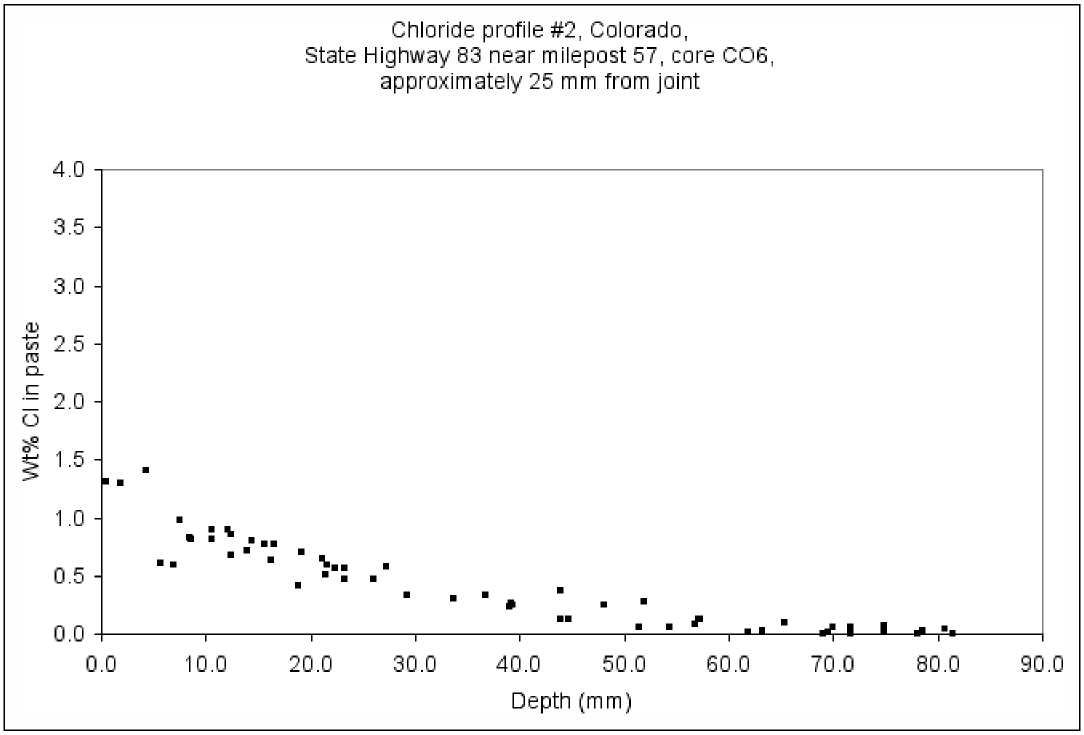

Figure CO-14: Chloride profile through cement paste, from billet prepared from core CO-6.

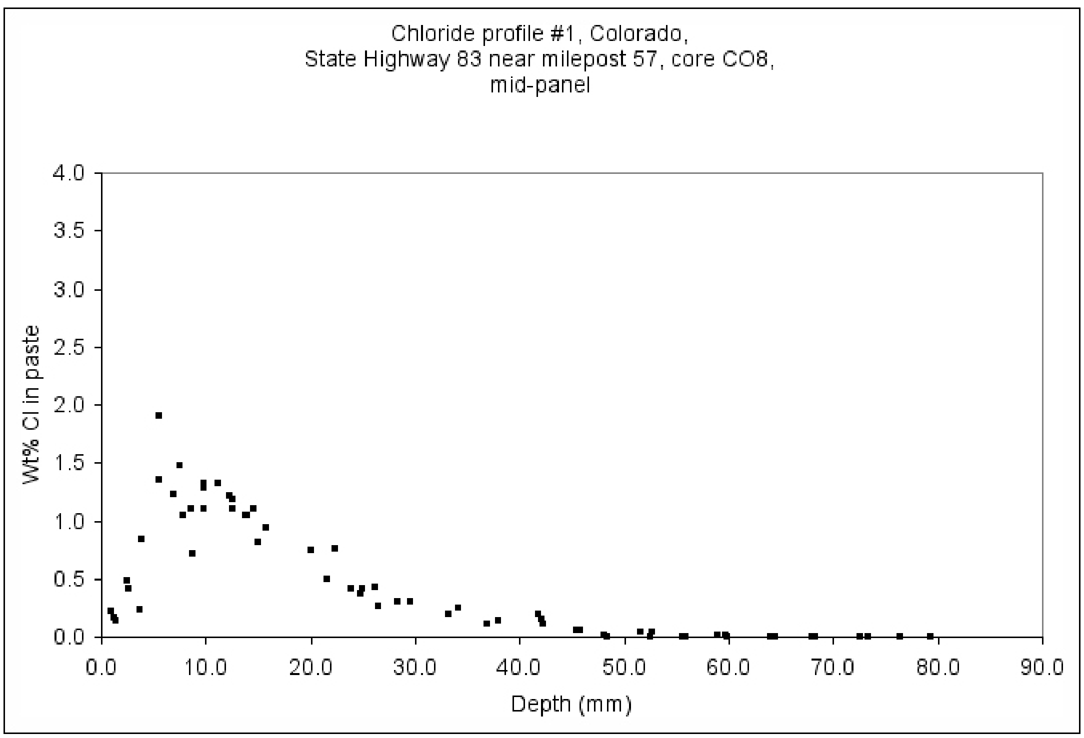

Figure CO-15: Chloride profile through cement paste, from billet prepared from core CO-8.

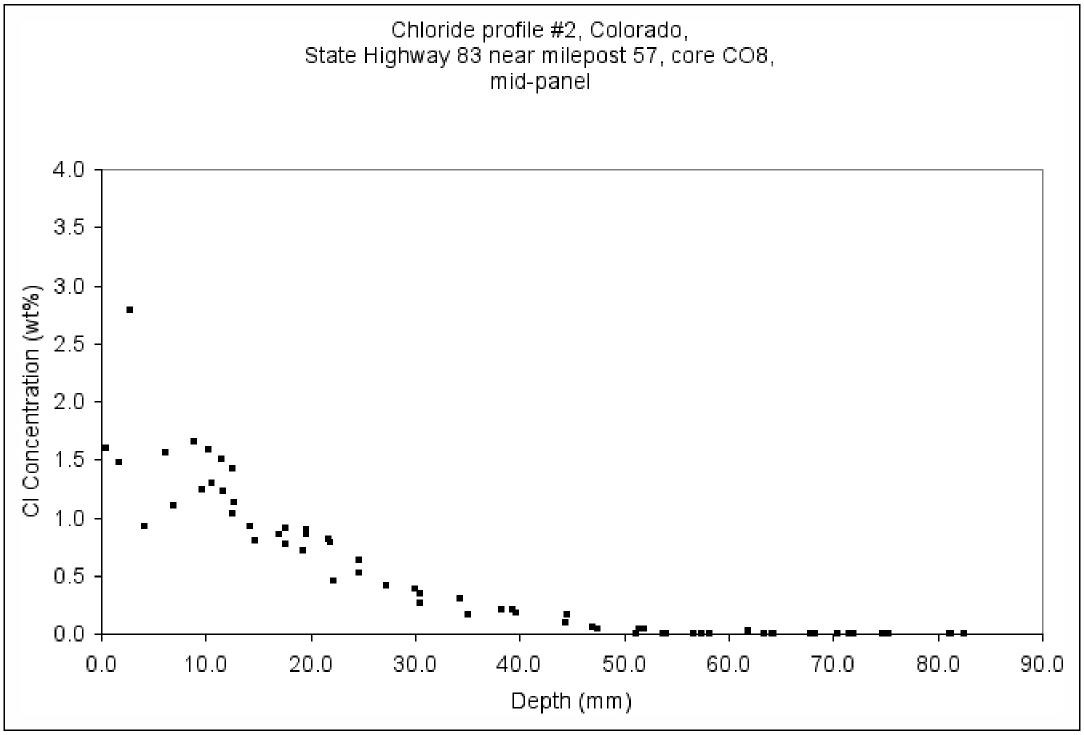

Figure CO-16: Chloride profile through cement paste, from billet prepared from core CO-8.

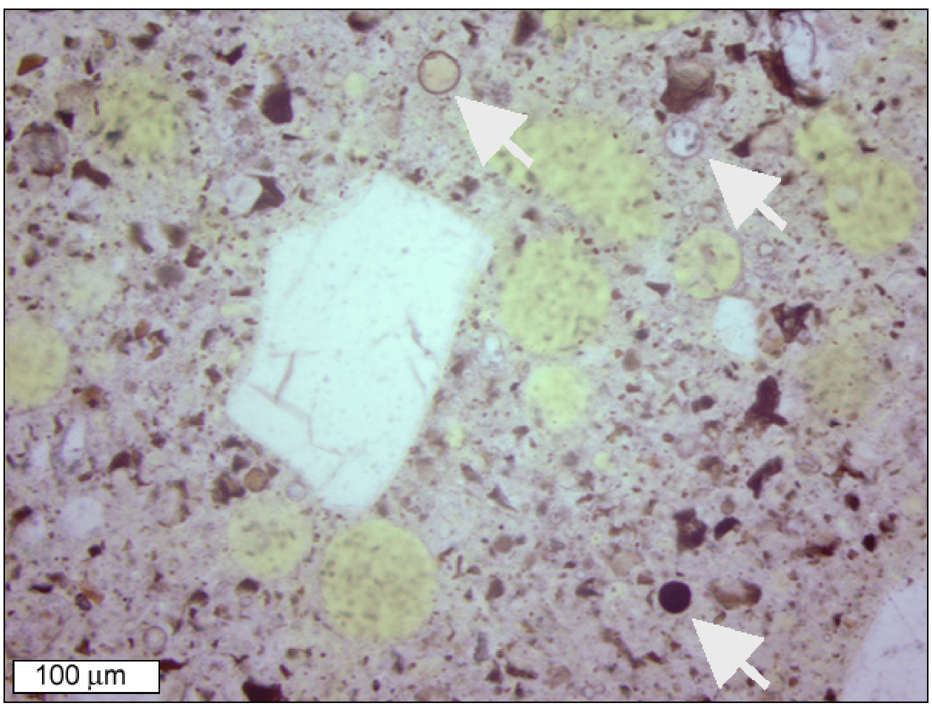

Figure CO-17: Transmitted light image, with arrows indicating some of the fly ash particles.

Iowa, eastbound US Highway 34, western end of the Burlington Bridge.

This bridge deck is reported to have been exposed exclusively to calcium magnesium acetate deicer. Figure IA-1 shows the locations of the cores, and Figure IA-2 shows an example of surface cracking observed in the field. Figures IA-3 and IA-4 show photographs of the partial depth cores, which primarily sampled the approximately 2" thick concrete overlay. Two of the cores were cut into slabs and polished: core IA-6 (over a surface crack), and core IA-5 (no surface crack). Figures IA-5 and IA-6 show the slabs as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation depths. The black and white treatment did not reveal any macro-cracking in either of the cores, other than the obvious surface crack of core IA-6, which extended both through the overlay and into the original concrete below. Table IA-1 summarizes the air void parameters. The overlay from both slabs exhibited borderline entrained air parameters, with spacing factors of 0.276 mm and 0.217 mm for cores IA-5 and IA-6 respectively. Figure IA-7 shows an example stereomicroscope image of the air void structure. Some alkali silica reactivity was observed with minor gel production but no cracking, as illustrated in Figure IA-8. A w/c ratio estimation was performed on a thin section prepared from the top concrete overlay portion of core IA-3, and from the original concrete below in core IA-11. Figures IA-9 through IA-12 show the images used to make the measurements. The results of the w/c estimations are summarized in Tables IA-2 and IA-3, with an average w/c value of 0.30 for the overlay, and an average w/c value of 0.42 for the original concrete, (as compared to 28-day moist cured mortar sample standards). Figures IA-13 through IA-16 show chloride profiles collected from core IA-3 (over a surface crack) and core IA-11 (no surface crack). All of the profiles show an increase in Cl concentration near the pavement surface. Although CMA may have been used exclusively on the bridge deck, it is possible that contamination from the preceding roadway contributed to the observed Cl gradient. A careful comparison of the profiles from cores IA-3 and IA-11 shows an increased Cl penetration in core IA-3, which was taken directly over a surface crack in the pavement. Figure IA-17 shows secondary calcium hydroxide deposits in air voids, which were commonly observed in the concrete overlay.

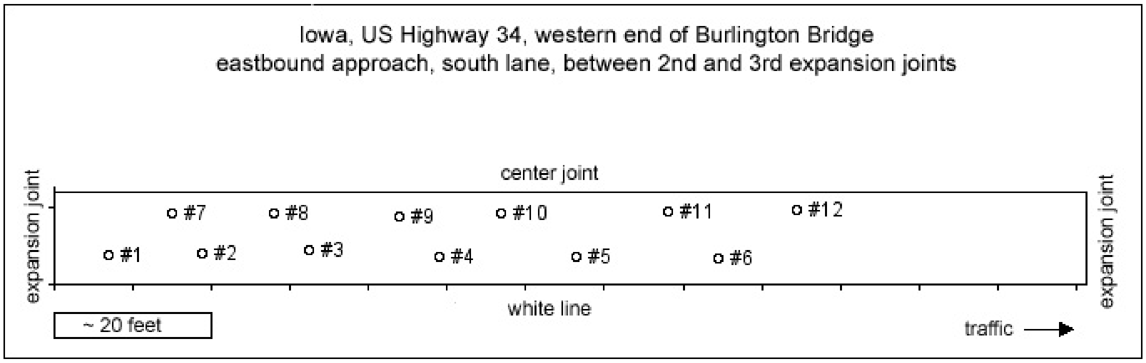

Figure IA-1: Diagram of core locations based on submitted field information.

Figure IA-2: Photograph of crack in bridge deck.

Figure IA-3: Partial depth cores through bridge deck from right hand side of lane.

Figure IA-4: Partial depth cores through bridge deck from left hand side of lane.

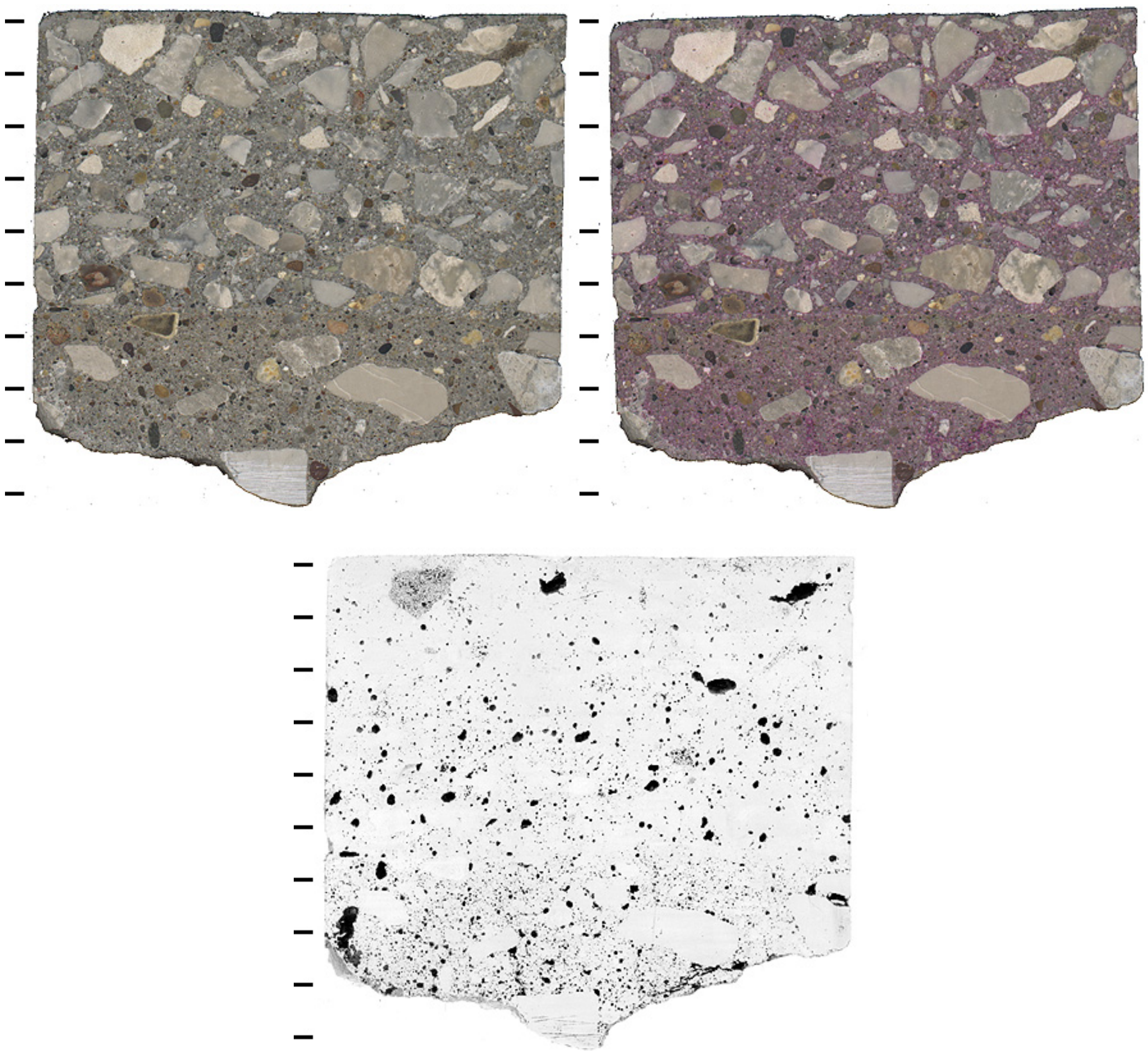

Figure IA-5: Polished slabs to show complete cross-section through core IA-4, before (upper left) and after application of phenolphthalein stain (upper right) and after treatment to enhance appearance of air voids and cracks (bottom) tic marks every cm.

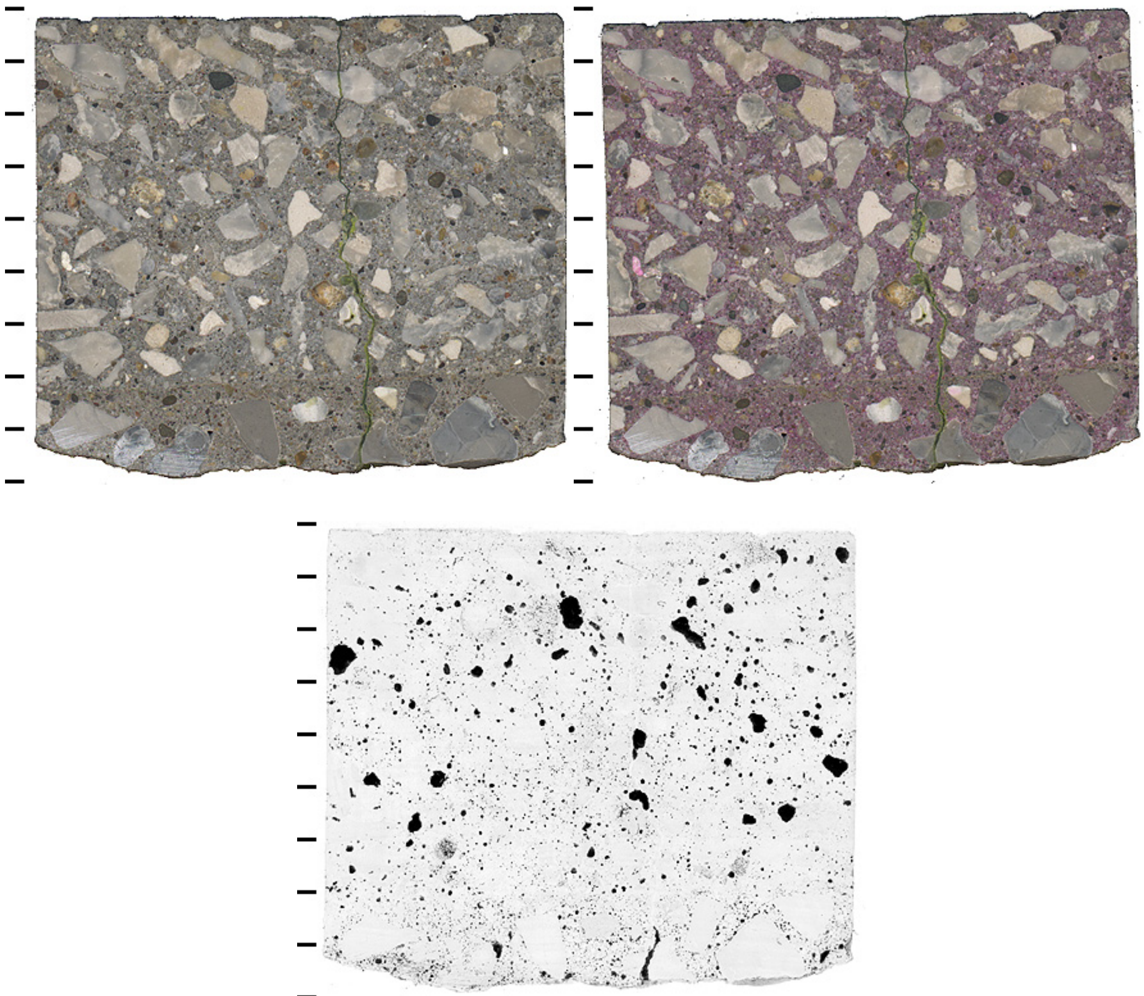

Figure IA-6: Polished slabs to show complete cross-section through core IA-7, before (upper left) and after application of phenolphthalein stain (upper right) and after treatment to enhance appearance of air voids and cracks (bottom) tic marks every cm. The slab was stabilized with epoxy prior to polishing due to the large crack running the down the middle of the core. Since the crack was filled with epoxy, it does not appear in the black and white enhanced image.

Table IA-1: Air void parameters of concrete overlay.

Sample ID	IA_07	IA_04
Location	at crack	away from crack
Raw data		
Total traverse length (mm)	3411.272	4197.484
Area analyzed (cm^2)	66.8	82.2
Air stops	86	123
Paste stops	400	400
Aggregate stops	817	1083
Secondary deposit stops	3	1
Total stops	1306	1607
Number of air intercepts	835	1198
Number of filled void intercepts	6	5
Results		
Air vol%	6.6	7.7
Paste vol%	30.6	24.9
Aggregate vol%	62.8	67.5
Secondary deposit vol%	0.2	0.1
Existing average chord length (mm)	0.302	0.268
Existing paste/air ratio	4.7	3.3
Existing air void specific surface (mm^{-1})	14.9	14.9
Existing air void frequency (voids/m)	245	285
Existing spacing factor (mm)	0.269	0.219
Original average chord length (mm)	0.305	0.269
Original paste/air ratio	4.5	3.2
Original air void specific surface (mm^{-1})	14.5	14.9
Original air void frequency (voids/m)	247	287
Original spacing factor (mm)	0.276	0.217

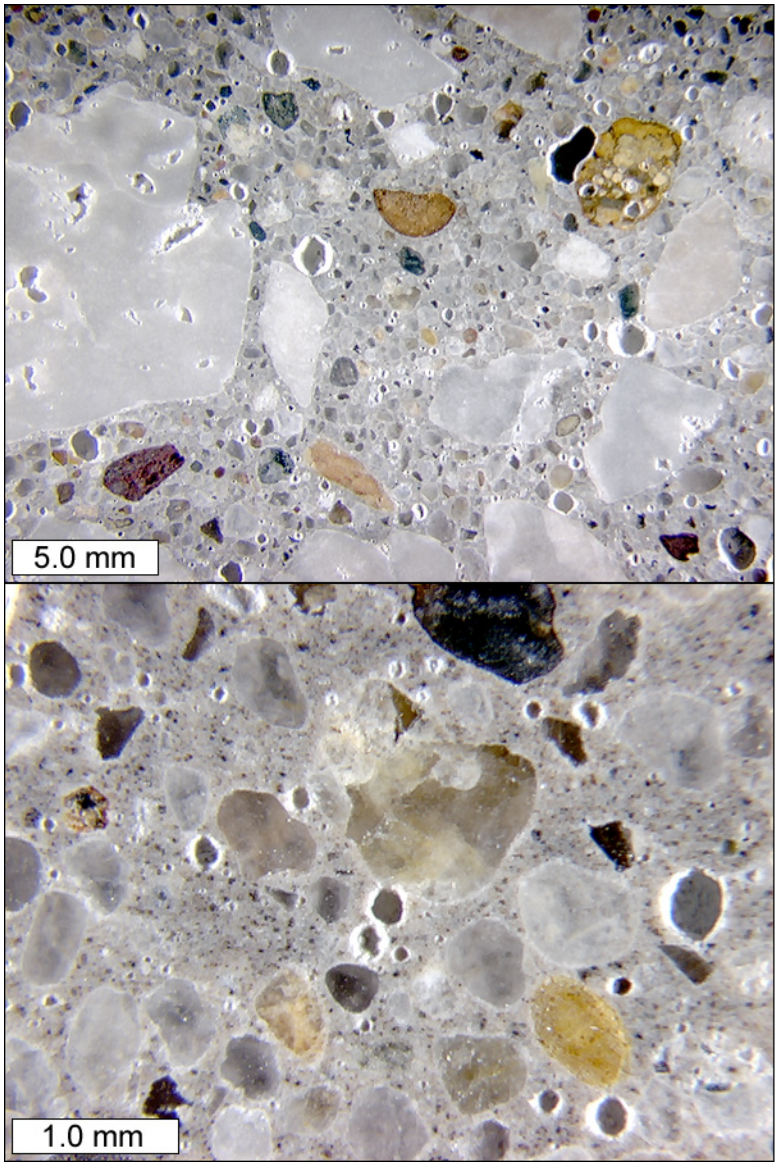

Figure IA-7: Stereo microscope images to show air void structure of concrete overlay on polished slab from core IA-4.

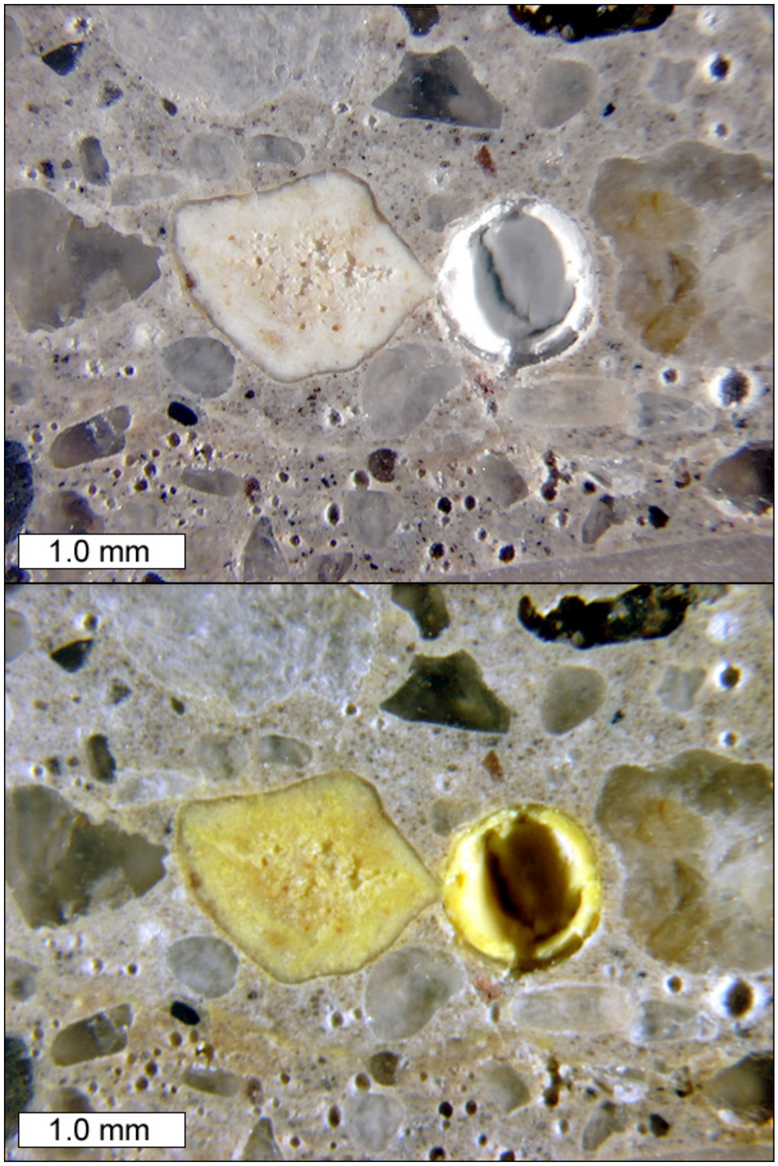

Figure IA-8: Stereo microscope images to show reactive aggregate particle both before (top) and after (bottom) treatment with sodium cobaltinitrite stain (sample IA-7). Image also illustrates the contrast in texture between the concrete overlay (top $^3/_4$ of image) and the original concrete below (bottom $^1/_4$ of image).

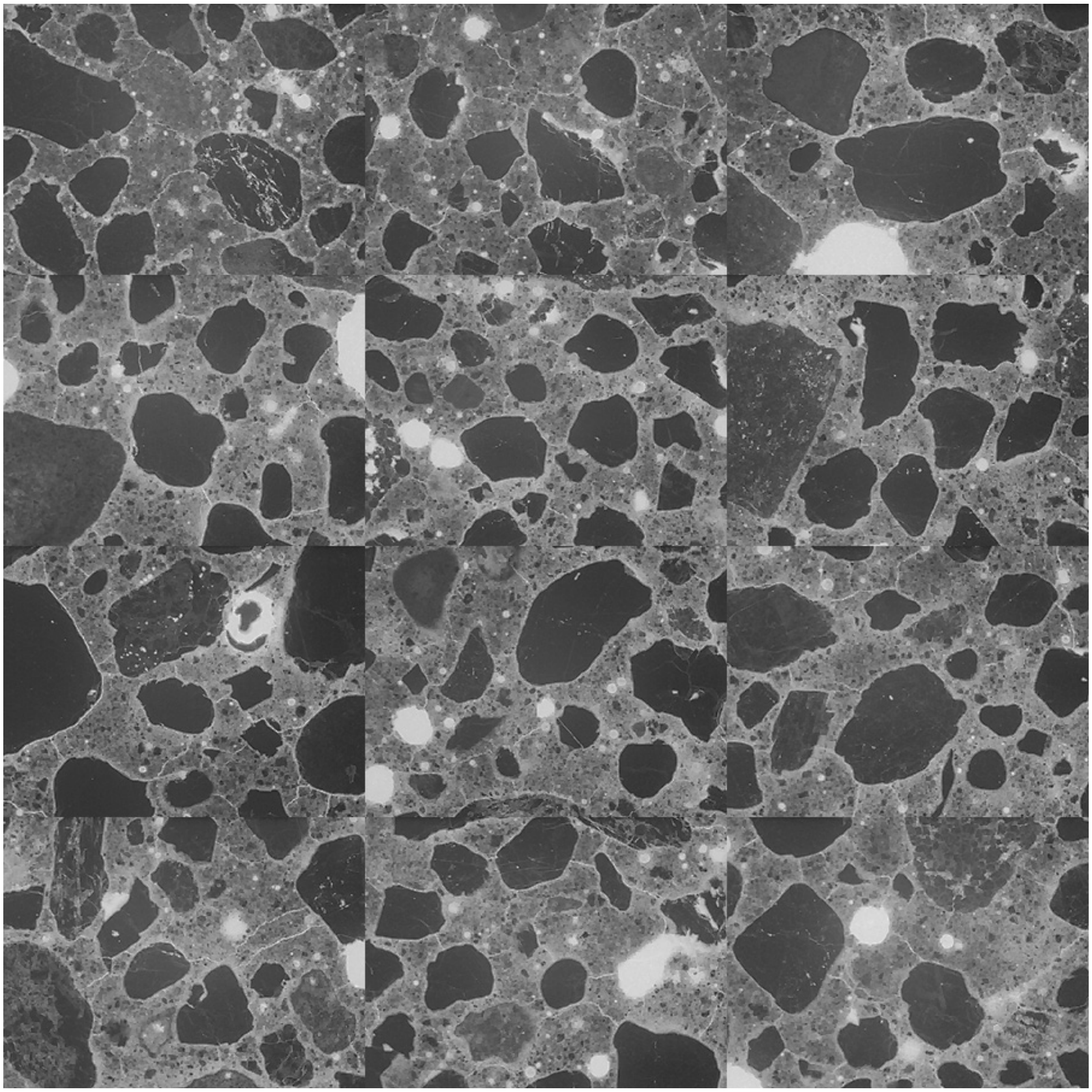

Figure IA-9: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of concrete overlay, core IA-3 (each individual frame measures 2.612 x 1.959 mm).

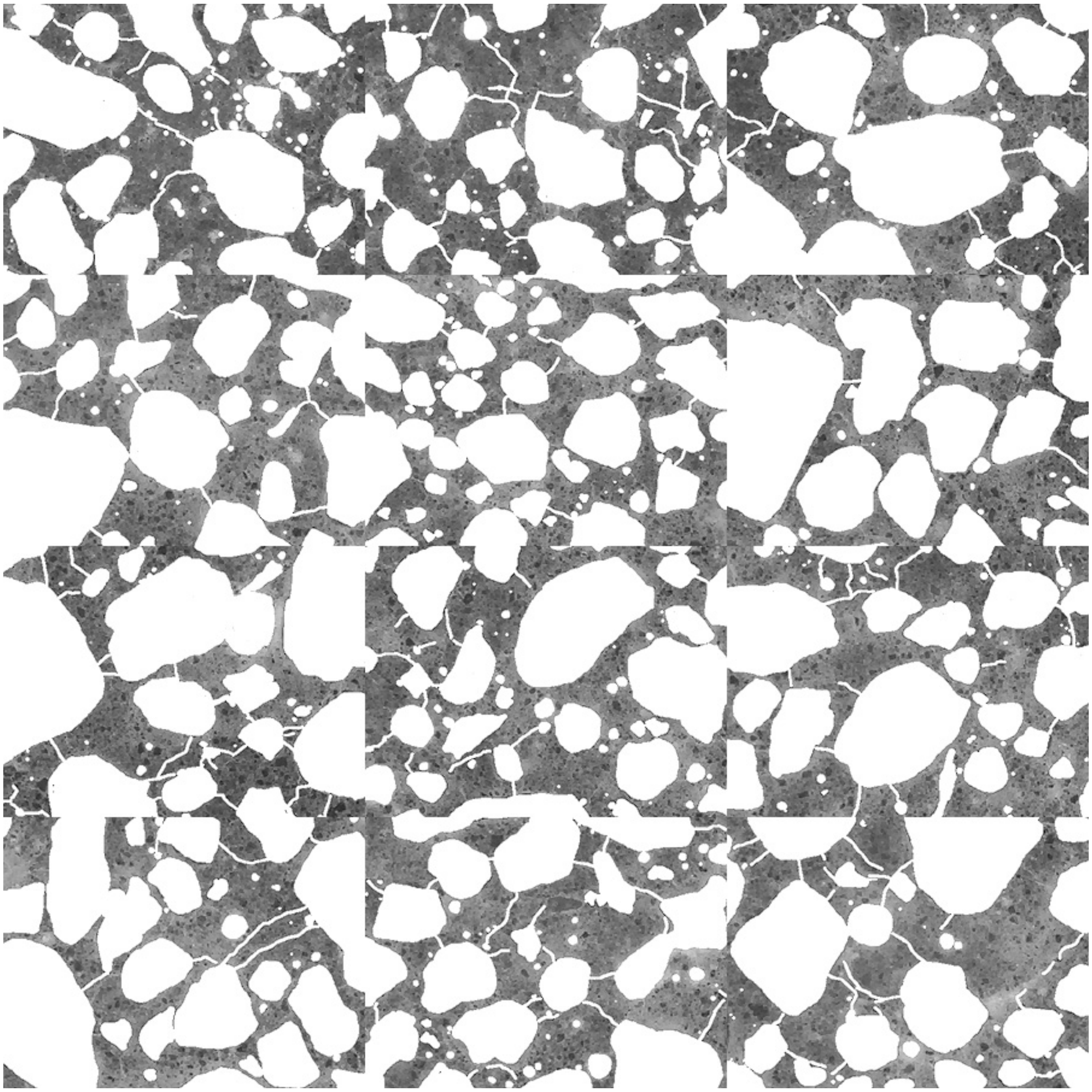

Figure IA-10: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of concrete overlay, core IA-3, after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table IA-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) from concrete overlay, core IA-3.

cement paste pixel fluorescence measurements (average intensity per frame)			
54	54	55	69
68	64	55	61
64	67	68	68
equivalent w/c (y = 0.0044x + 0.0329)			
0.27	0.27	0.27	0.34
0.33	0.31	0.27	0.30
0.31	0.32	0.33	0.33

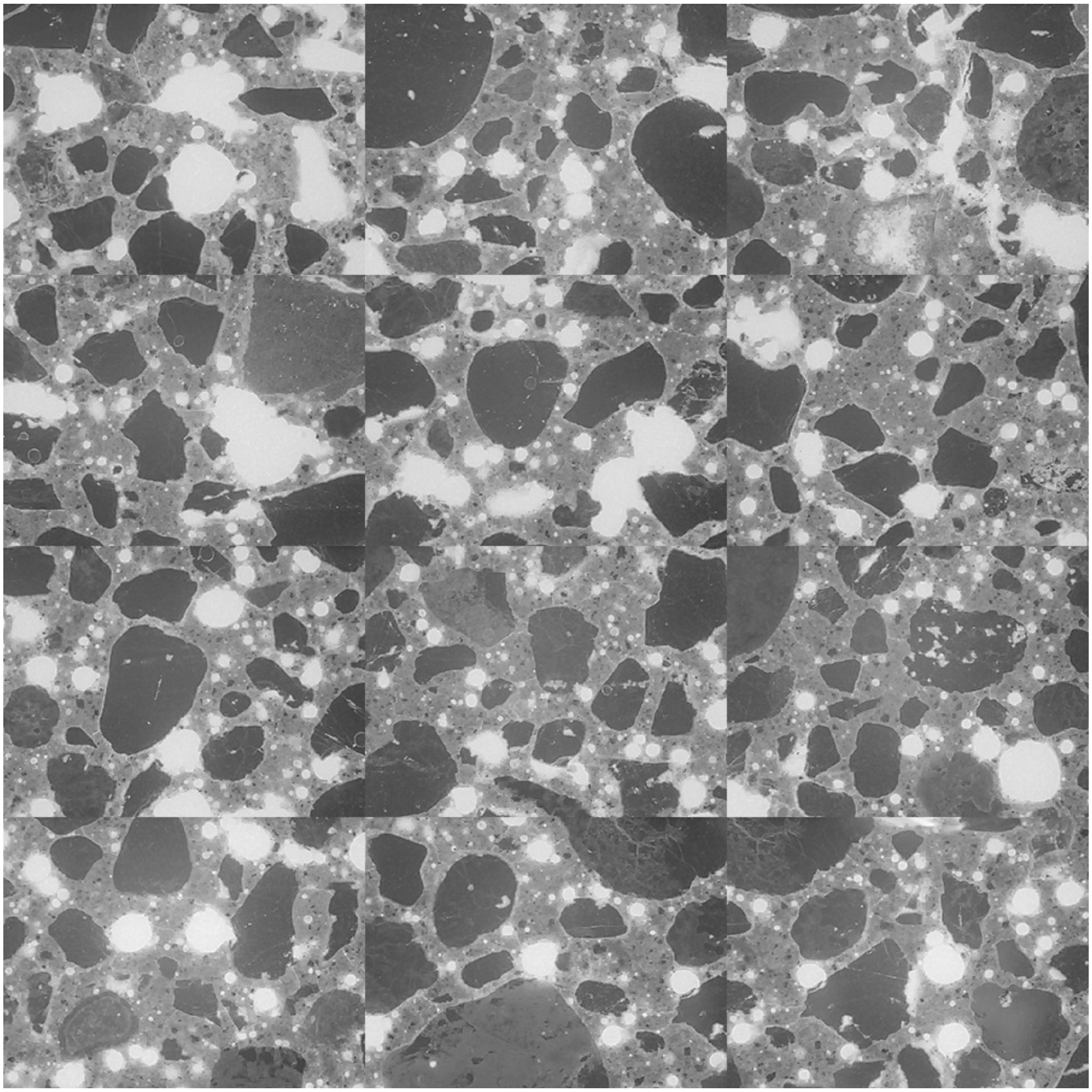

Figure IA-11: Mosaic of 12 frames collected from area of thin section representing the original concrete below the concrete overlay, core IA-11 (each individual frame measures 2.612 x 1.959 mm).

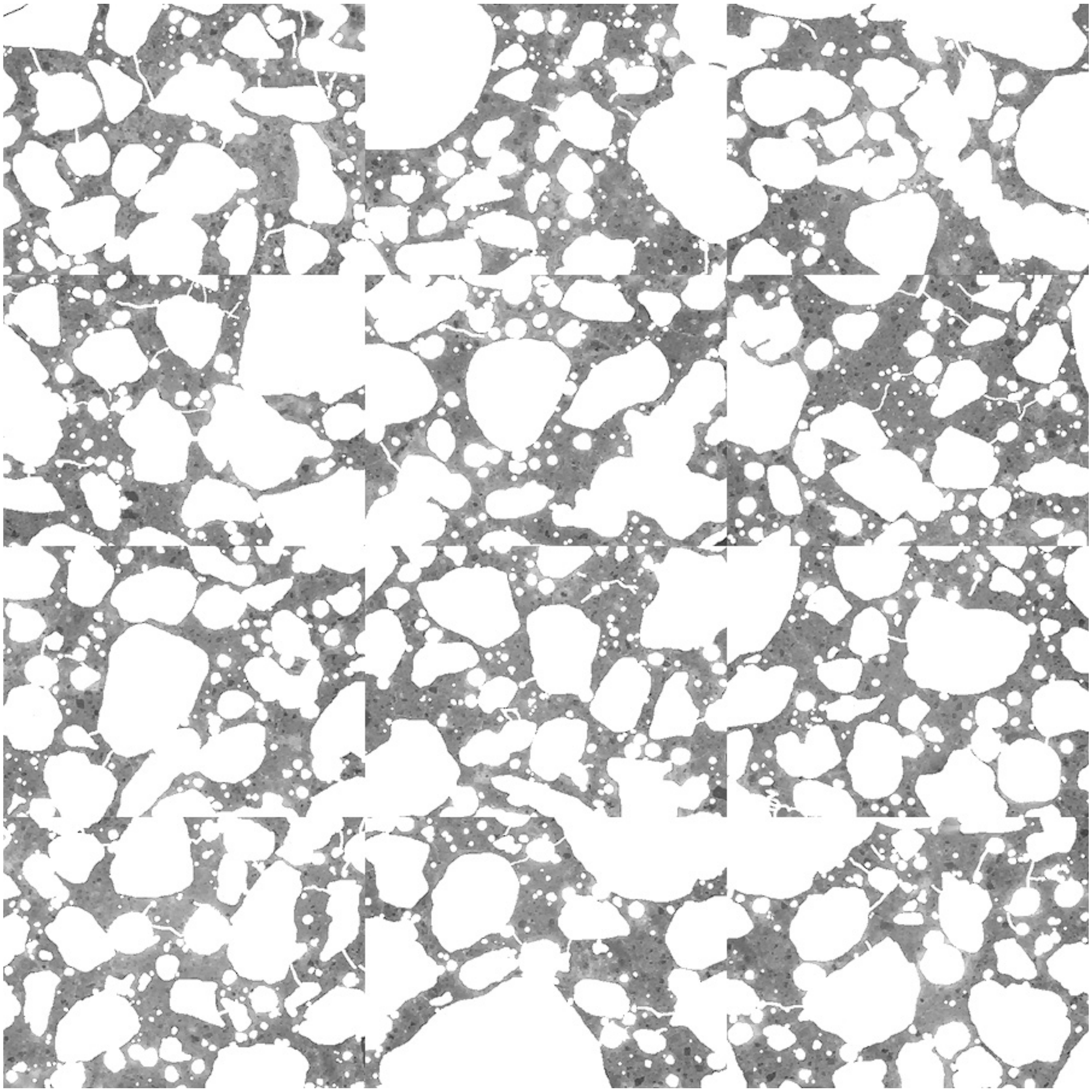

Figure IA-12: Mosaic of 12 frames collected area of thin section representing the original concrete below the concrete overlay, core IA-11, after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table IA-3: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) from original concrete below the overlay, core IA-11.

cement paste pixel fluorescence measurements (average intensity per frame)			
90	91	87	85
90	81	88	92
85	96	88	90
equivalent w/c ($y = 0.0044x + 0.0329$)			
0.42	0.43	0.41	0.40
0.42	0.39	0.42	0.43
0.40	0.45	0.41	0.43

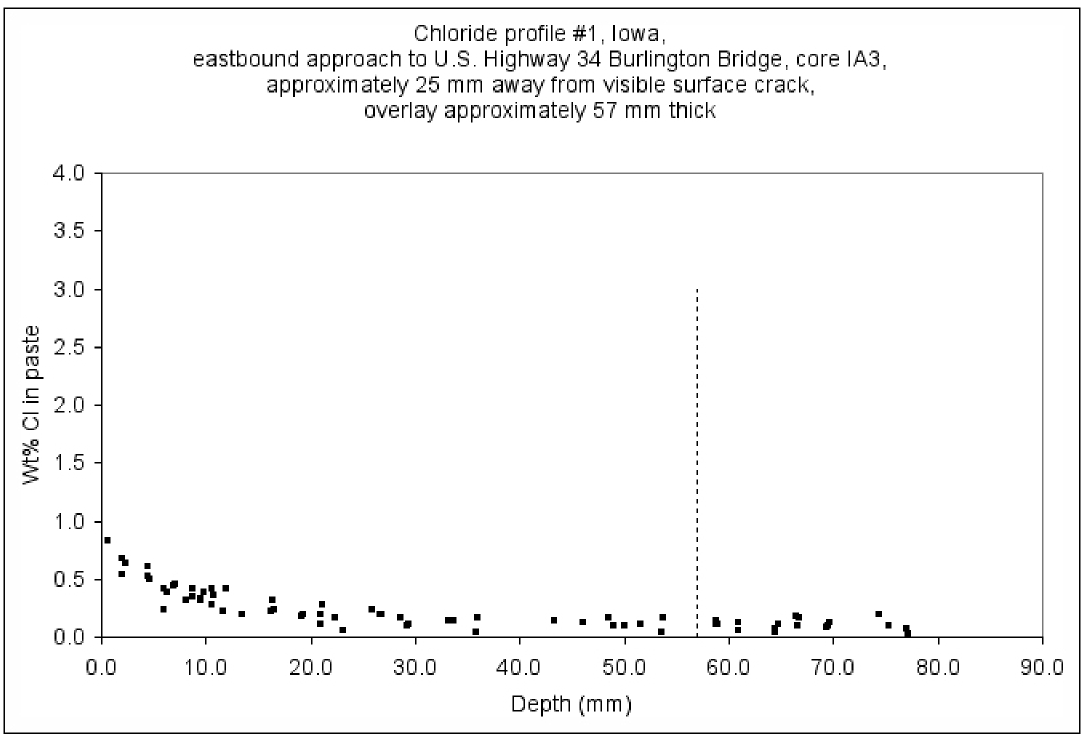

Figure IA-13: Chloride profile through cement paste about 25 mm away from visible surface crack, from billet prepared from core IA-3, dashed line marks the transition point between concrete overlay and the original concrete below the overlay.

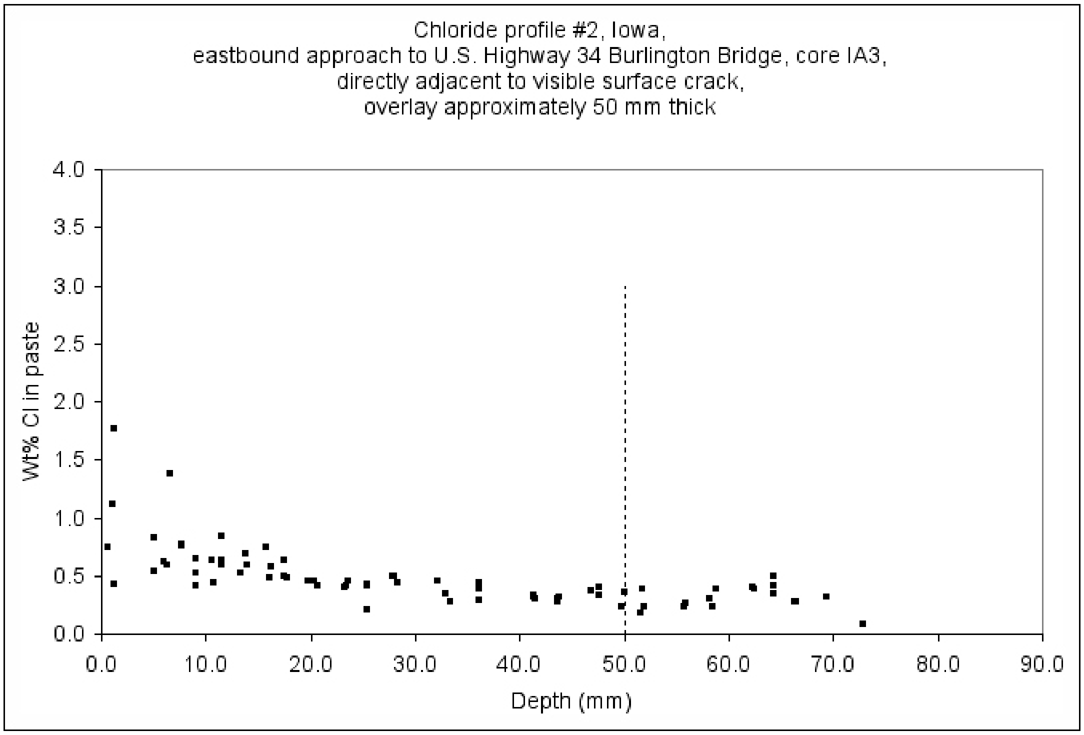

Figure IA-14: Chloride profile through cement paste, directly adjacent to visible surface crack, from billet prepared from core IA-3, dashed line marks the transition point between concrete overlay and the original concrete below the overlay.

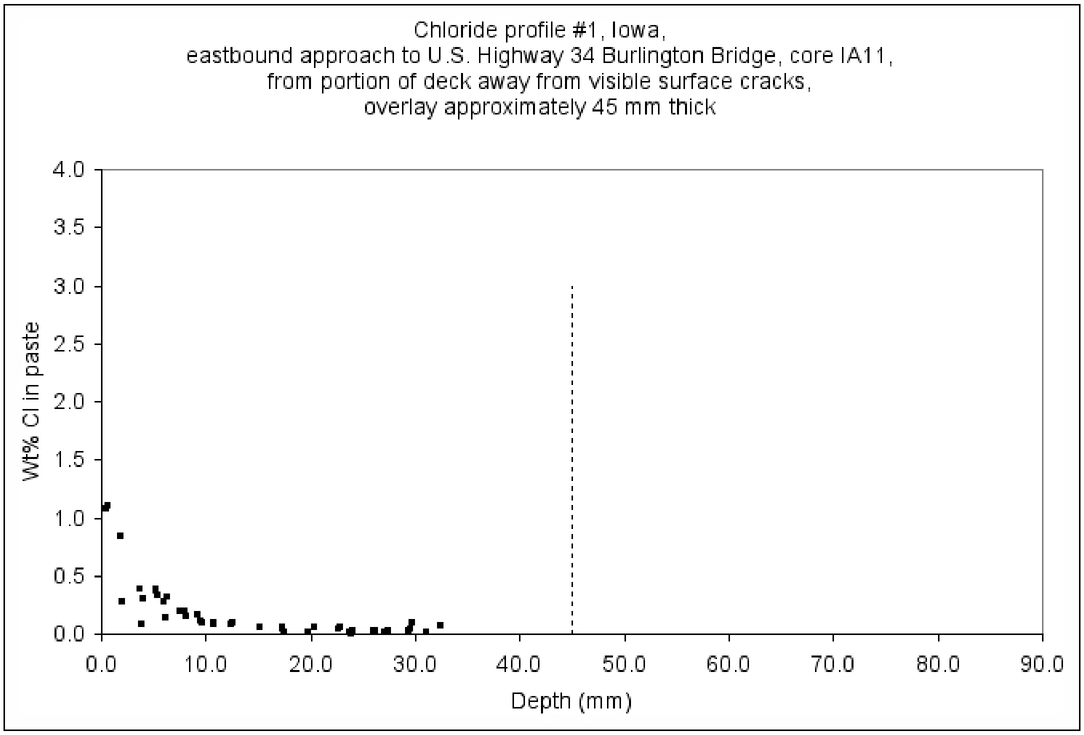

Figure IA-15: Chloride profile through cement paste, from billet prepared from core IA-11, dashed line marks the transition point between concrete overlay and the original concrete below the overlay.

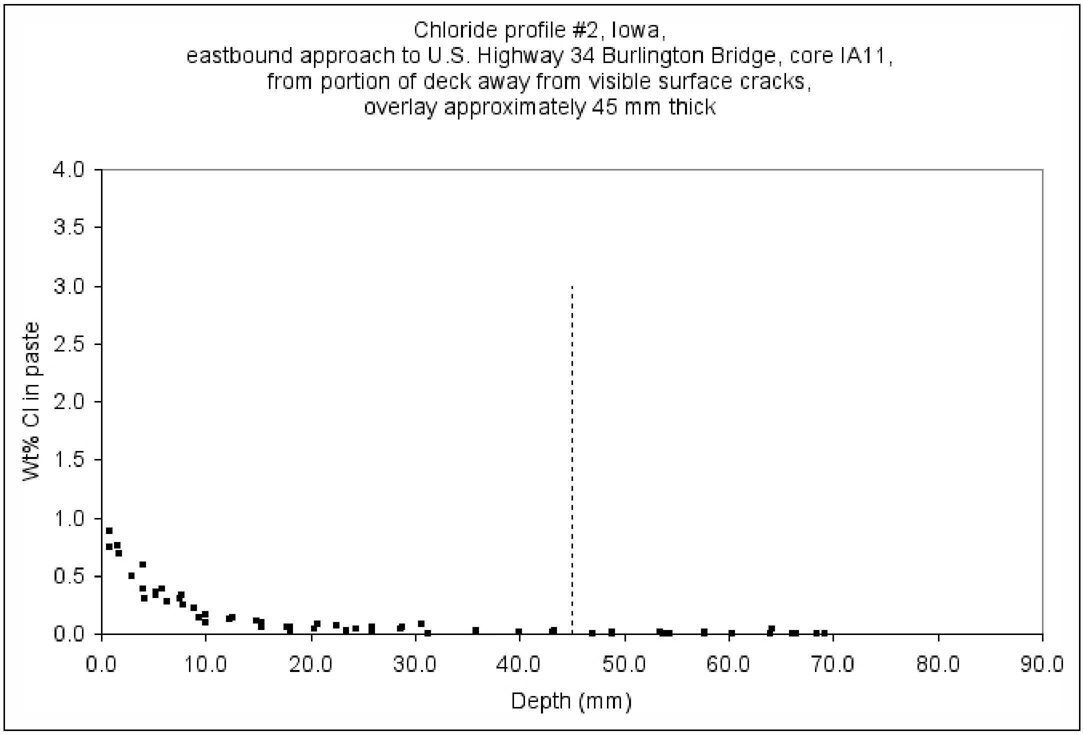

Figure IA-16: Chloride profile through cement paste, from billet prepared from core IA-11, dashed line marks the transition point between concrete overlay and the original concrete below the overlay.

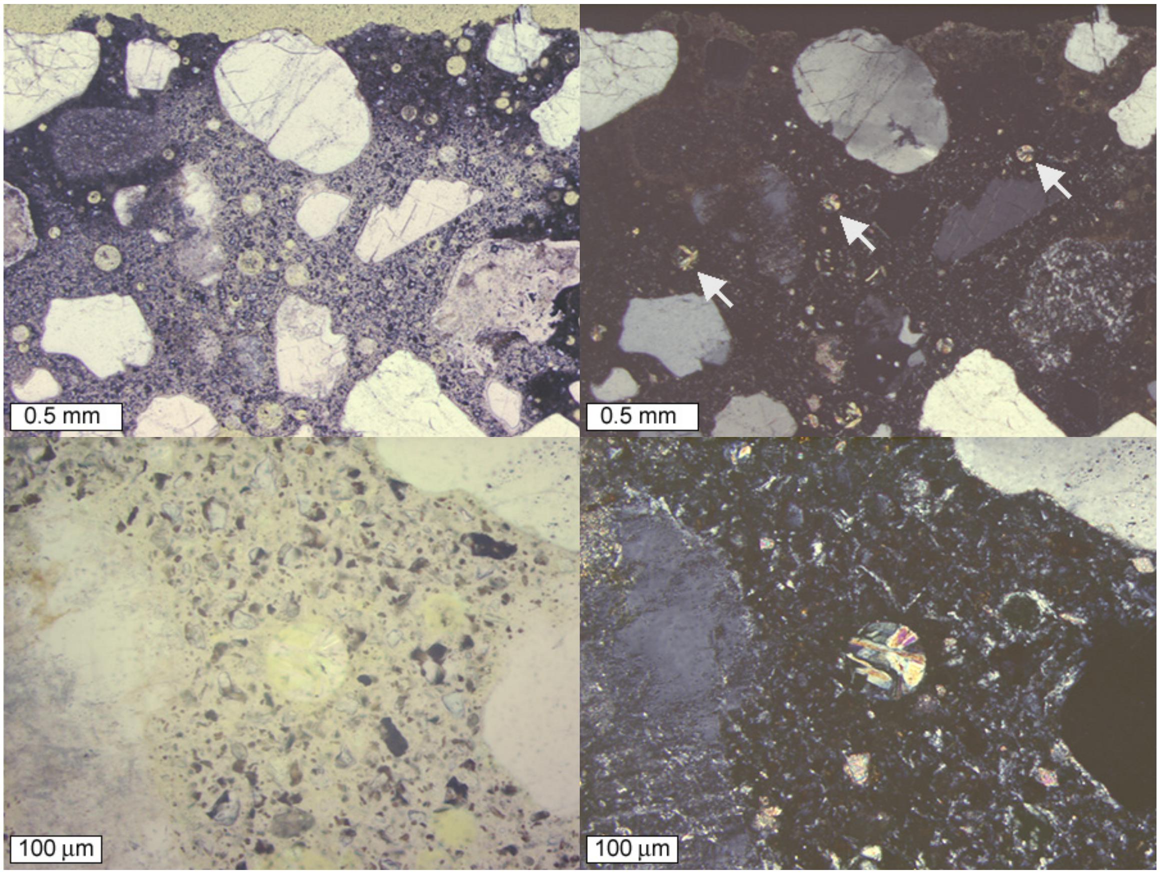

Figure IA-17: Transmitted light (left) and crossed polars (right) images showing $Ca(OH)_2$ deposits in air voids just below the pavement wear surface. White arrows in crossed polars image indicate some of the filled voids.

Idaho, westbound Interstate Highway 184 west of Boise, near milepost 3.

This pavement was constructed in 1992. It is reported to have been exposed to $MgCl_2$ for anti-icing, and NaCl for deicing. Figure ID-1 shows the locations of the cores, which came from both the far left and far right lanes. Figures ID-2 through ID-5 show photographs of the cores. Cores were slabbed and polished from both lanes, both at the joint, and away from the joint. Figures ID-6 through ID-13 show the slabs as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation depths. The black and white treatment did not reveal any macro-cracking in either of the cores, except for one crack at depth in core IDR-7, as shown in Figure ID-11. Table ID-1 summarizes the air void parameters, which varied considerably, from a low spacing factor value of 0.118 mm for core IDR-3, to a high spacing factor value of 0.267 mm for core IDL-6. Figure ID-14 shows an example stereomicroscope image of the more borderline air void structure from core IDR-7, (spacing factor 0.238 mm). A w/c ratio estimation was performed on a thin section prepared from the top of core IDL-1. Figures ID-15 and ID-16 show the images used to make the measurements. The results of the w/c estimation are summarized in Table ID-2, with an average w/c value of 0.46 as compared to the 28-day moist cured mortar sample standards. Figures ID-17 through ID-20 show chloride profiles from cores IDL-1 (at joint) and IDL-5 (mid-panel). The profiles from core IDL-1 show increased Cl penetration as compared to the profiles from core IDL-5.

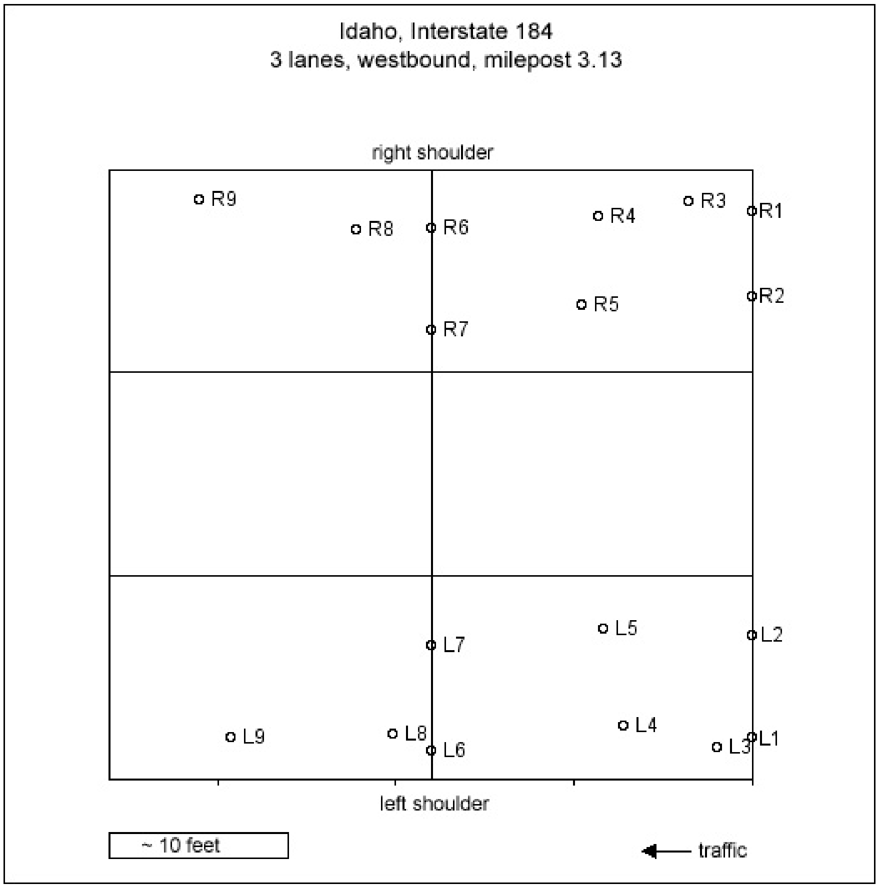

Figure ID-1: Diagram of core locations based on submitted field information.

Figure ID-2: Cores from left lane taken near pavement joints.

Figure ID-3: Cores from left lane taken away from pavement joints.

Figure ID-4: Cores from right lane taken near pavement joints.

Figure ID-5: Cores from right lane taken away from pavement joints.

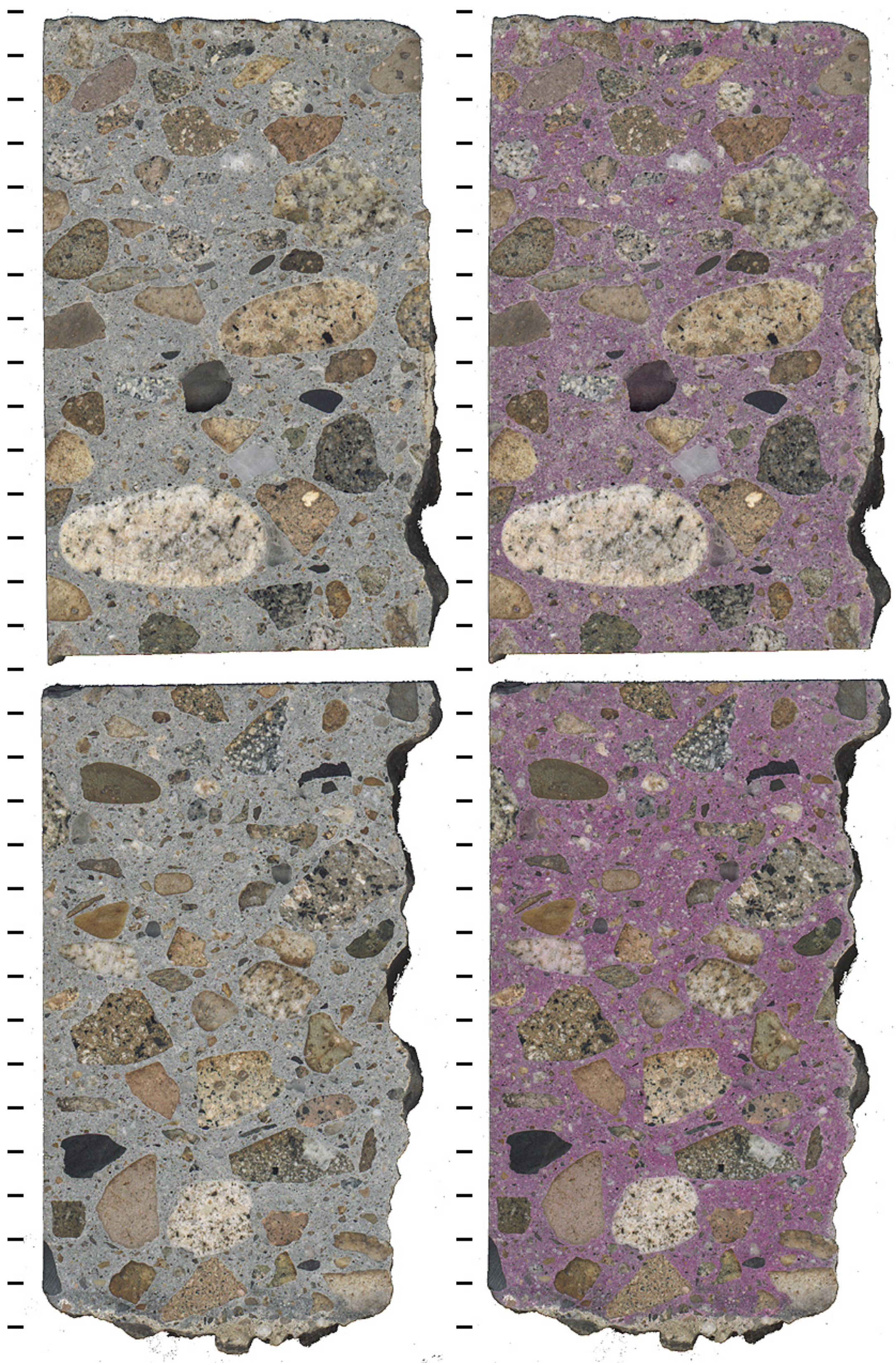

Figure ID-6: Polished slabs to show complete cross-section through core IDL-6 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

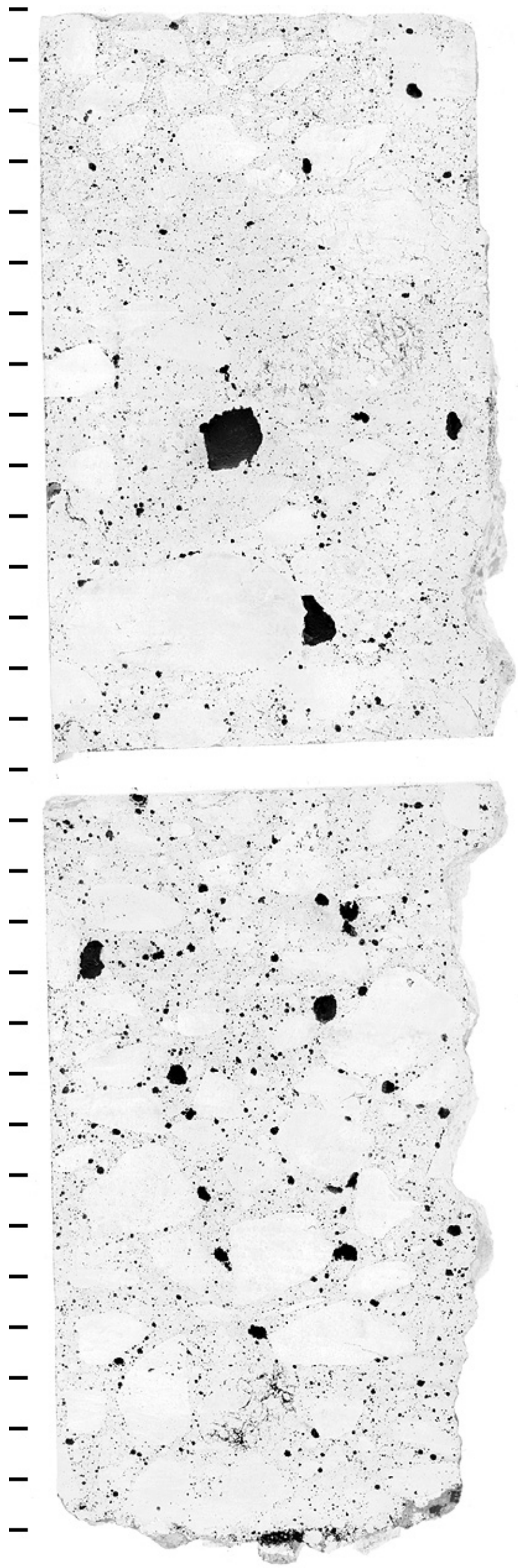

Figure ID-7: Polished slabs to show complete cross-section through core IDL-6 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

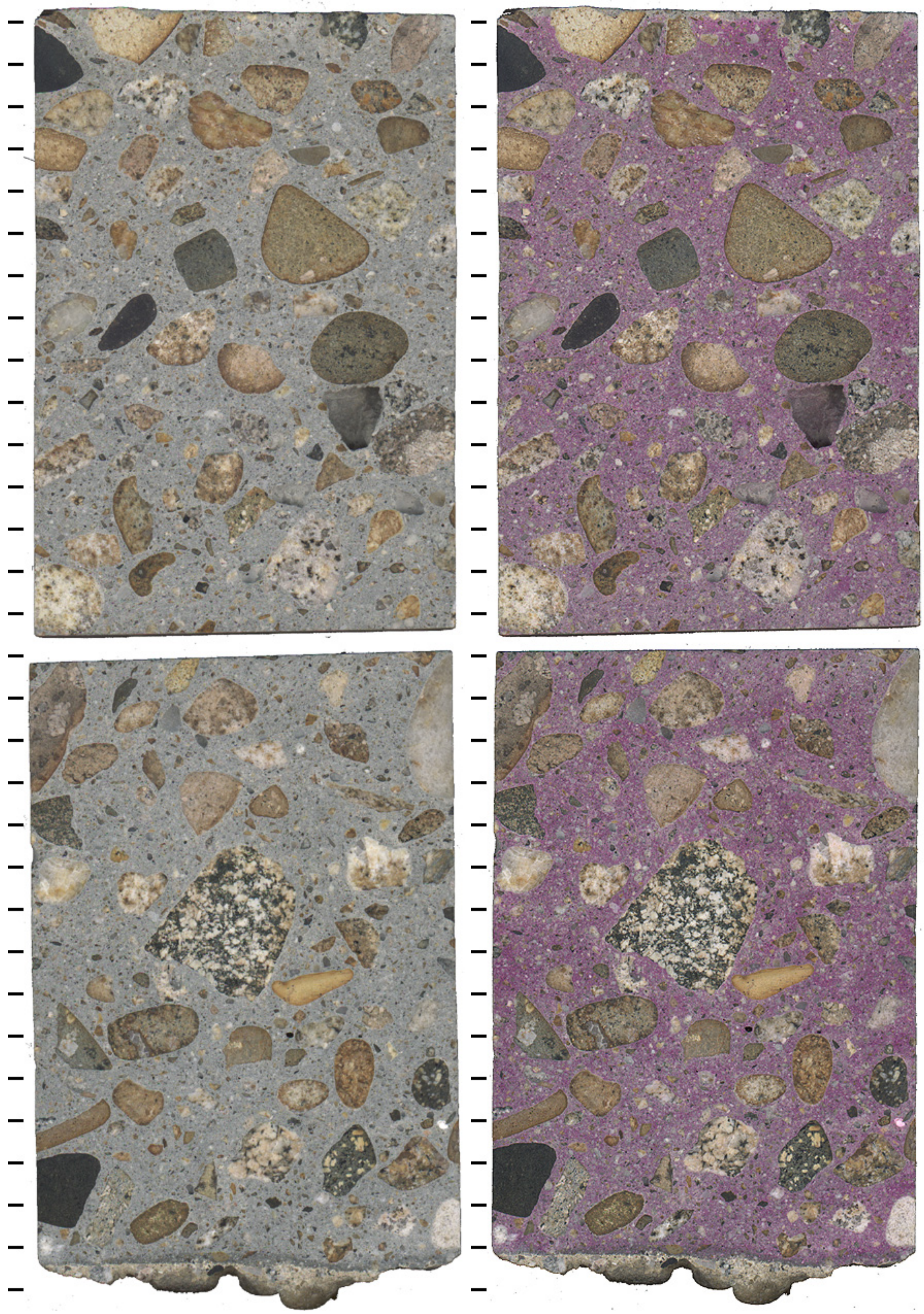

Figure ID-8: Polished slabs to show complete cross-section through core IDL-4 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

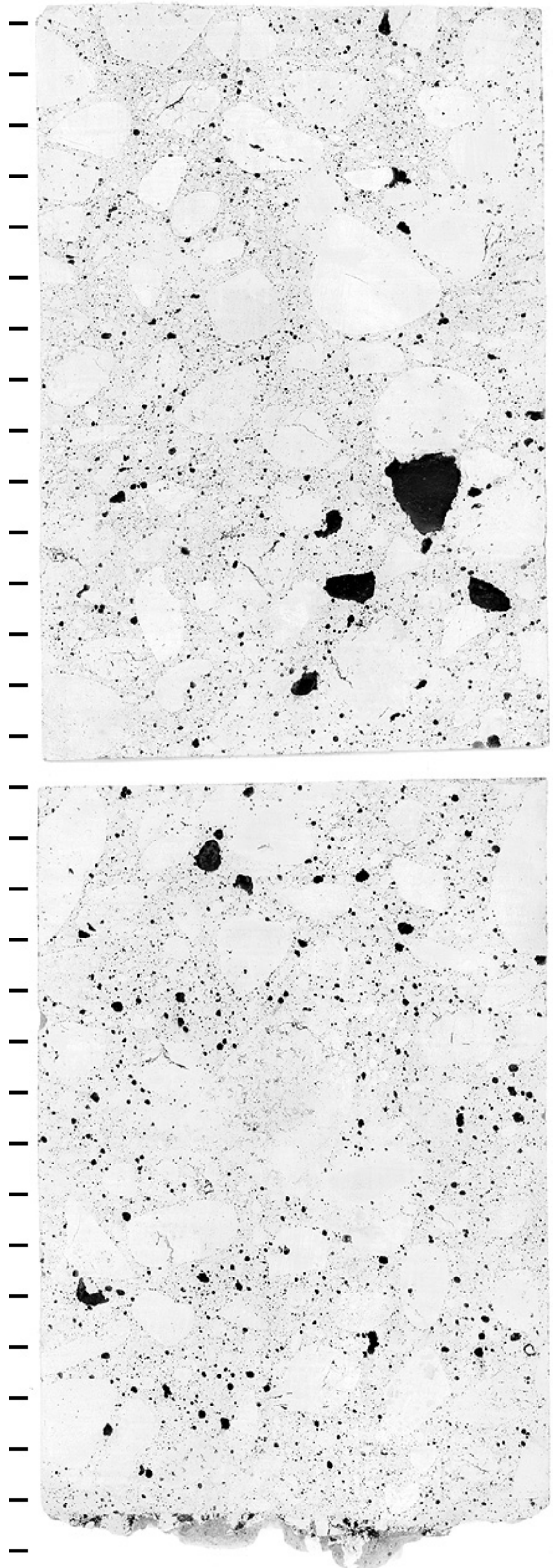

Figure ID-9: Polished slabs to show complete cross-section through core IDL-4 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

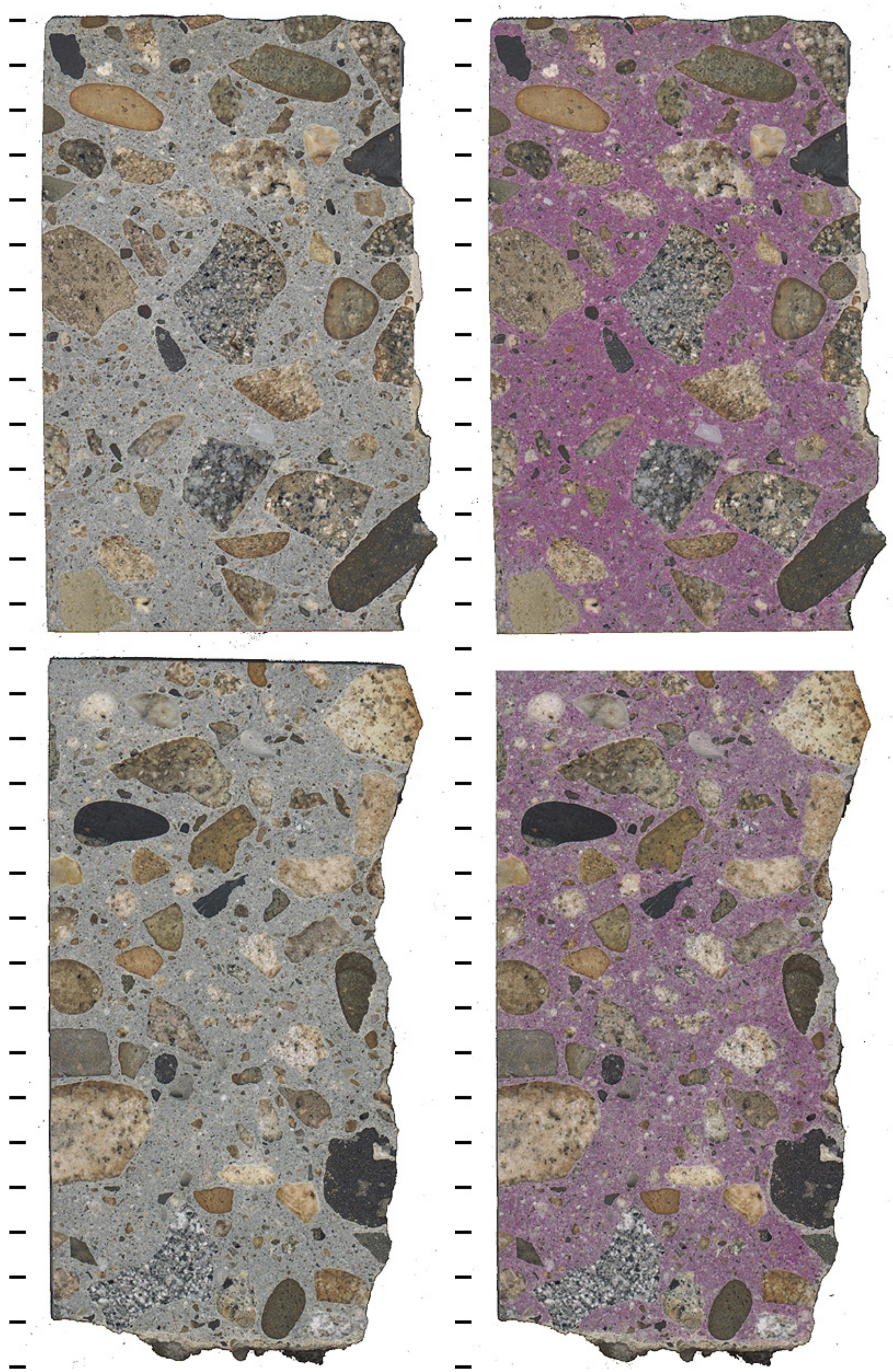

Figure ID-10: Polished slabs to show complete cross-section through core IDR-7 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

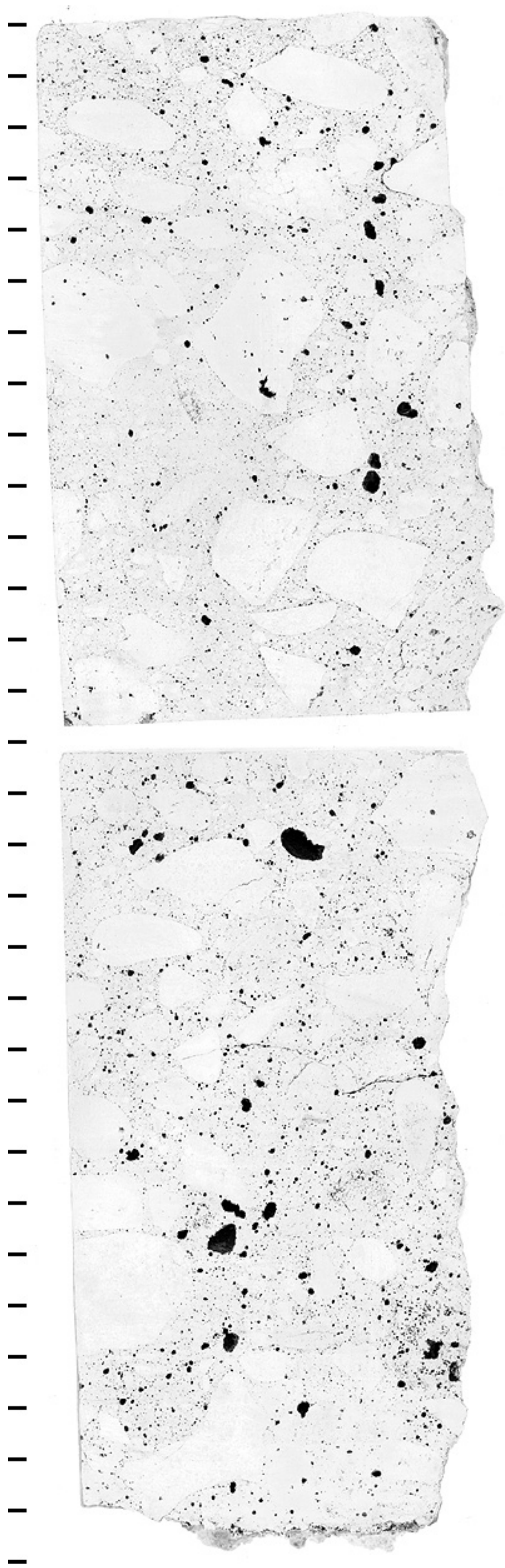

Figure ID-11: Polished slabs to show complete cross-section through core IDR-7 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

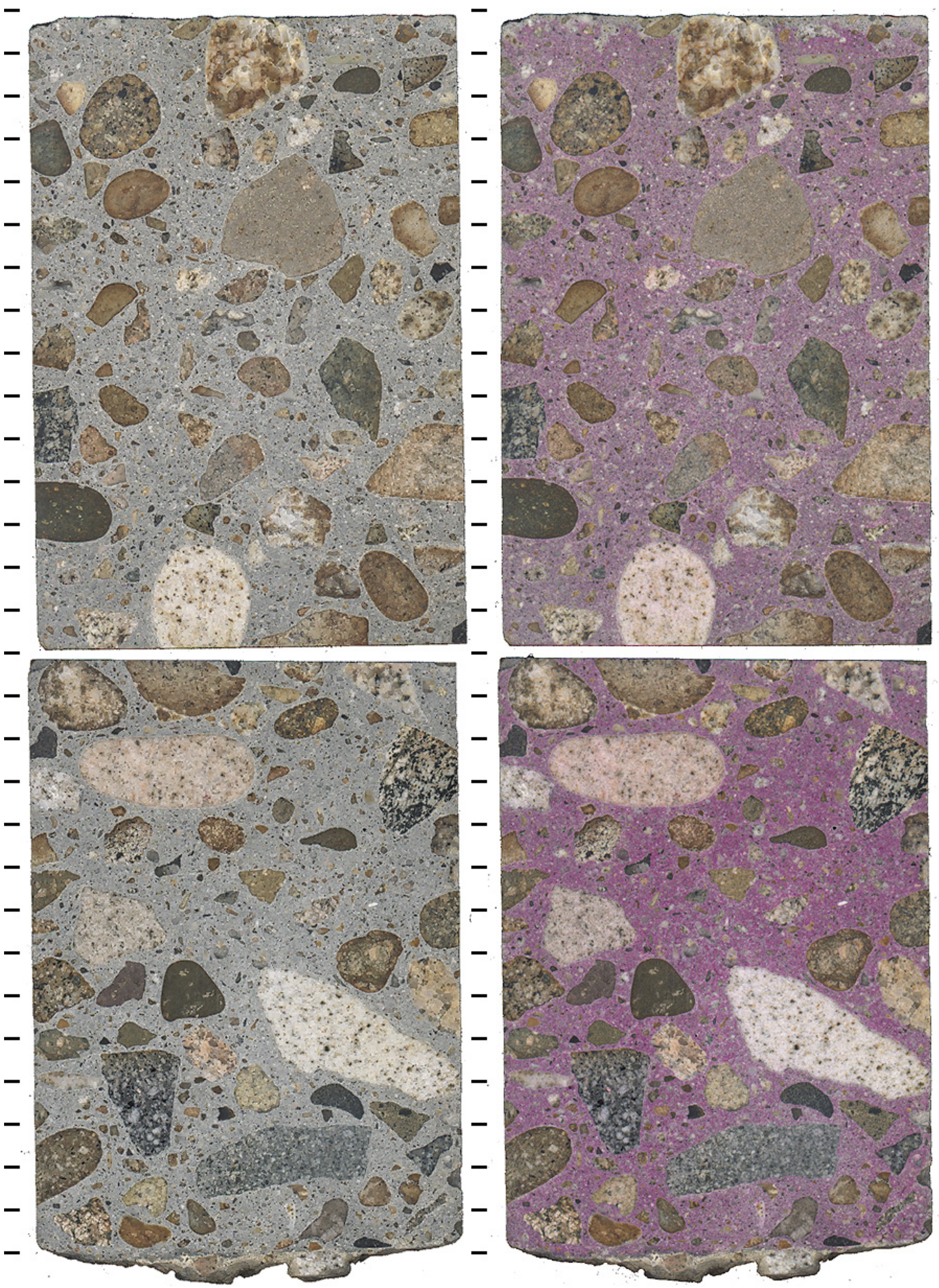

Figure ID-12: Polished slabs to show complete cross-section through core IDR-3 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

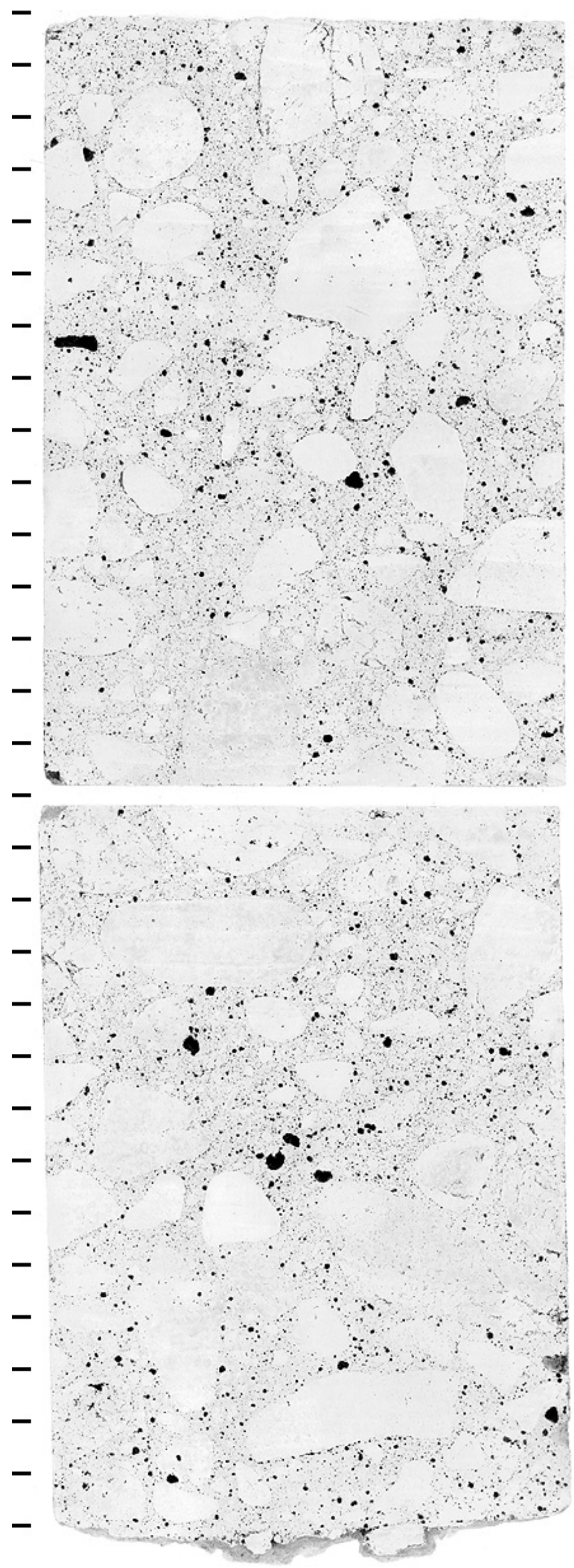

Figure ID-13: Polished slabs to show complete cross-section through core IDR-3 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

Table ID-1: Air void parameters.

Sample ID	ID_L06	ID_L04	ID_R07	ID_R03
Location	left-most lane, at joint	left-most lane, away from joint	right-most lane, at joint	right-most lane, away from joint
Raw data				
Total traverse length (mm)	3931.060	3931.060	3931.060	3931.060
Area analyzed (cm^2)	77.0	77.0	77.0	77.0
Air stops	102	143	100	152
Paste stops	365	358	433	353
Aggregate stops	1038	1004	972	1000
Secondary deposit stops	0	0	0	0
Total stops	1505	1505	1505	1505
Number of air intercepts	875	1630	1178	1949
Number of filled void intercepts	18	0	10	1
Results				
Air vol%	6.8	9.5	6.6	10.1
Paste vol%	24.3	23.8	28.8	23.5
Aggregate vol%	69.0	66.7	64.6	66.4
Secondary deposit vol%	0.0	0.0	0.0	0.0
Existing average chord length (mm)	0.304	0.229	0.222	0.204
Existing paste/air ratio	3.6	2.5	4.3	2.3
Existing air void specific surface (mm^{-1})	13.1	17.5	18.0	19.6
Existing air void frequency (voids/m)	223	415	300	496
Existing spacing factor (mm)	0.272	0.143	0.240	0.118
Original average chord length (mm)	0.298	0.229	0.220	0.204
Original paste/air ratio	3.6	2.5	4.3	2.3
Original air void specific surface (mm^{-1})	13.4	17.5	18.2	19.6
Original air void frequency (voids/m)	227	415	302	496
Original spacing factor (mm)	0.267	0.143	0.238	0.118

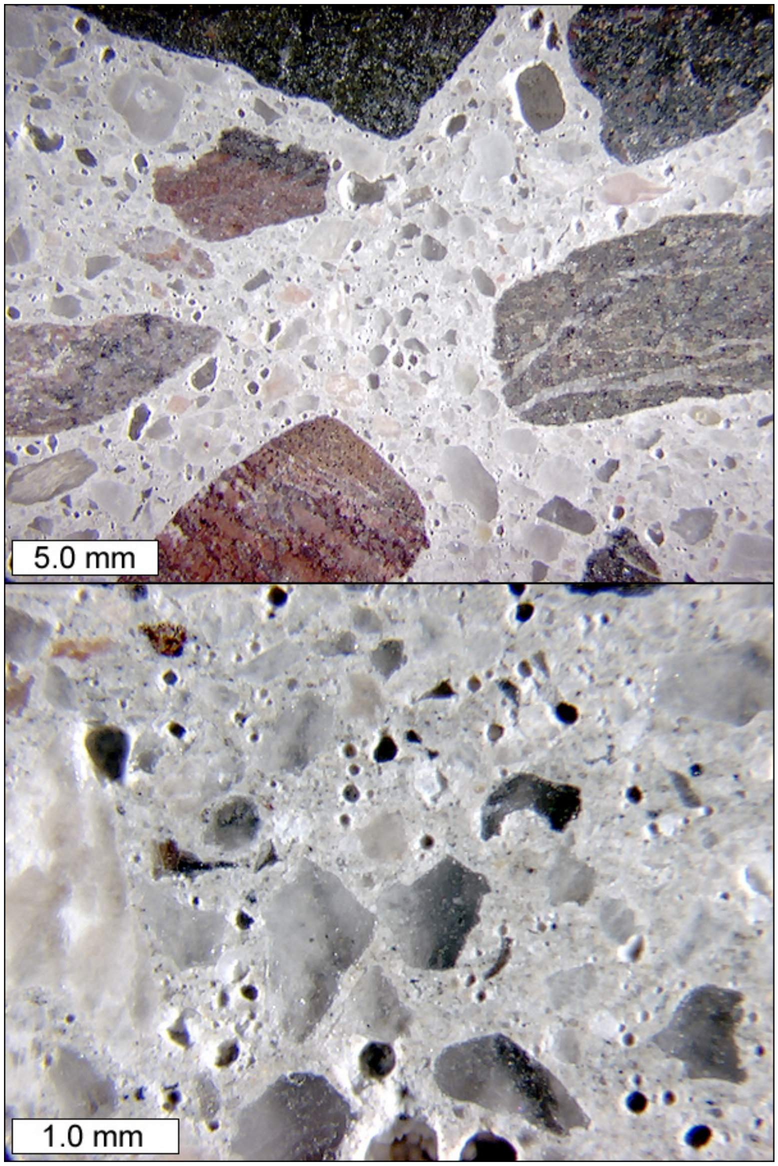

Figure ID-14: Stereo microscope images to show air void structure on polished slab from core IDR-7.

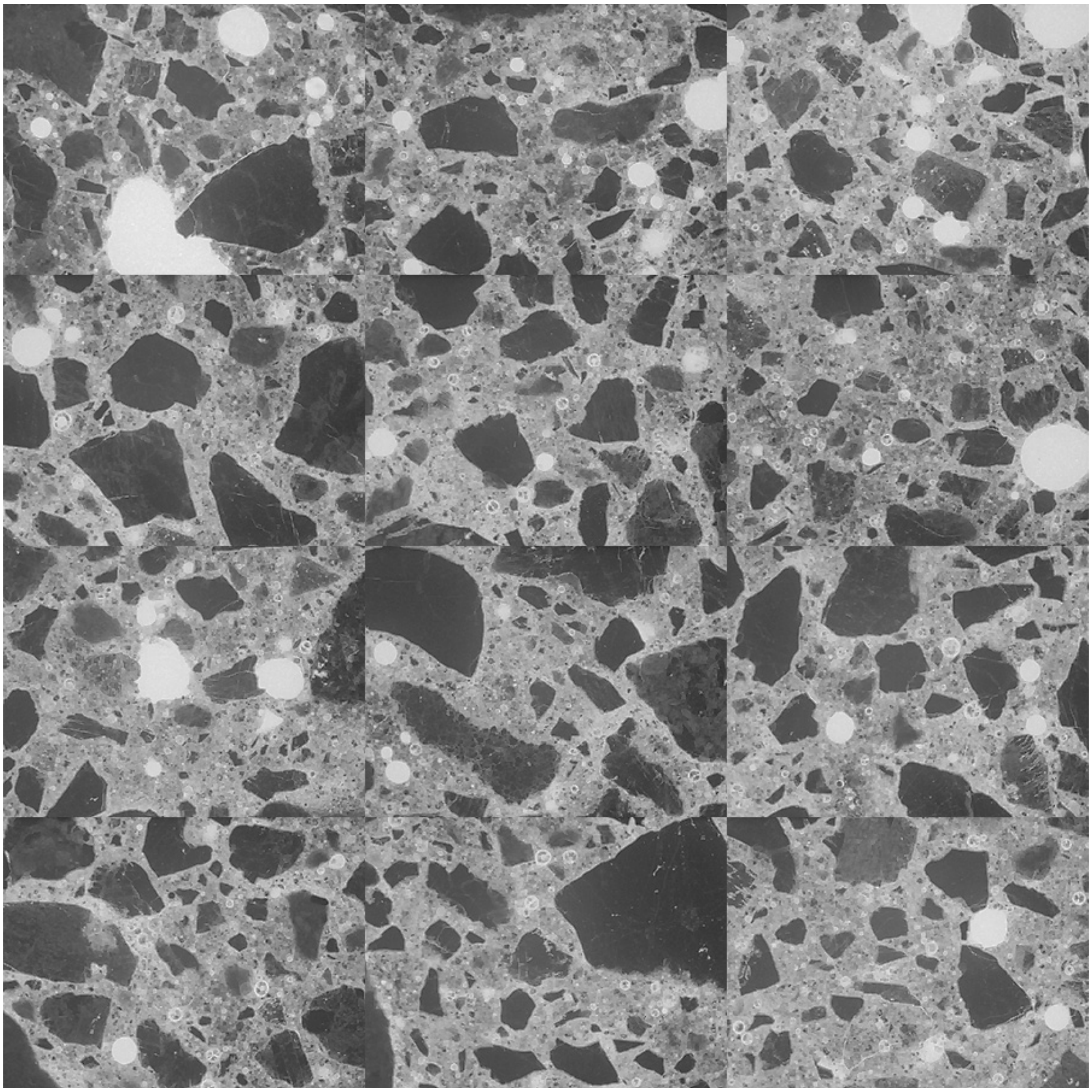
Figure ID-15: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core IDL-1 (each individual frame measures 2.612 x 1.959 mm).

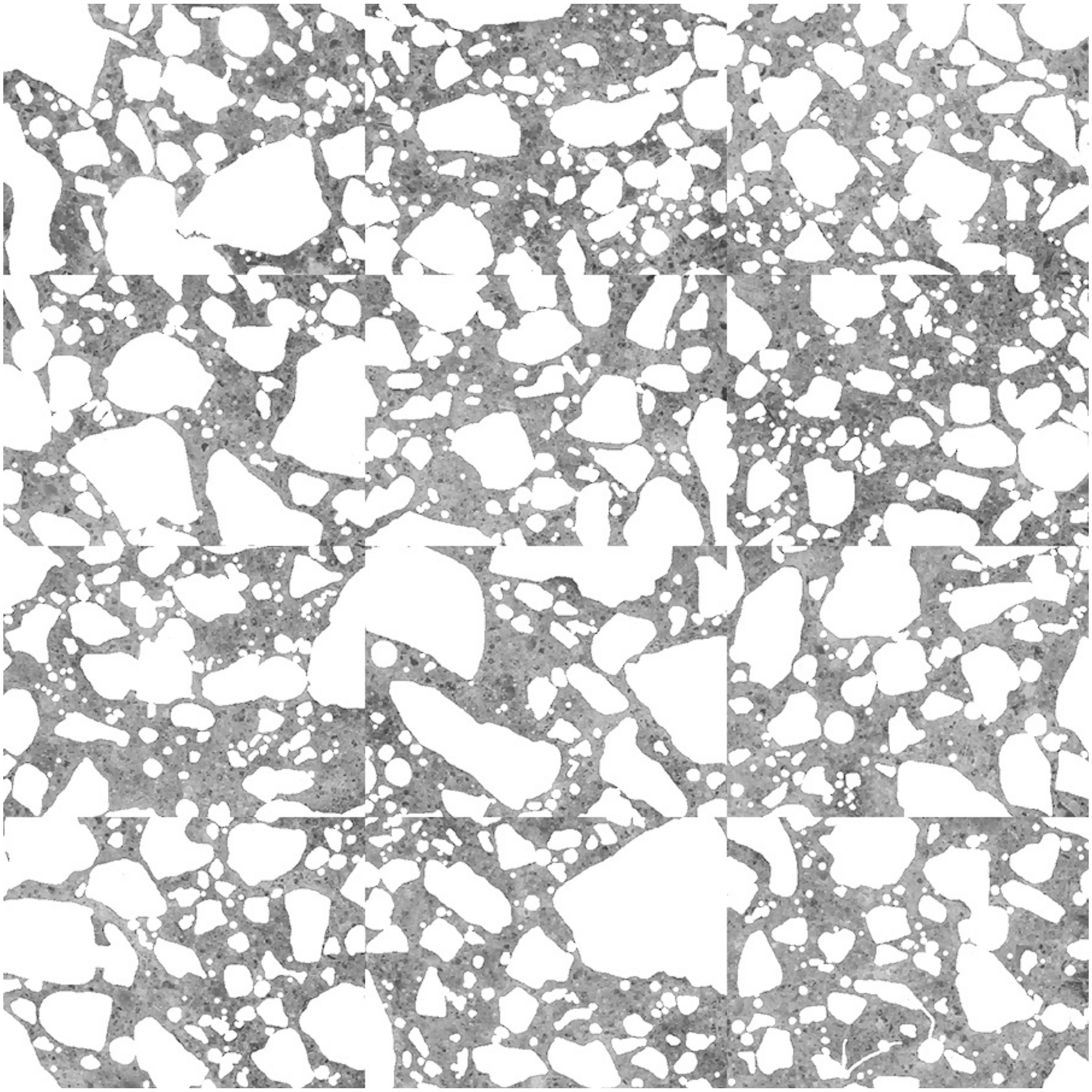

Figure ID-16: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core IDL-1 after masking out air voids and fine aggregate to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table ID-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples).

cement paste pixel fluorescence measurements (average intensity per frame)			
90	88	105	105
101	86	99	98
105	98	99	104
equivalent w/c ($y = 0.0044x + 0.0329$)			
0.43	0.42	0.49	0.49
0.47	0.41	0.47	0.46
0.49	0.46	0.47	0.49

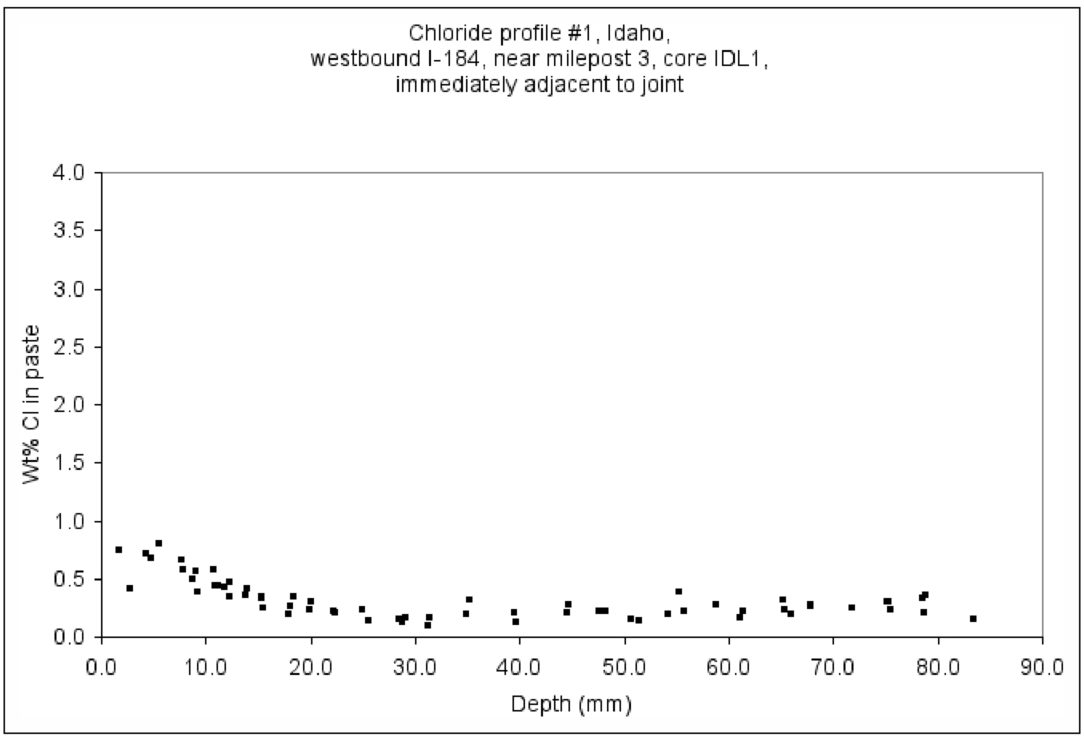

Figure ID-17: Chloride profile through cement paste immediately adjacent to joint, from billet prepared from core IDL-1.

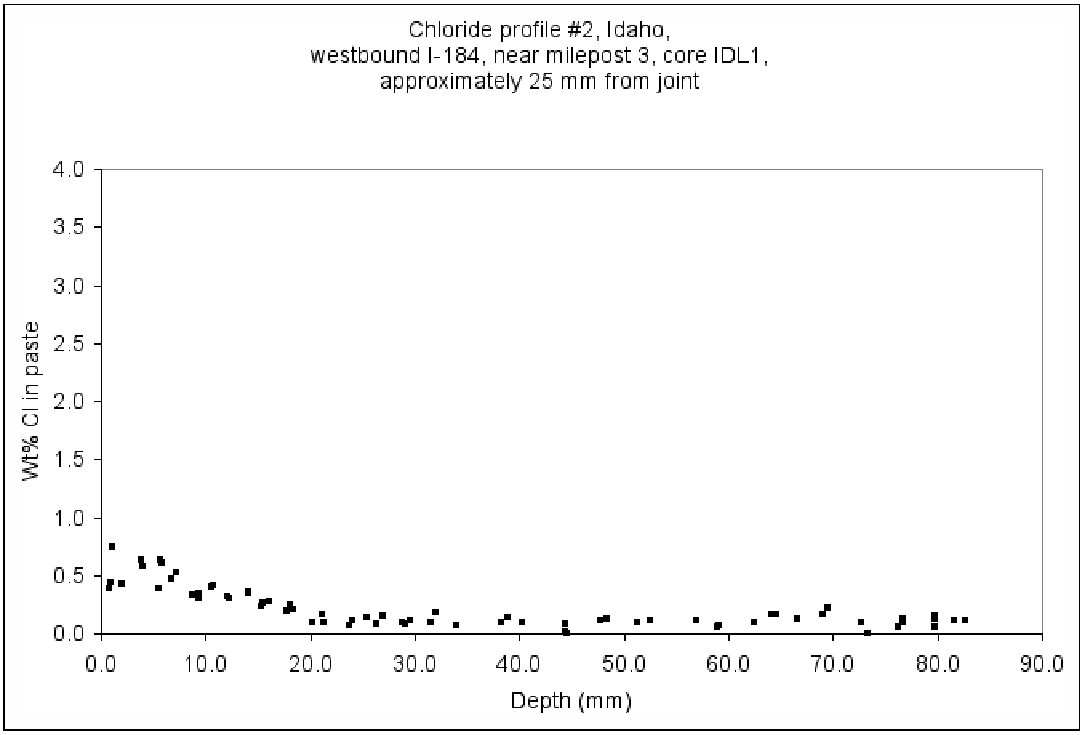

Figure ID-18: Chloride profile through cement paste 25 mm away from joint, from billet prepared from core IDL-1.

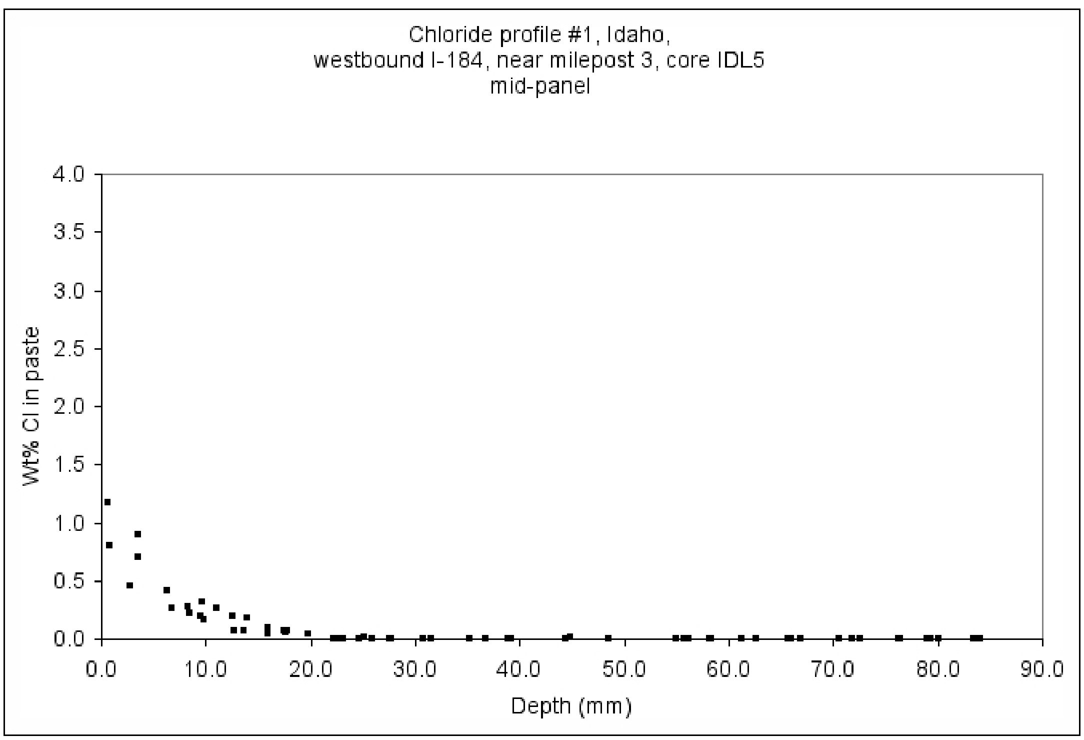

Figure ID-19: Chloride profile through cement paste at mid-panel, from billet prepared from core IDL-5.

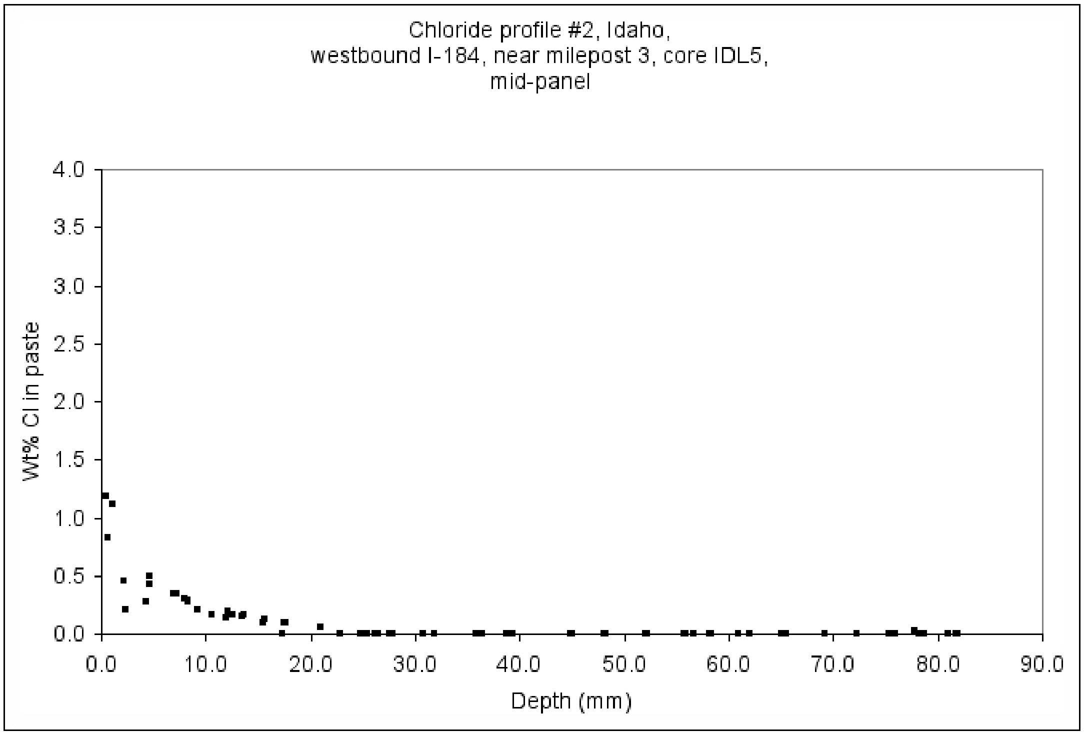

Figure ID-20: Chloride profile through cement paste at mid-panel, from billet prepared from core IDL-5.

Montana, westbound Interstate Highway 90 bridge deck near milepost 117

Partial depth cores 5 to 6" in depth were received from this bridge deck. The top 2" of the cores consisted of a latex modified concrete overlay. The deck is reported to have been exposed to $MgCl_2$ for anti-icing, and NaCl for deicing. Figure MT-1 shows the locations of the cores, and Figure MT-2 shows an incomplete series of photographs of the cores as received. Figure MT-3 shows the variation in surface wear observed on some of the cores. Two of the cores were cut into slabs and polished: core MT-2 and core MT-8. Figures MT-4 through MT-6 show the slabs as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation depths. The black and white treatment did not reveal any macro-cracking in either of the cores. Table MT-1 summarizes the air void parameters. The overlay from both slabs exhibited inadequate entrained air parameters, with spacing factors of 0.432 mm and 0.687 mm for cores MT-2 and MT-8 respectively. However, considering the extreme density of the cement paste, air entrainment is not likely a requirement for the latex-modified overlay. Figure MT-7 shows an example stereomicroscope image of the air void structure. A w/c ratio estimation was performed on a thin section prepared from the top concrete overlay portion and from the original concrete portion of core MT-3. Figures MT-8 through MT-11 show the images used to make the measurements. The results of the w/c estimations are summarized in Tables MT-2 and MT-3, with an average w/c value of 0.13 for the overlay, and an average w/c value of 0.42 for the original concrete. The unusual w/c value of 0.13 should not be interpreted as an accurate measure of the actual w/c, but rather as a comparison to the 28-day moist cured straight portland cement mortar standards. Figures MT-12 through MT-15 show chloride profiles collected from core MT-1 and core MT-3. The transition from overlay to original concrete is apparent in the profiles, and it appears that there is some diffusion of chlorine from the original concrete up into the base of the overlay.

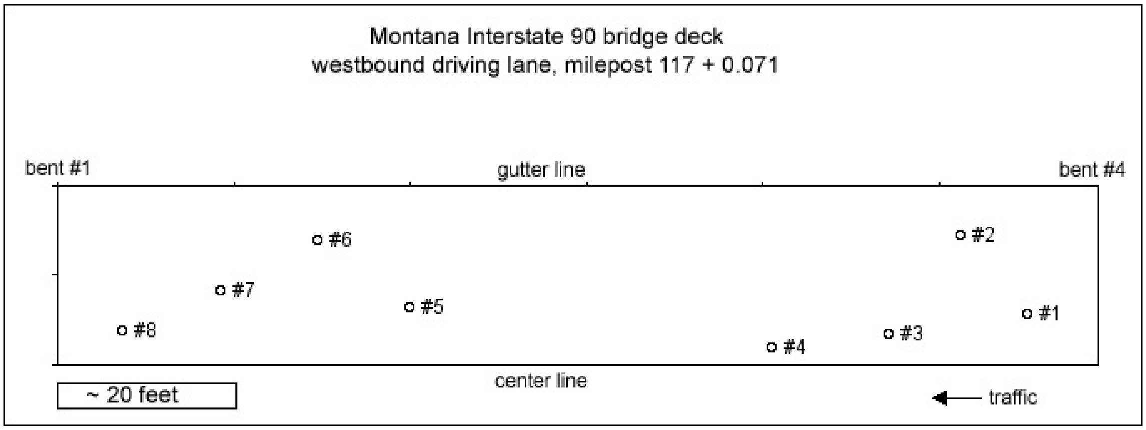

Figure MT-1: Diagram to show core locations based on submitted field information.

Figure MT-2: Photographs of cores.

Figure MT-3: Photograph to show variation in surface wear from core to core.

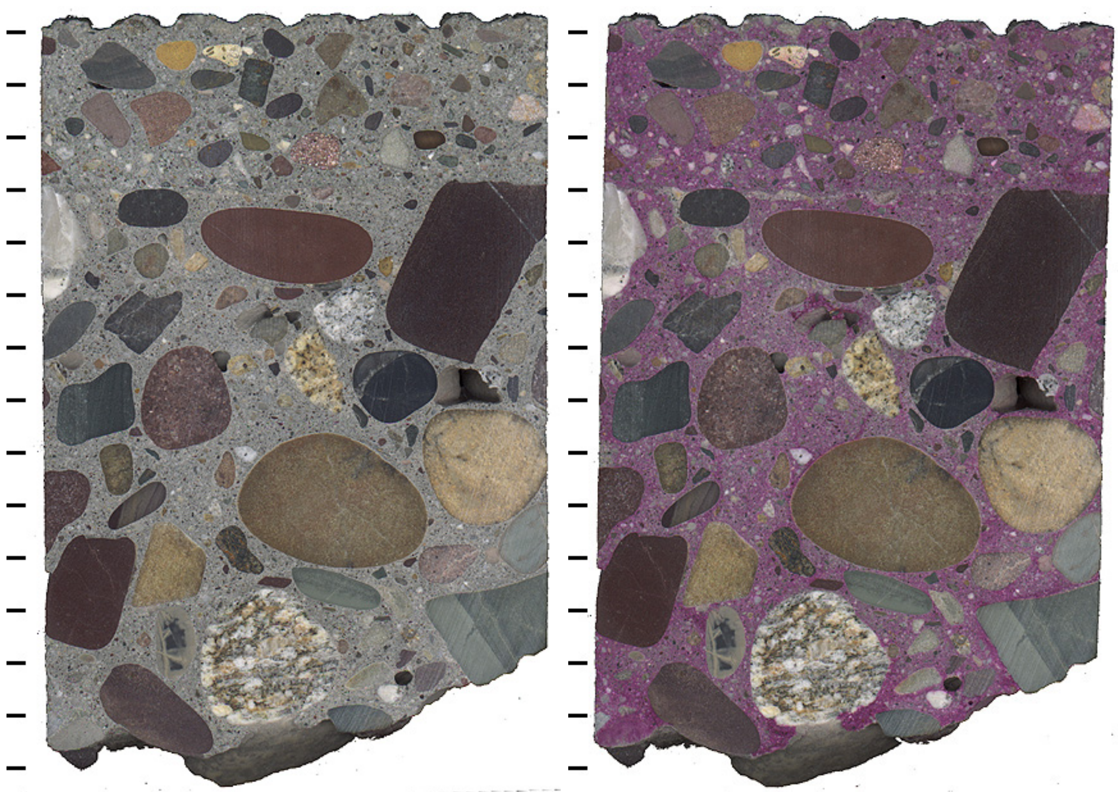
Figure MT-4: Polished slabs to show complete cross-section through core MT-2 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

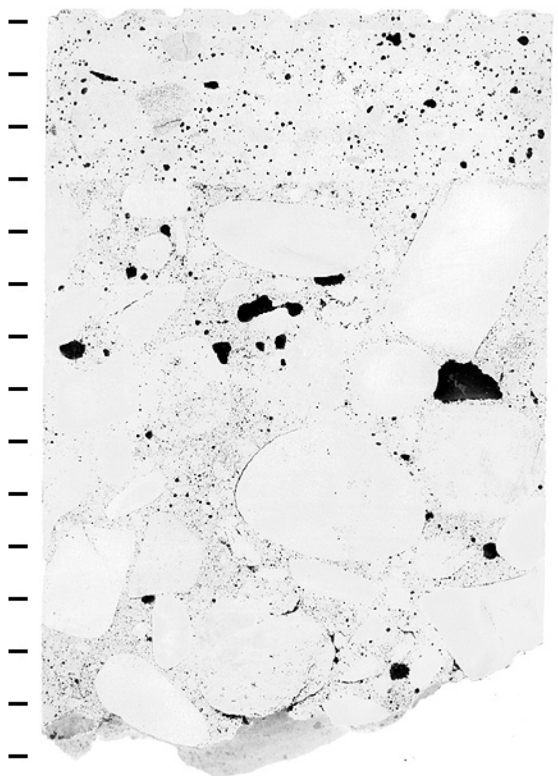

Figure MT-5: Polished slabs to show complete cross-section through core MT-2 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

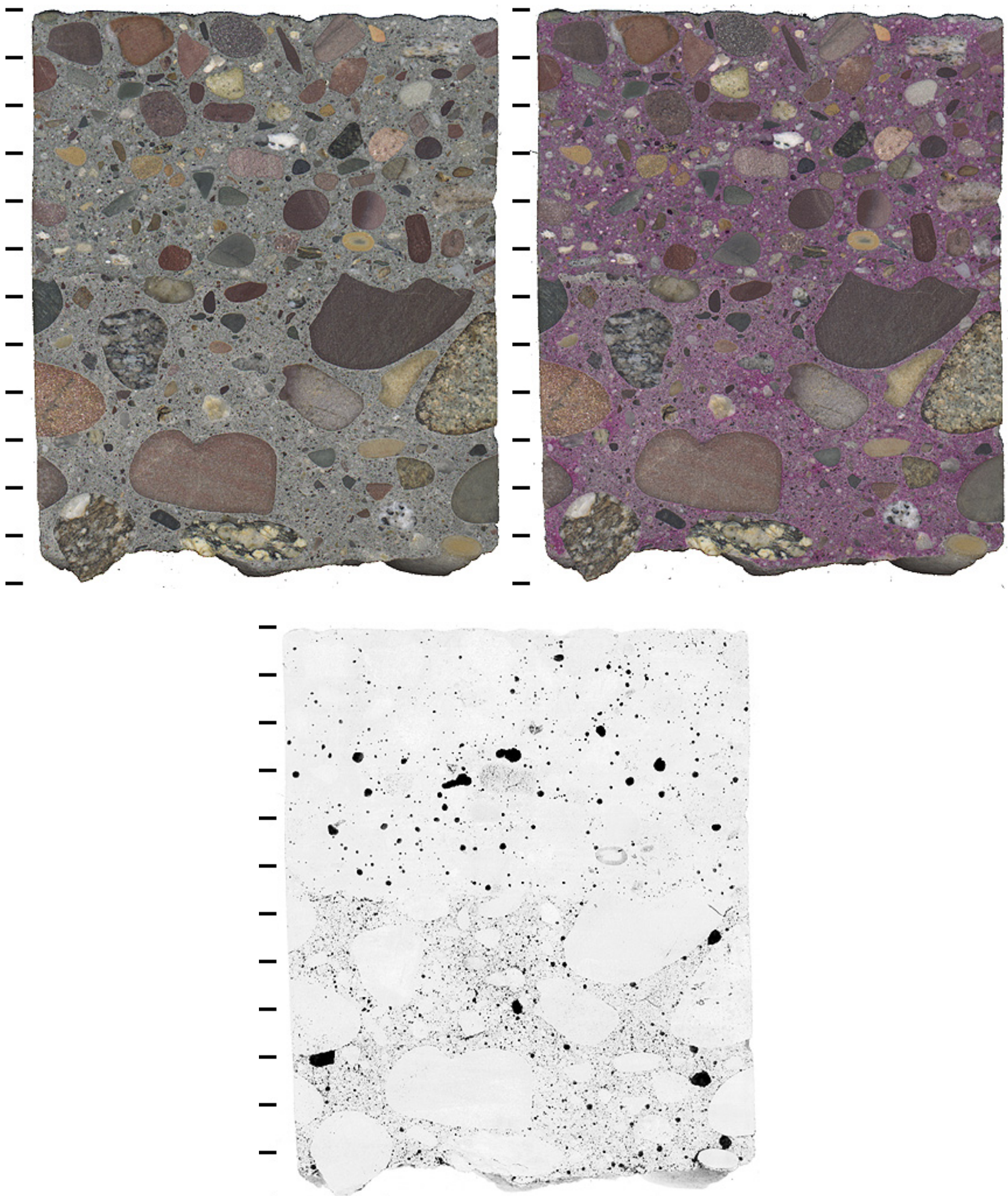

Figure MT-6: Polished slabs to show complete cross-section through core MT-8, before (upper left) and after application of phenolphthalein stain (upper right) and after treatment to enhance appearance of air voids and cracks (bottom) tic marks every cm.

Table MT-1: Air void parameters from concrete overlay.

Sample ID	MT_02	MT_08
Location	tining intact	tining worn
Raw data		
Total traverse length (mm)	3400.824	3408.660
Area analyzed (cm^2)	66.6	66.8
Air stops	47	43
Paste stops	419	424
Aggregate stops	833	836
Secondary deposit stops	3	2
Total stops	1302	1305
Number of air intercepts	419	234
Number of filled void intercepts	24	30
Results		
Air vol%	3.6	3.3
Paste vol%	32.2	32.5
Aggregate vol%	64.2	64.2
Secondary deposit vol%	0.2	0.2
Existing average chord length (mm)	0.293	0.480
Existing paste/air ratio	9.0	9.9
Existing air void specific surface (mm^{-1})	13.7	8.3
Existing air void frequency (voids/m)	123	69
Existing spacing factor (mm)	0.443	0.758
Original average chord length (mm)	0.295	0.445
Original paste/air ratio	8.4	9.4
Original air void specific surface (mm^{-1})	13.6	9.0
Original air void frequency (voids/m)	130	77
Original spacing factor (mm)	0.432	0.687

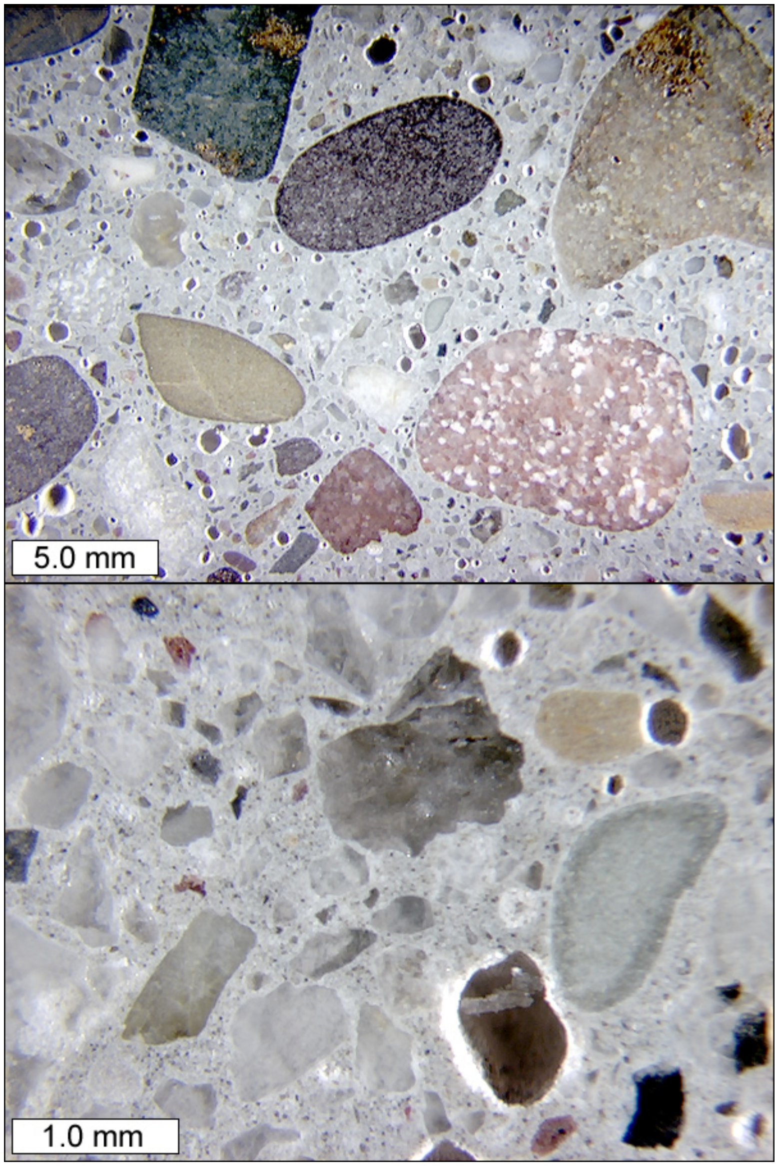

Figure MT-7: Stereo microscope images to show air void structure of concrete overlay on polished slab from core MT-2.

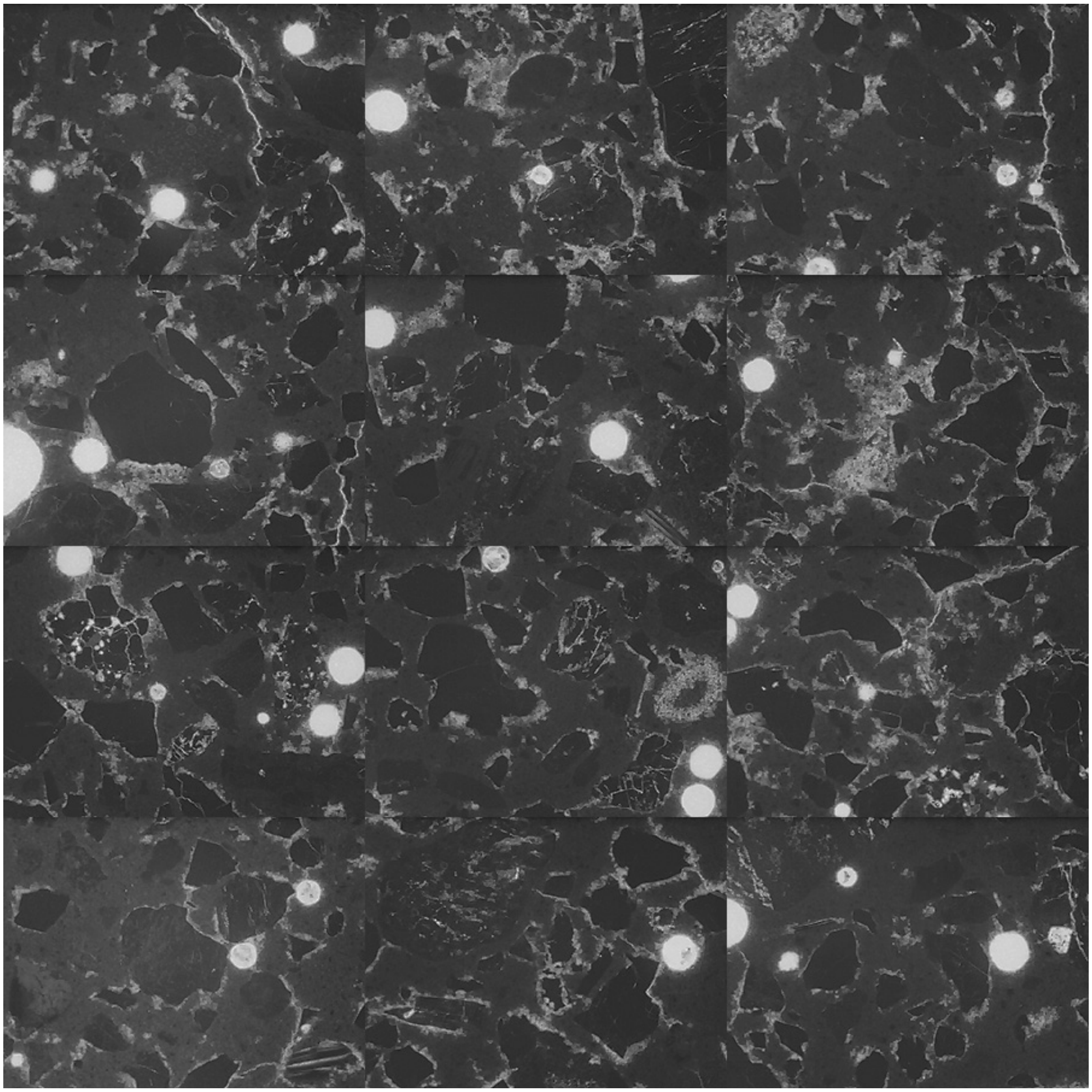

Figure MT-8: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of concrete overlay, core MT-3 (each individual frame measures 2.612 x 1.959 mm).

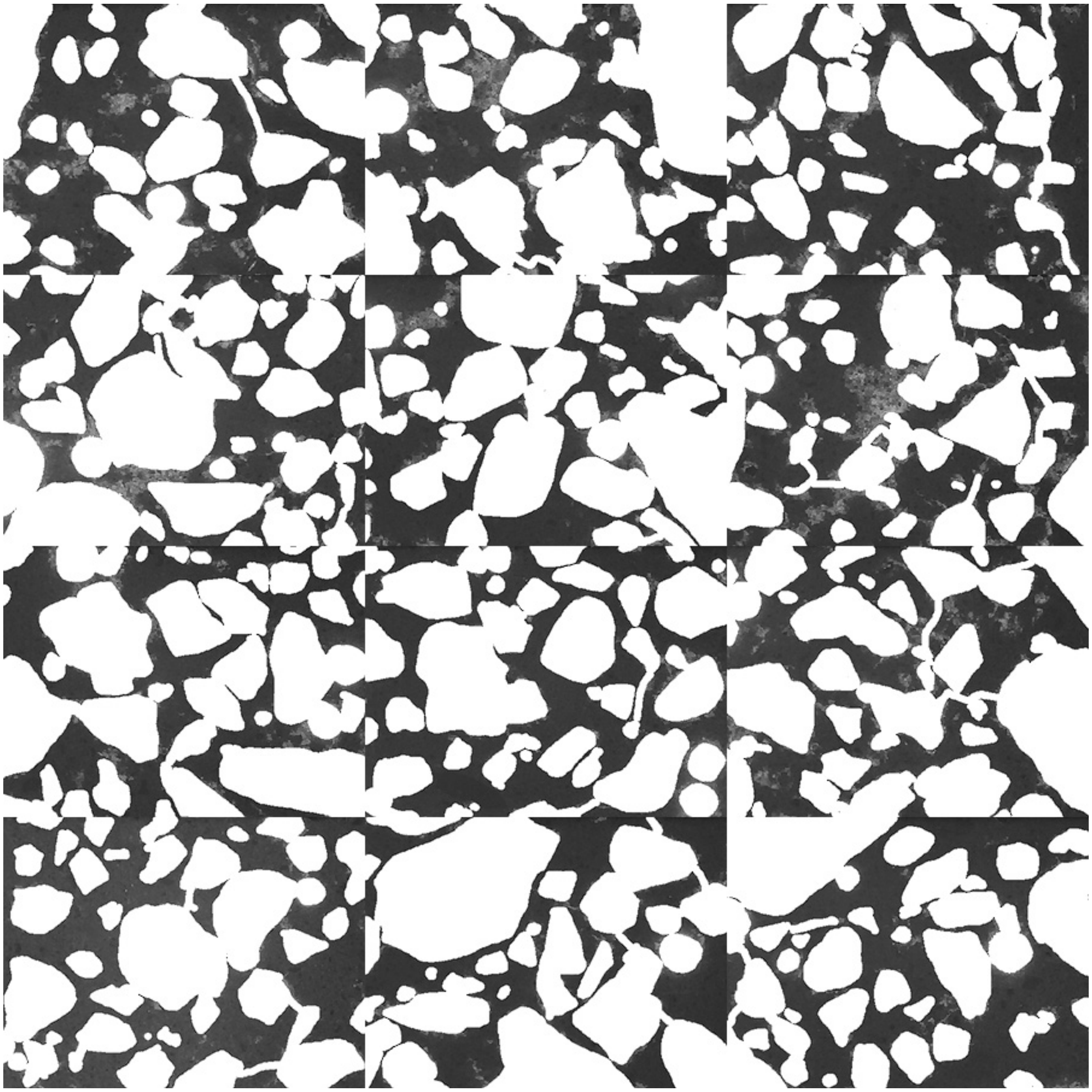

Figure MT-9: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of concrete overlay, core MT-3, after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table MT-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) from concrete overlay, core MT-3.

cement paste pixel fluorescence measurements (average intensity per frame)			
23	23	20	25
20	23	20	19
21	24	18	19
equivalent *w/c* ($y = 0.0044x + 0.0329$)			
0.13	0.14	0.12	0.14
0.12	0.13	0.12	0.12
0.13	0.14	0.11	0.12

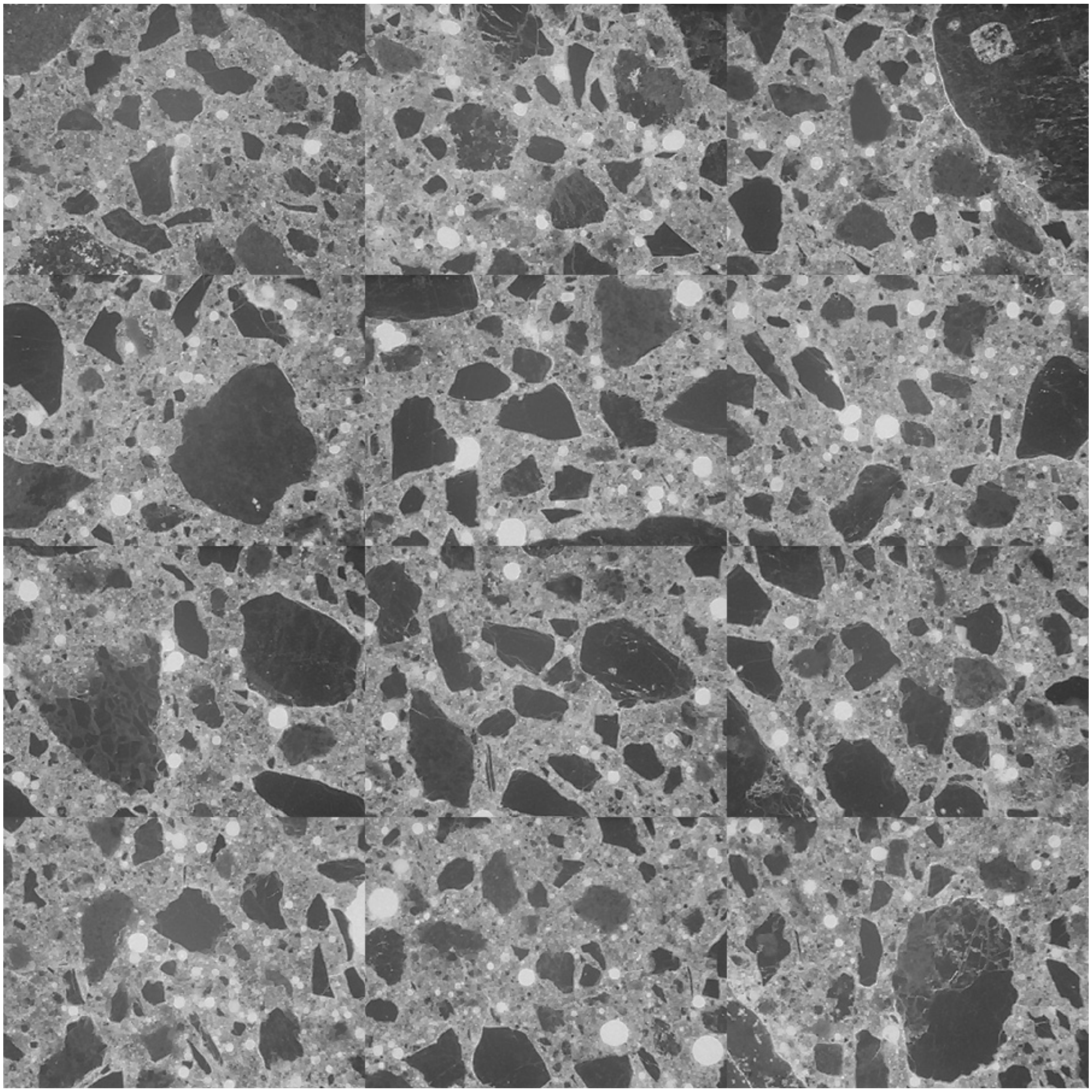

Figure MT-10: Mosaic of 12 frames collected from area of thin section representing the original concrete below the concrete overlay, core MT-3 (each individual frame measures 2.612 x 1.959 mm).

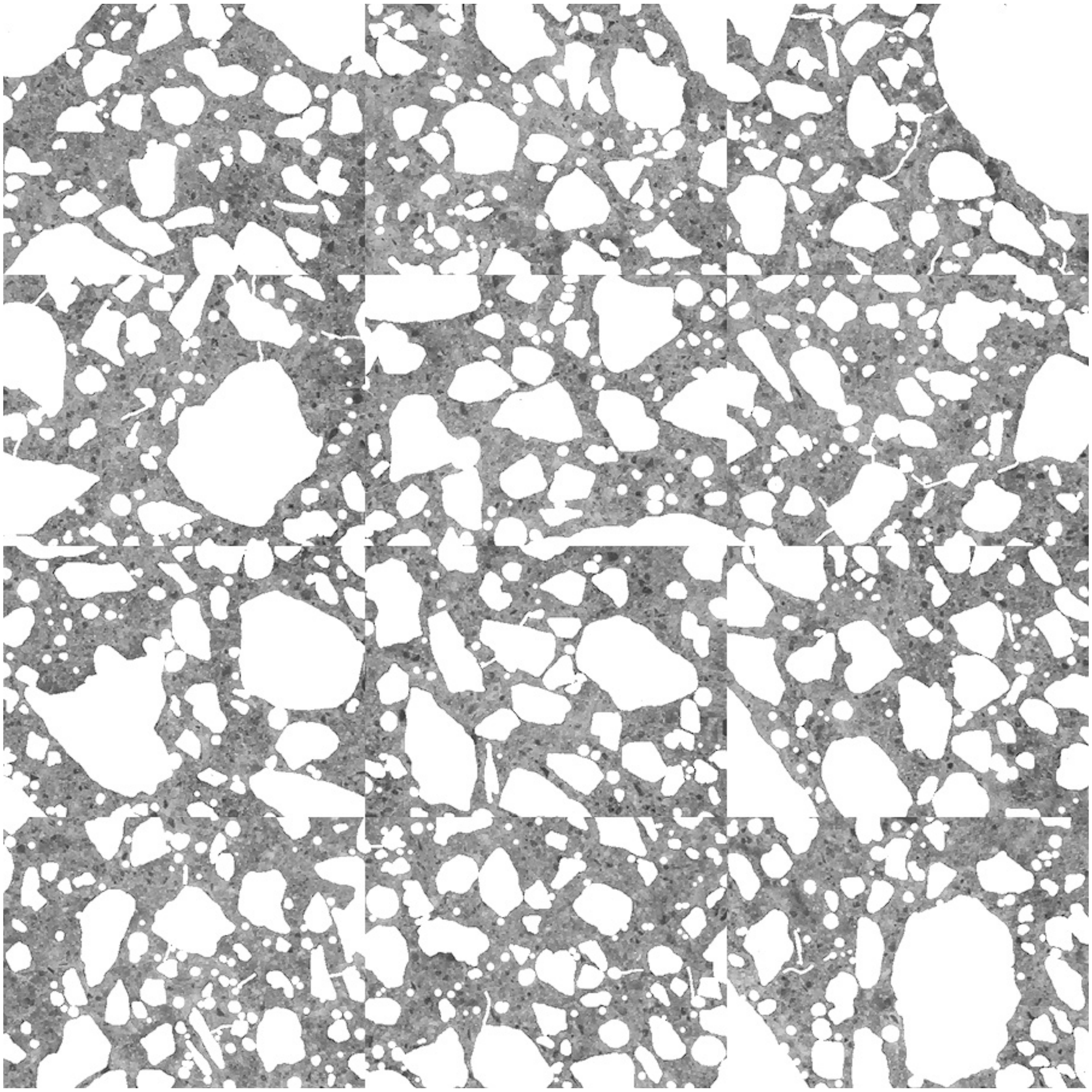

Figure MT-11: Mosaic of 12 frames collected area of thin section representing the original concrete below the concrete overlay, core MT-3, after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table MT-3: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) from original concrete below the overlay, core MT-3.

cement paste pixel fluorescence measurements (average intensity per frame)			
83	93	85	87
92	91	84	86
85	92	89	91
equivalent w/c ($y = 0.0044x + 0.0329$)			
0.40	0.44	0.41	0.41
0.43	0.43	0.40	0.41
0.40	0.44	0.42	0.43

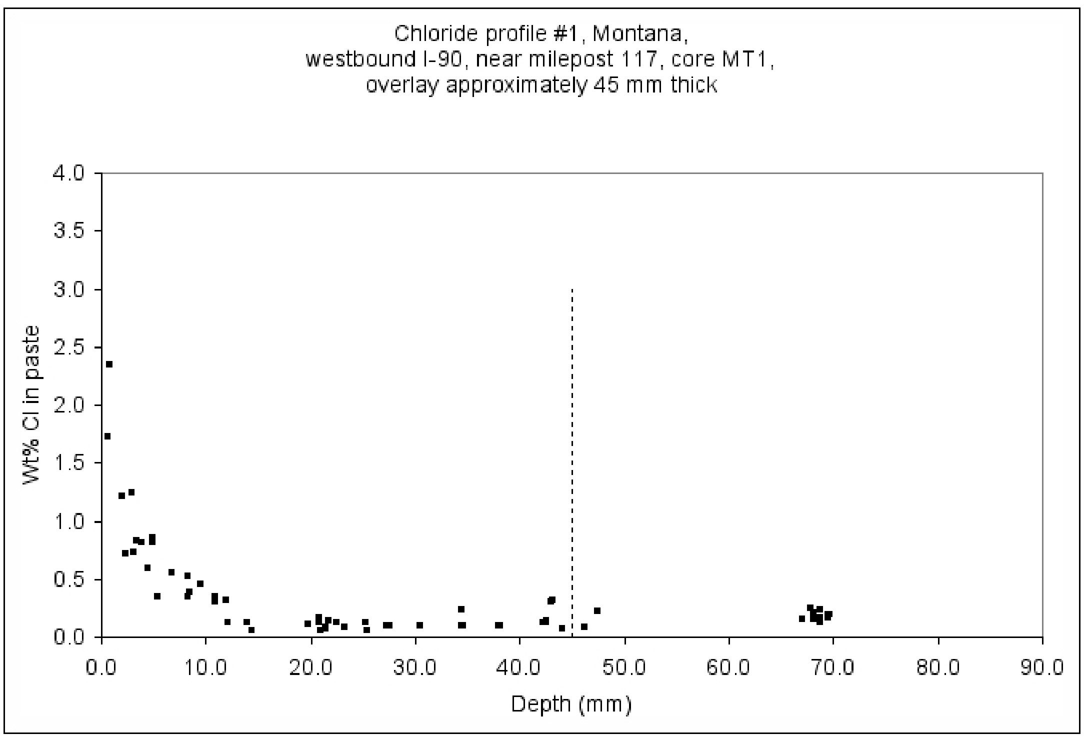

Figure MT-12: Chloride profile through cement paste from billet prepared from core MT-1, dashed line marks the transition between the overlay and the original concrete below.

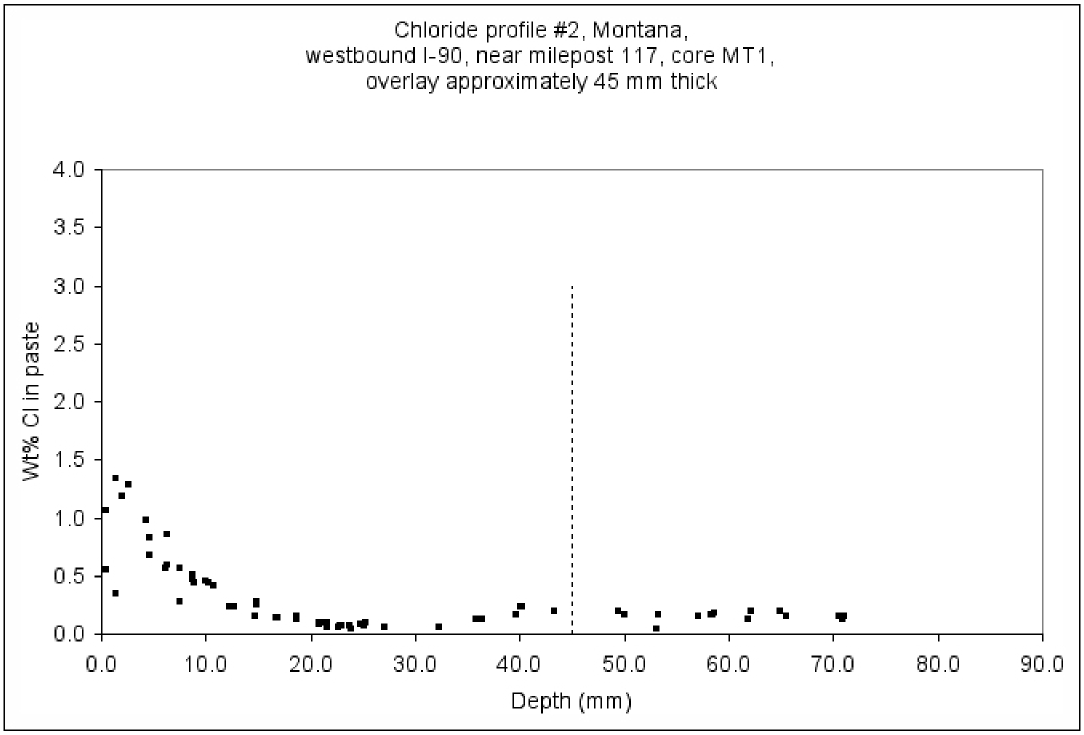

Figure MT-13: Chloride profile through cement paste from billet prepared from core MT-1, dashed line marks the transition between the overlay and the original concrete below.

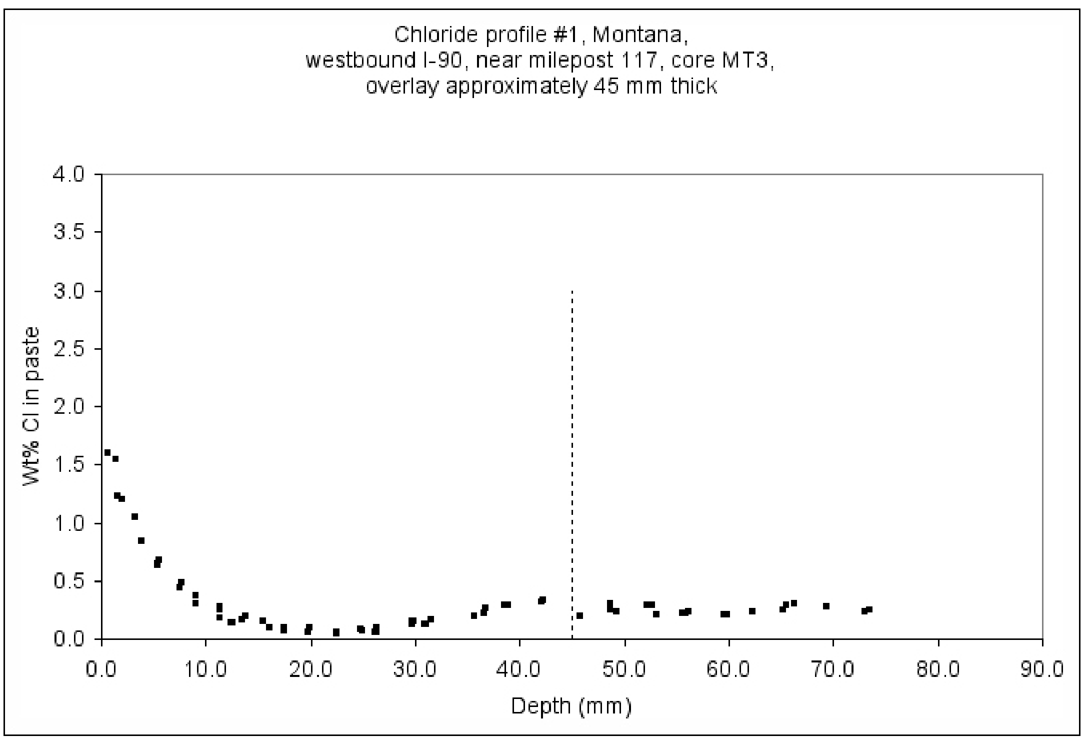

Figure MT-14: Chloride profile through cement paste from billet prepared from core MT-3, dashed line marks the transition between the overlay and the original concrete below.

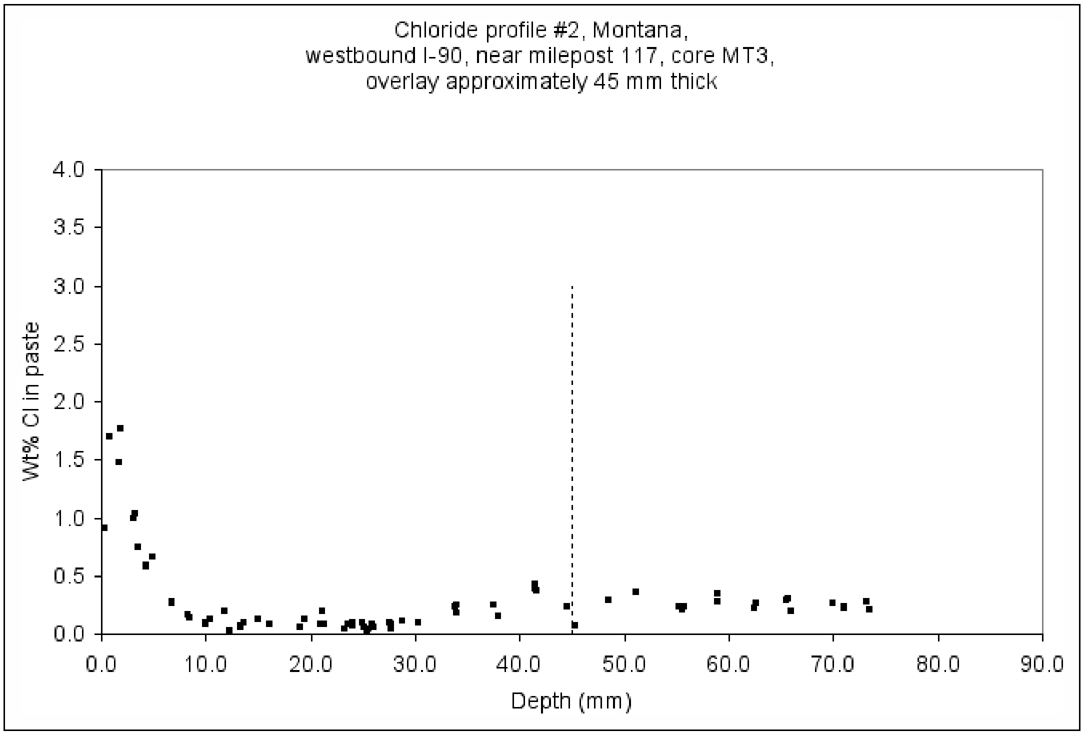

Figure MT-15: Chloride profile through cement paste from billet prepared from core MT-3, dashed line marks the transition between the overlay and the original concrete below.

Montana, eastbound Interstate Highway 90 bridge deck,
near milepost 61.8, Torkio interchange

According to discussions with maintenance crew members, (Scott and Bruce) the Torkio interchange lies at the border of two maintenance areas: 1113, and 1114. It was suggested that Bill Sampson might have deicer records for 1113, and Larry Bullick might have deicer records for 1114. Scott said that they used both $MgCl_2$ brine, and a combination of NaCl and sand. Bruce described spalling at many of the bridge decks that had been coated with a thick (~ 1/4") layer of epoxy and aggregate. In order to patch the spalls, he had to first scrape away the epoxy layer, which had debonded and came off in sheets. It was never stated that this was the case at the Torkio interchange. Figure T-1 shows the locations of the cores, and Figure T-2 shows the condition of the bridge deck, covered with cold patch material. Figure T-3 shows the underside of the bridge deck with pronounced efflorescence, especially in areas directly below regions covered with cold patch material. Figure T-4 shows photographs of the cores. Core T-1 exhibited a crack plane at a depth of about 45 mm. The entire core was vacuum impregnated with epoxy and used only for thin section preparation. Core T-2 was intact, and cut into slabs and polished. Figures T-5 and T-6 show the slab as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation at the surface, but pronounced carbonation of over a centimeter thick at the base of the deck. The black and white treatment did not reveal any macro-cracking. Table T-1 summarizes the air void parameters. The slab showed inadequate entrained air, with a spacing factor of 0.296 mm. Figure T-7 shows an example stereomicroscope image of the air void structure. A w/c ratio estimation was performed on a thin section prepared from the top of core T-2. Figures T-8 and T-9 show the images used to make the measurements. The results of the w/c estimation are summarized in Table T-2, with an average w/c value of 0.33 as compared to the 28-day moist cured mortar sample standards. Figures T-10 through T-12 show chloride profiles from cores T-2. Figures T-13 and T-14 show locations on the thin sections prepared from core T-1 that were used for elemental mapping. Regions were mapped to represent the pavement surface and the crack at depth. Figures T-15 and T-16 show the elemental maps from the two regions. Chloride profiles were not recorded from core T-1 because it had been epoxy impregnated; the epoxy contains chlorine. The most interesting feature of the elemental maps is the Mg map from Figure T-16 that shows magnesium enrichment at the surface of the bridge deck.

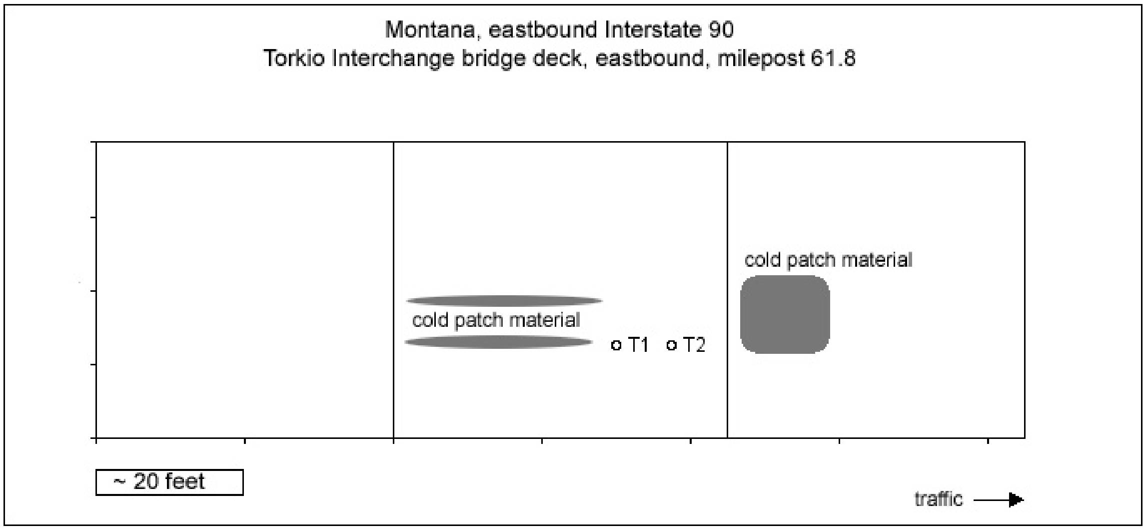

Figure T-1: Diagram to show location of cores according to field notes.


Figure T-2: Photograph of core site.

Figure T-3: Photograph from beneath bridge deck after coring operation. Hole from core T-2 is visible. Dampness permeating through cracks visible beneath the area of core T-1. White efflorescence common in areas directly below regions covered with cold patch material.

Figure T-4: Cores retrieved from site, core T-1 (top), core T-2 (bottom).

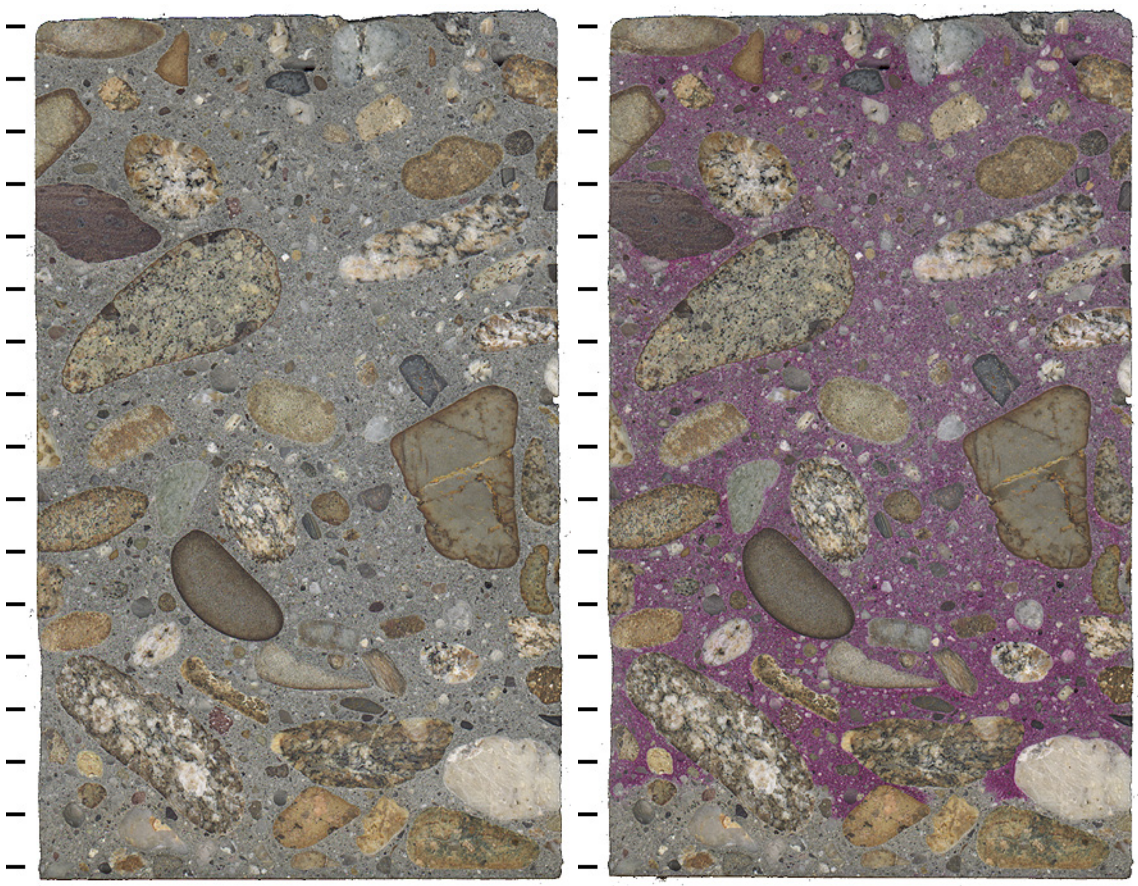

Figure T-5: Polished slabs to show complete cross-section through core T-2 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

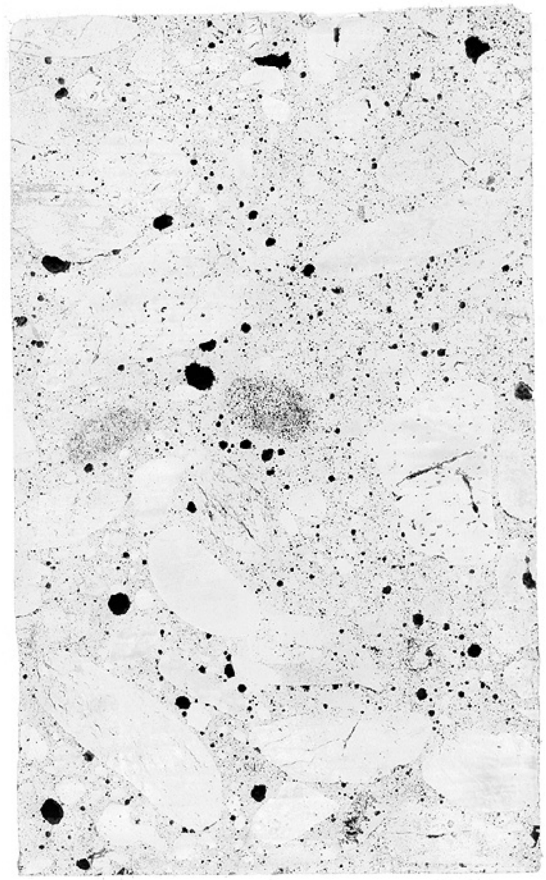

Figure T-6: Polished slabs to show complete cross-section through core T-2 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

Table-T1: Air void parameters.

Sample ID	T-2
Location	area in good condition
Raw data	
Total traverse length (mm)	3772.082
Area analyzed (cm^2)	73.9
Air stops	70
Paste stops	413
Aggregate stops	961
Secondary deposit stops	0
Total stops	1444
Number of air intercepts	617
Number of filled void intercepts	0
Results	
Air vol%	4.9
Paste vol%	28.6
Aggregate vol%	66.6
Secondary deposit vol%	0.0
Existing average chord length (mm)	0.370
Existing paste/air ratio	5.9
Existing air void specific surface (mm^{-1})	13.5
Existing air void frequency (voids/m)	164
Existing spacing factor (mm)	0.296
Original average chord length (mm)	0.370
Original paste/air ratio	5.9
Original air void specific surface (mm^{-1})	13.5
Original air void frequency (voids/m)	164
Original spacing factor (mm)	0.296

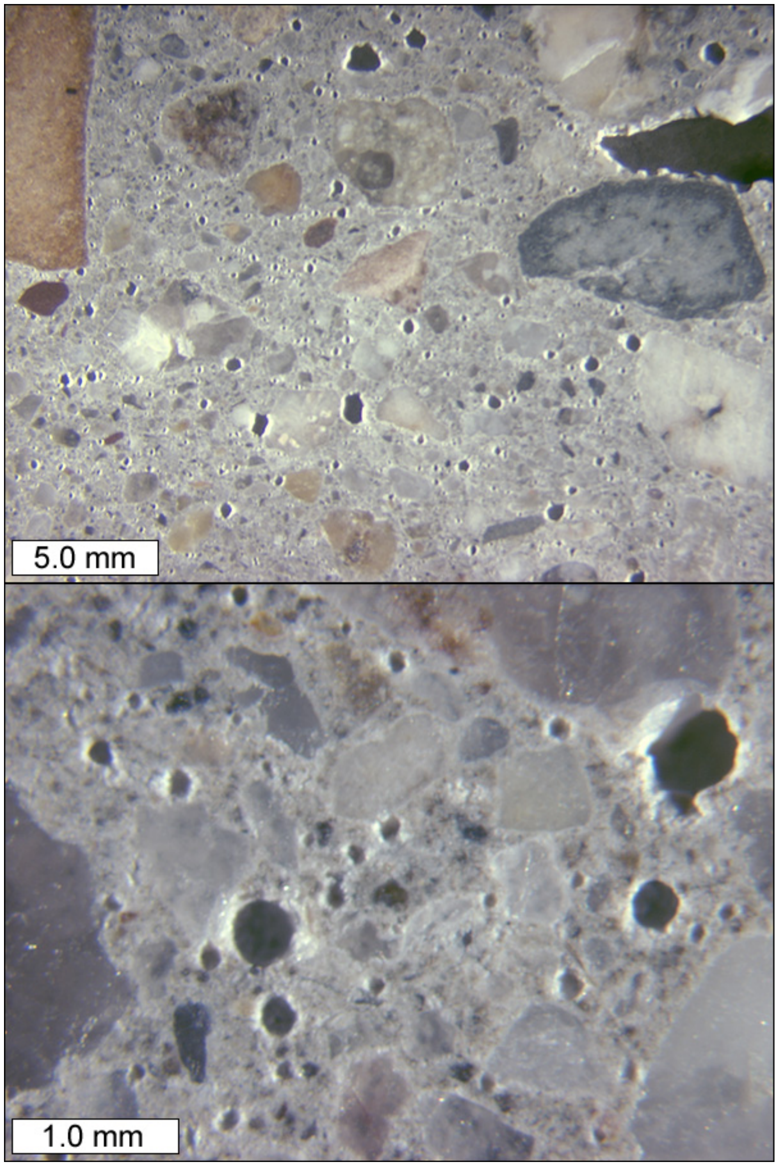

Figure T-7: Stereo microscope images to show air void structure on polished slab from core T-2.

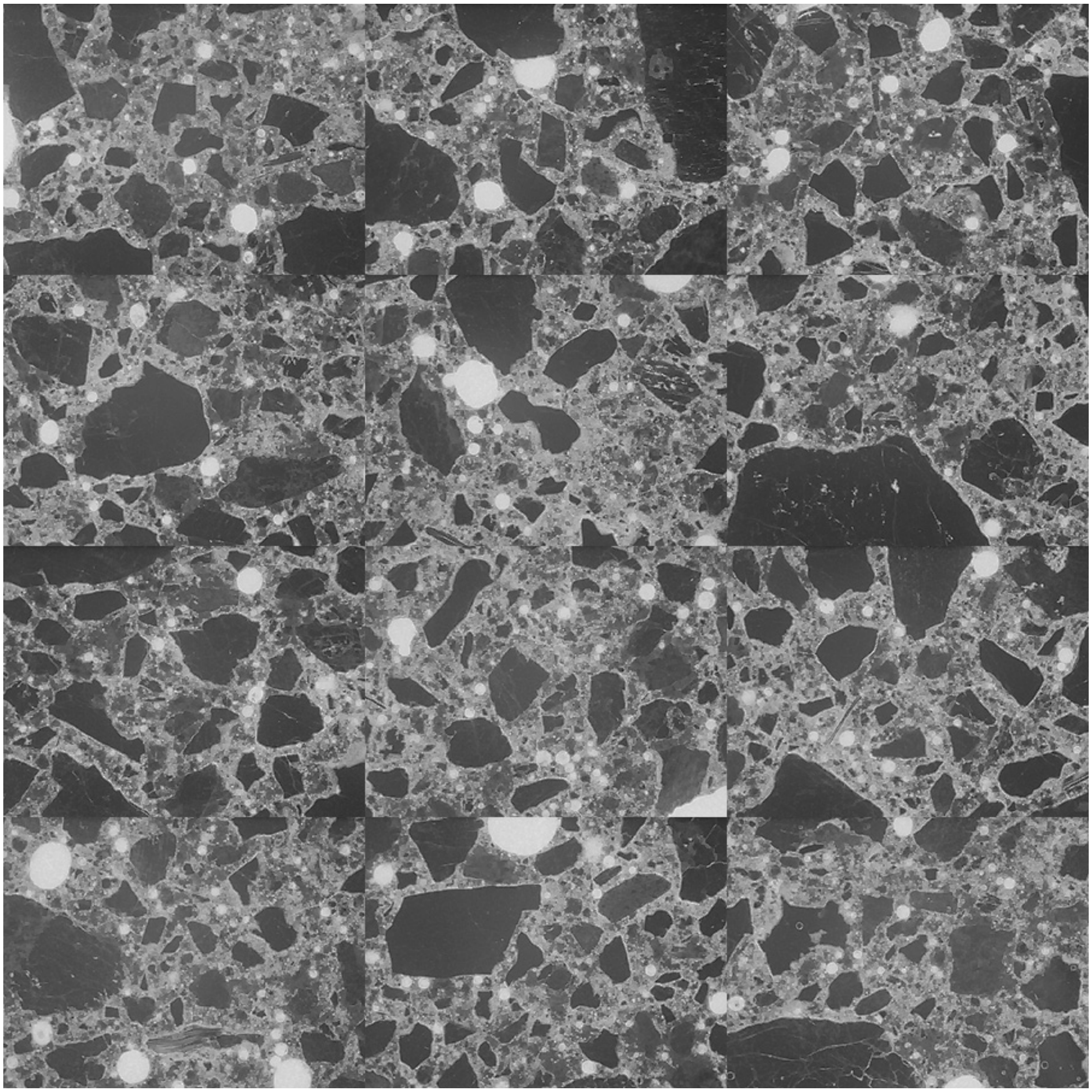

Figure T-8: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core T-2 (each individual frame measures 2.612 x 1.959 mm).

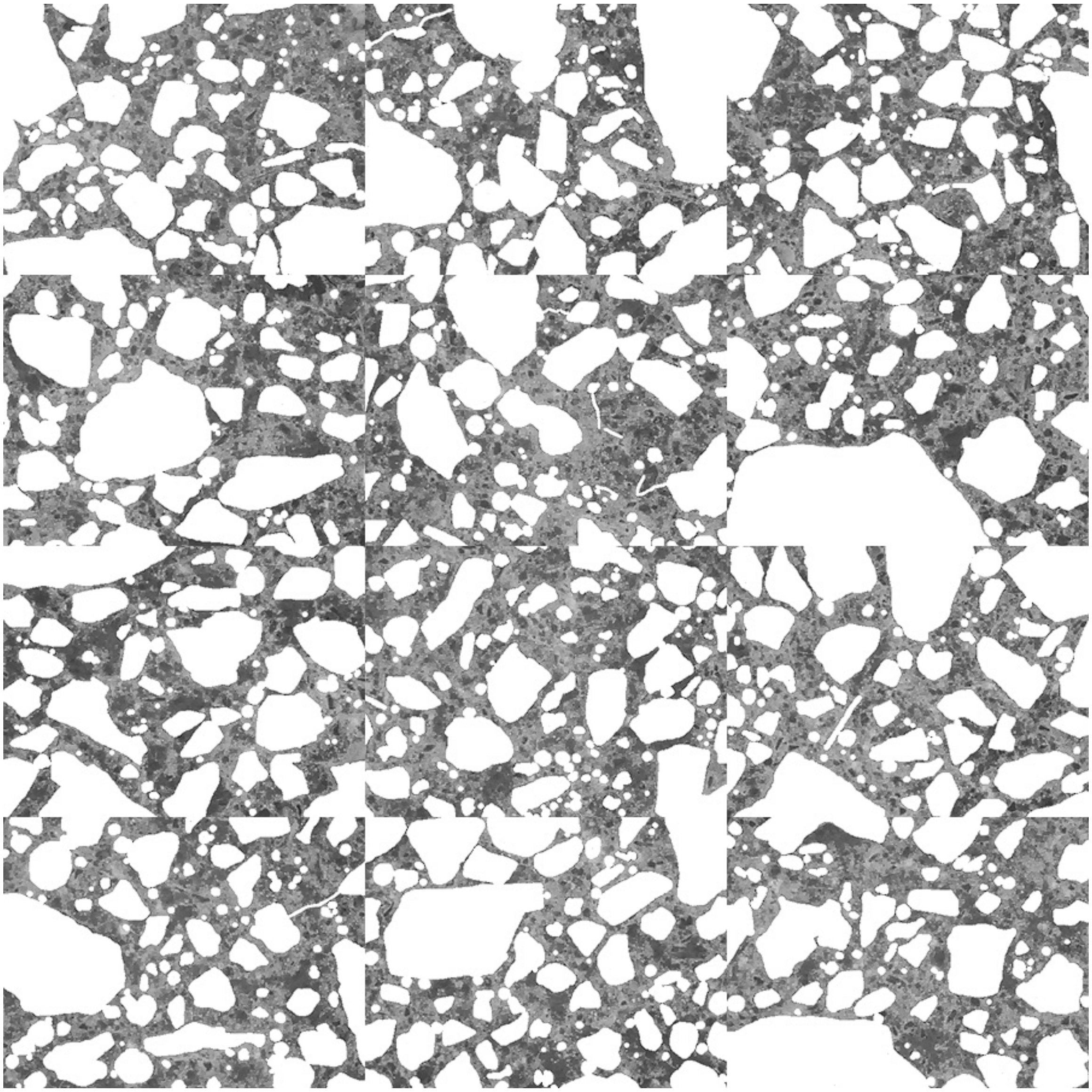

Figure T-9: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core T-2 after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table T-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples).

cement paste pixel fluorescence measurements (average intensity per frame)			
71	67	63	68
72	67	62	72
75	68	69	72
equivalent w/c (y = 0.0044x + 0.0329)			
0.34	0.33	0.31	0.33
0.35	0.32	0.31	0.35
0.36	0.33	0.33	0.35

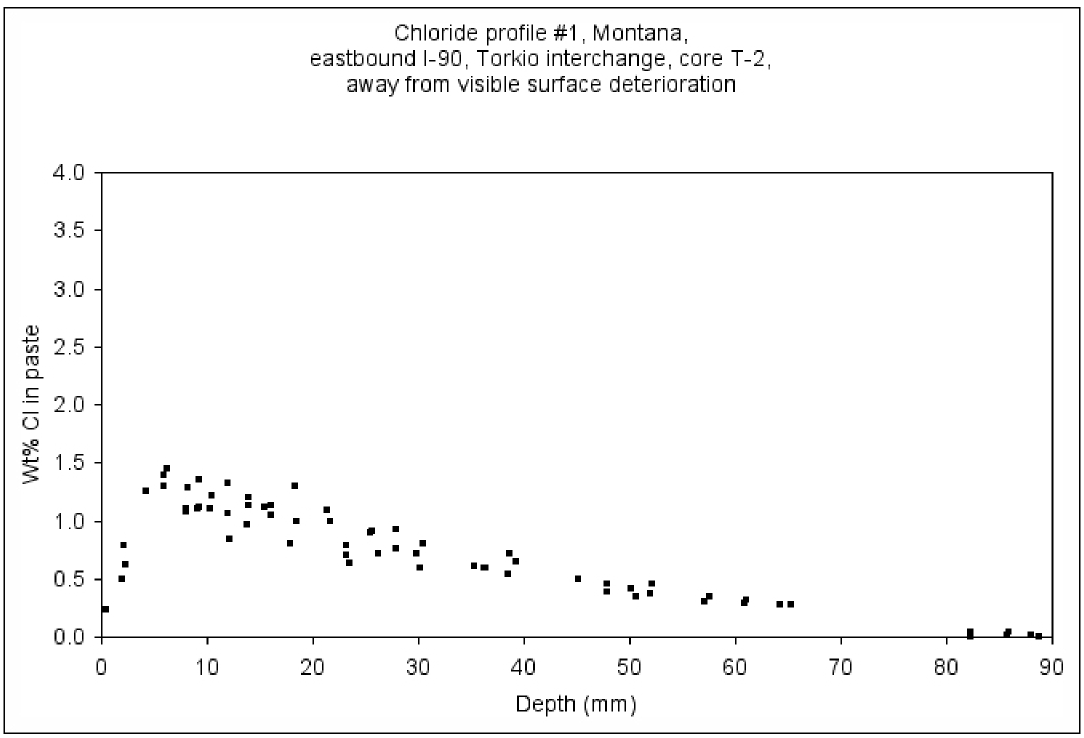

Figure T-10: Chloride profile through cement paste, from billet prepared from core T-2.

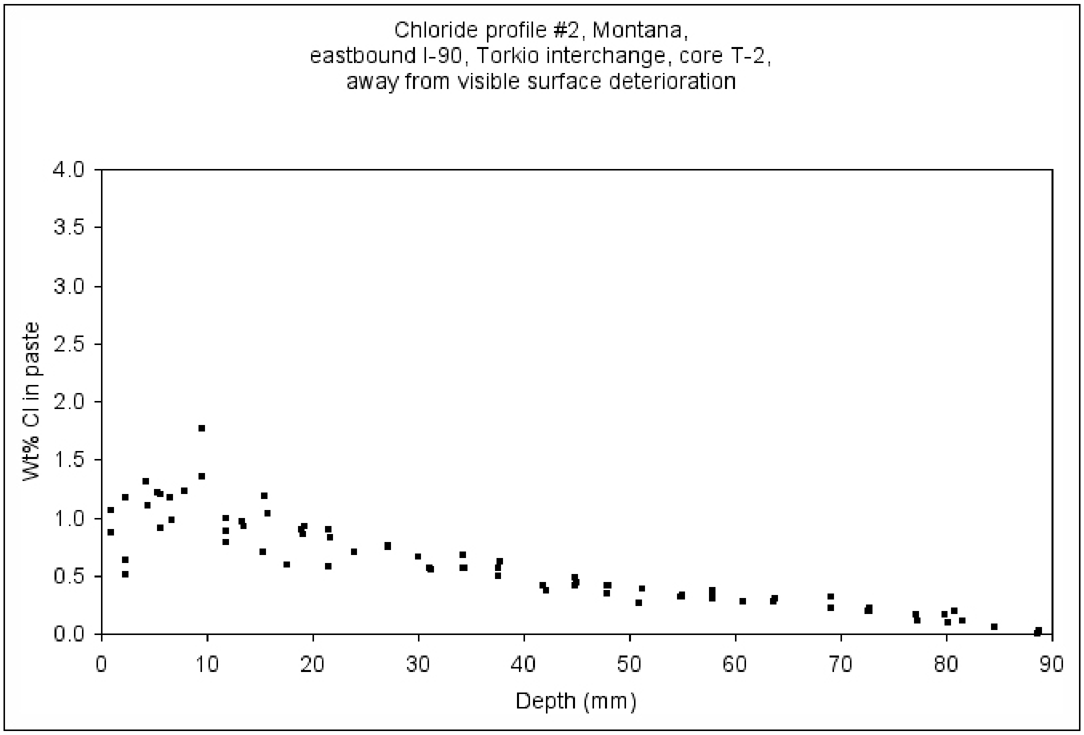

Figure T-11: Chloride profile through cement paste, from billet prepared from core T-2.

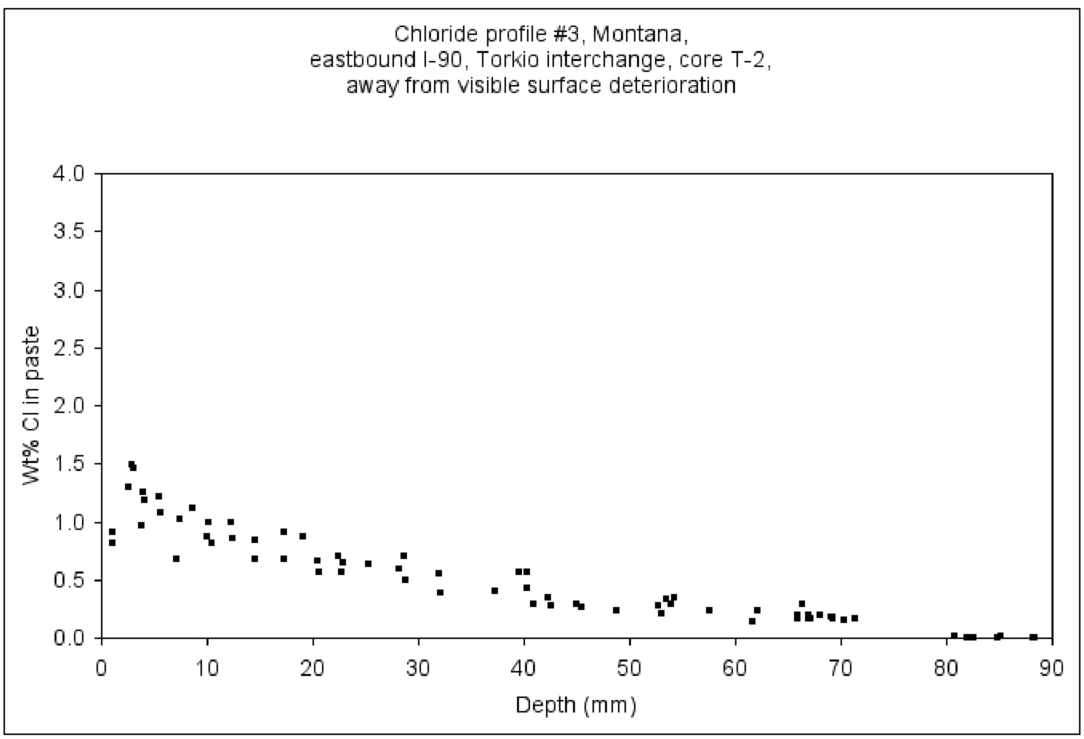

Figure T-12: Chloride profile through cement paste, from billet prepared from core T-2.

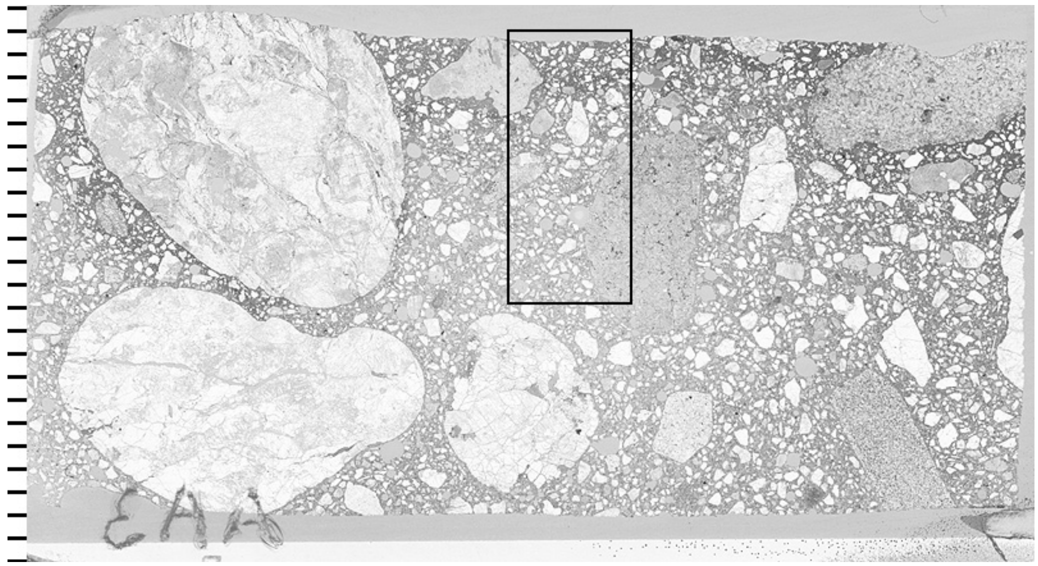

Figure T-13: Transmitted light scanned image of thin section to show location of elemental map. The top of the thin section represents the wear surface of the pavement, (tic marks every mm).

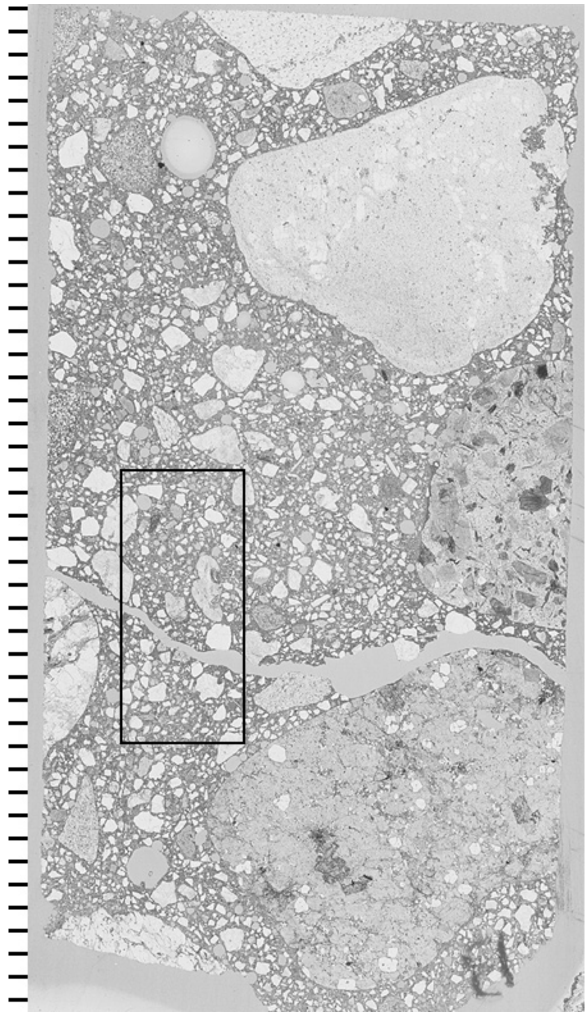

Figure T-14: Transmitted light scanned image of thin section to show location of elemental map. The large crack, sub-parallel to the pavement surface, is at a depth of about 40 mm, (tic marks every mm).

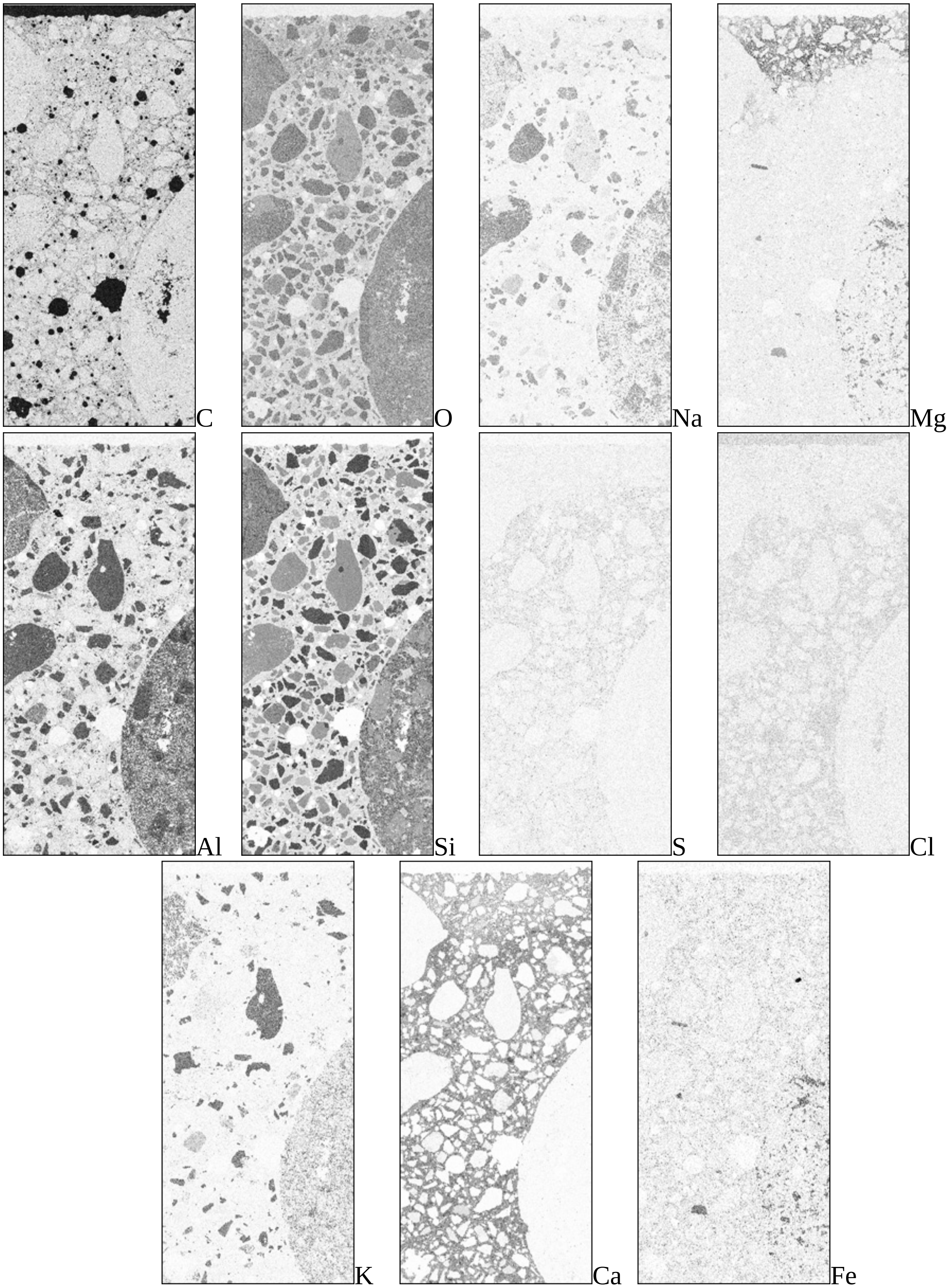

Figure T-15: Elemental maps from pavement surface, darker regions indicate higher concentrations.

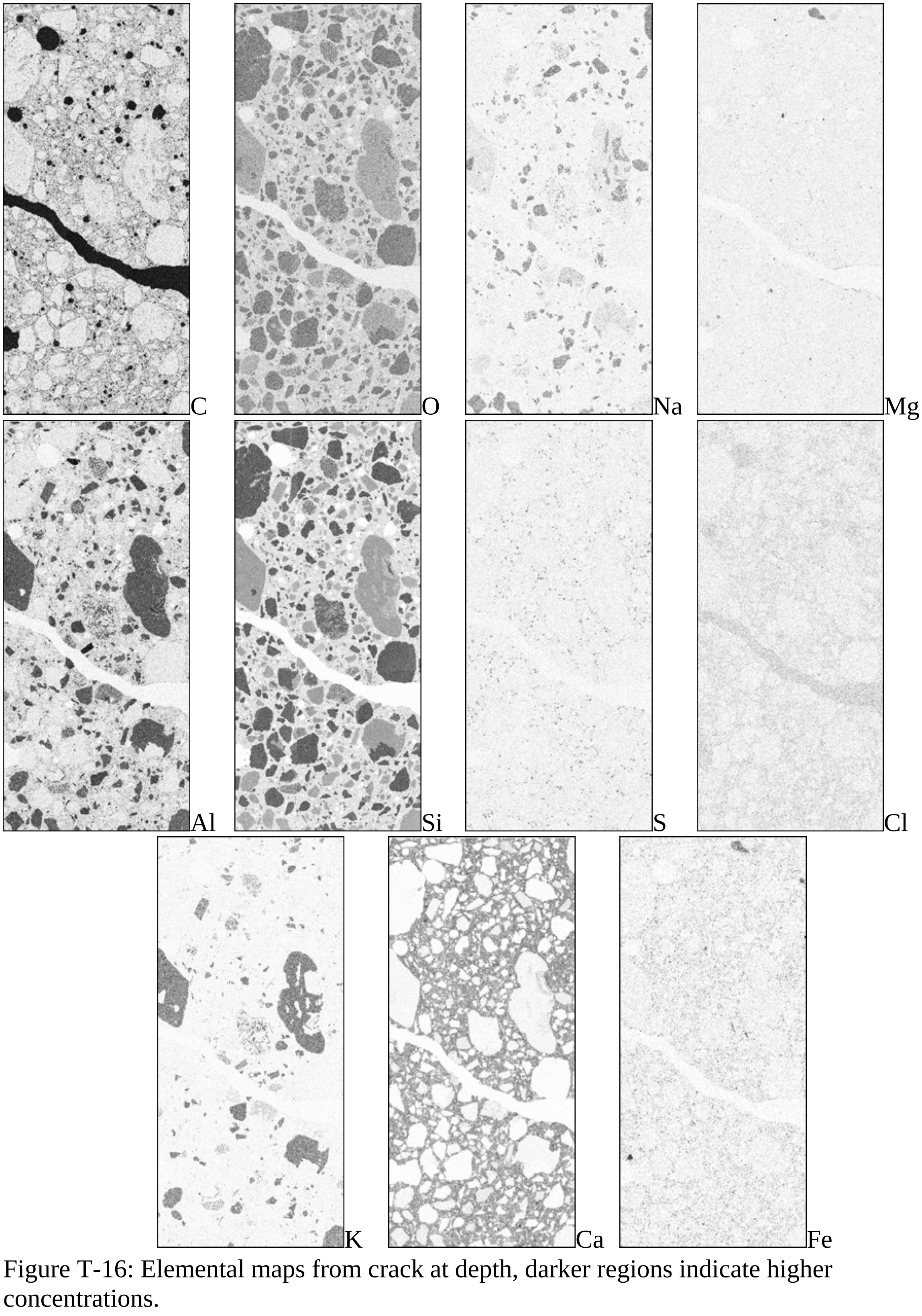

Figure T-16: Elemental maps from crack at depth, darker regions indicate higher concentrations.

Montana, westbound Interstate Highway 90 bridge deck,
near milepost 37.2, Sloway interchange

This bridge deck was in maintenance area 1114, and exposed to $MgCl_2$ brine, and a combination of NaCl and sand. Figure S-1 shows the locations of the cores, and Figure S-2 shows the condition of the bridge deck, with some spalling. Figure S-3 shows the underside of the bridge deck. Figure S-4 shows photographs of the cores. Core S-1 exhibited a crack plane at a depth of about 30 mm coinciding with reinforcement steel. The entire core was vacuum impregnated with epoxy and used only for thin section preparation. Core S-2 was intact, and cut into slabs and polished. Figures S-5 and S-6 show the slab as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation. The black and white treatment did not reveal any macro-cracking, with the exception of a small crack perpendicular to the pavement surface. Table S-1 summarizes the air void parameters. The slab showed adequate entrained air, with a spacing factor of 0.173 mm. Figure S-7 shows an example stereomicroscope image of the air void structure. A w/c ratio estimation was performed on a thin section prepared from the top of core S-2. Figures S-8 and S-9 show the images used to make the measurements. The results of the w/c estimation are summarized in Table S-2, with an average w/c value of 0.33 as compared to the 28-day moist cured mortar sample standards. Figures S-10 and S-11 show chloride profiles from cores S-2. Figure S-12 shows the locations on the thin sections prepared from core S-1 that were used for elemental mapping. Regions were mapped to represent the pavement surface and the crack at depth. Figures S-13 and S-14 show the elemental maps from the two regions. Chloride profiles were not recorded from core S-1 because it had been epoxy impregnated; the epoxy contains chlorine. The most interesting feature of the elemental maps is the Cl map from Figure S-14 that shows chlorine enrichment along the top surface of the crack at depth.

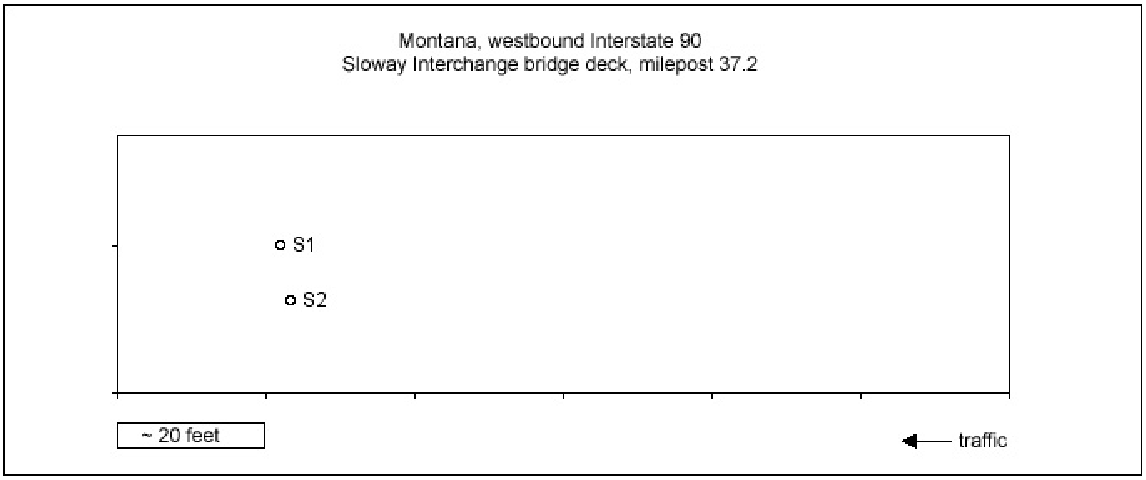

Figure S-1: Diagram to show location of cores based on field information.

Figure S-2: Photograph of core site.

Figure S-3: Photograph from beneath bridge deck after coring operation, hole from core S-1 is clearly visible, light coming through hole from core S-2 is partly obscured by the pre-stressed beam.

Figure S-4: Cores retrieved from site, core S-1 (top), core S-2 (bottom).

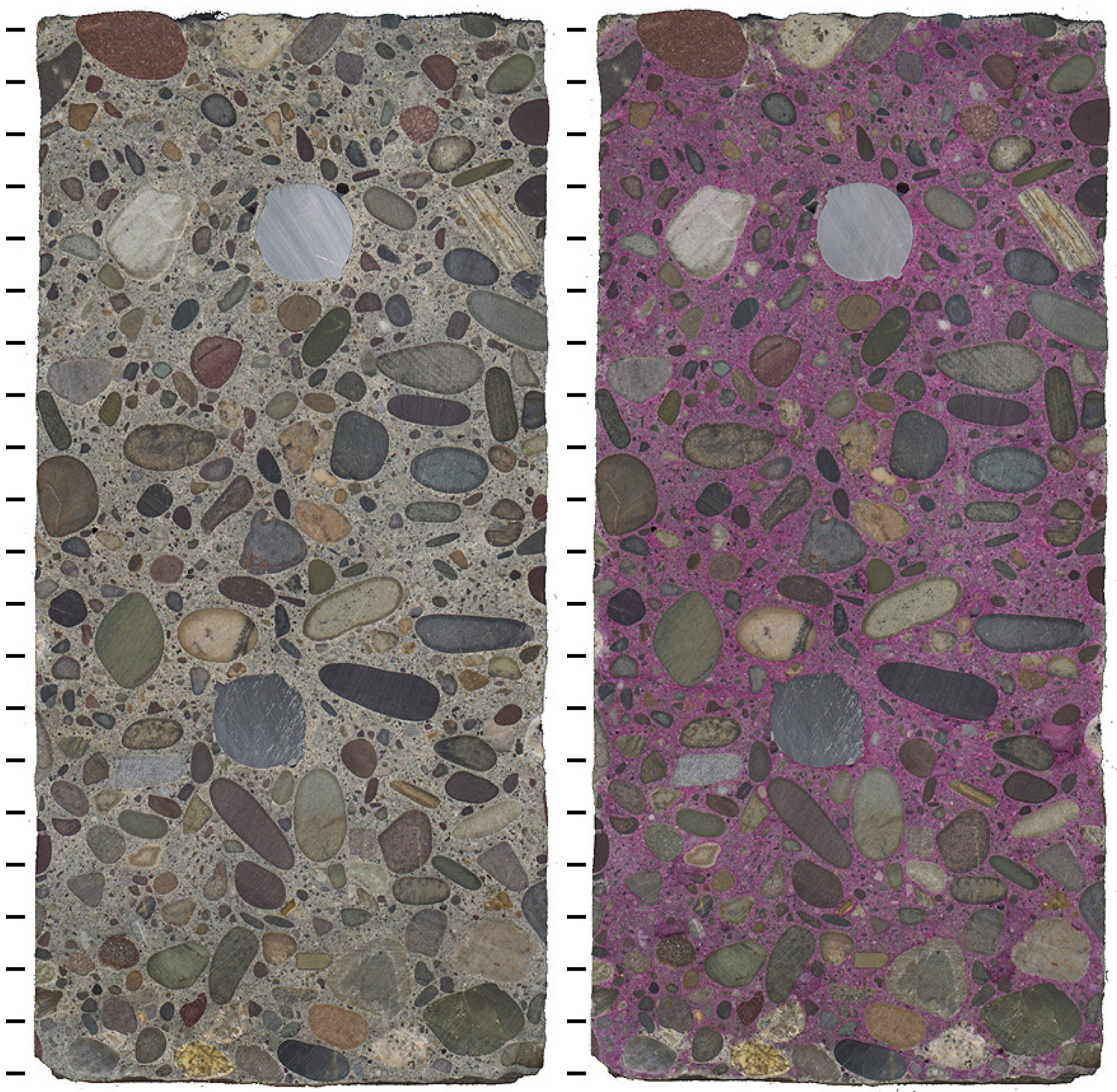

Figure S-5: Polished slabs to show complete cross-section through core S-2 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

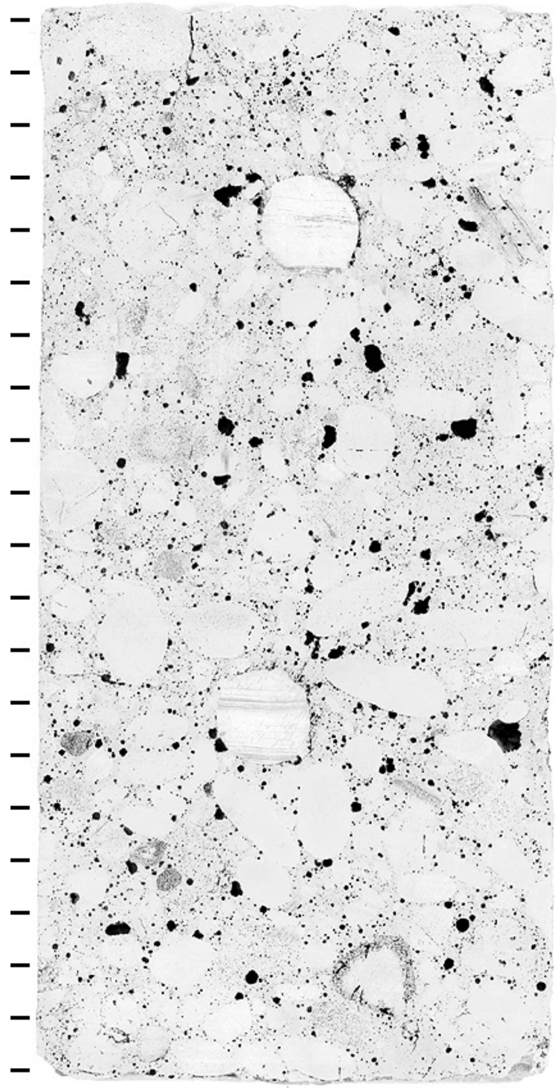

Figure S-6: Polished slabs to show complete cross-section through core S-2 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

Table S-1: Air void parameters.

Sample ID	S-2
Location	area in good condition
Raw data	
Total traverse length (mm)	4242.286
Area analyzed (cm^2)	83.1
Air stops	65
Paste stops	464
Aggregate stops	1092
Secondary deposit stops	3
Total stops	1624
Number of air intercepts	958
Number of filled void intercepts	66
Results	
Air vol%	4.0
Paste vol%	28.6
Aggregate vol%	67.2
Secondary deposit vol%	0.2
Existing average chord length (mm)	0.242
Existing paste/air ratio	7.2
Existing air void specific surface (mm^{-1})	22.6
Existing air void frequency (voids/m)	226
Existing spacing factor (mm)	0.177
Original average chord length (mm)	0.231
Original paste/air ratio	6.8
Original air void specific surface (mm^{-1})	23.1
Original air void frequency (voids/m)	241
Original spacing factor (mm)	0.173

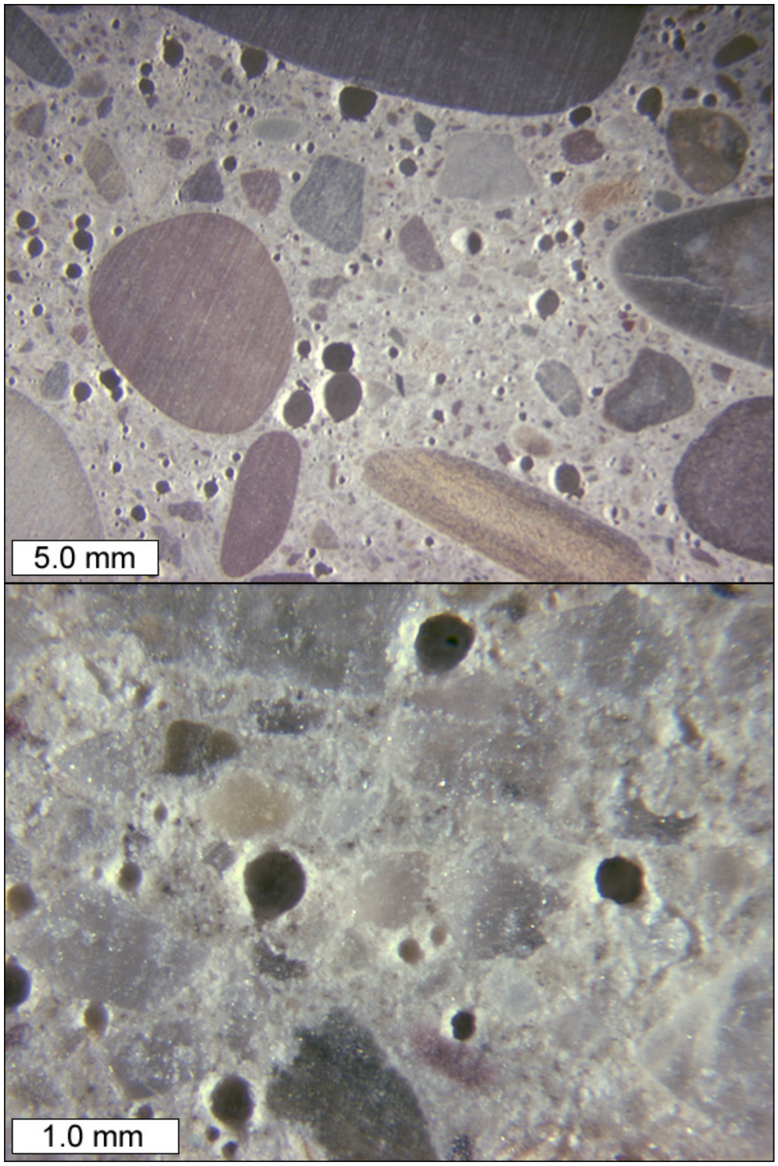

Figure S-7: Stereo microscope images to show air void structure on polished slab from core S-2.

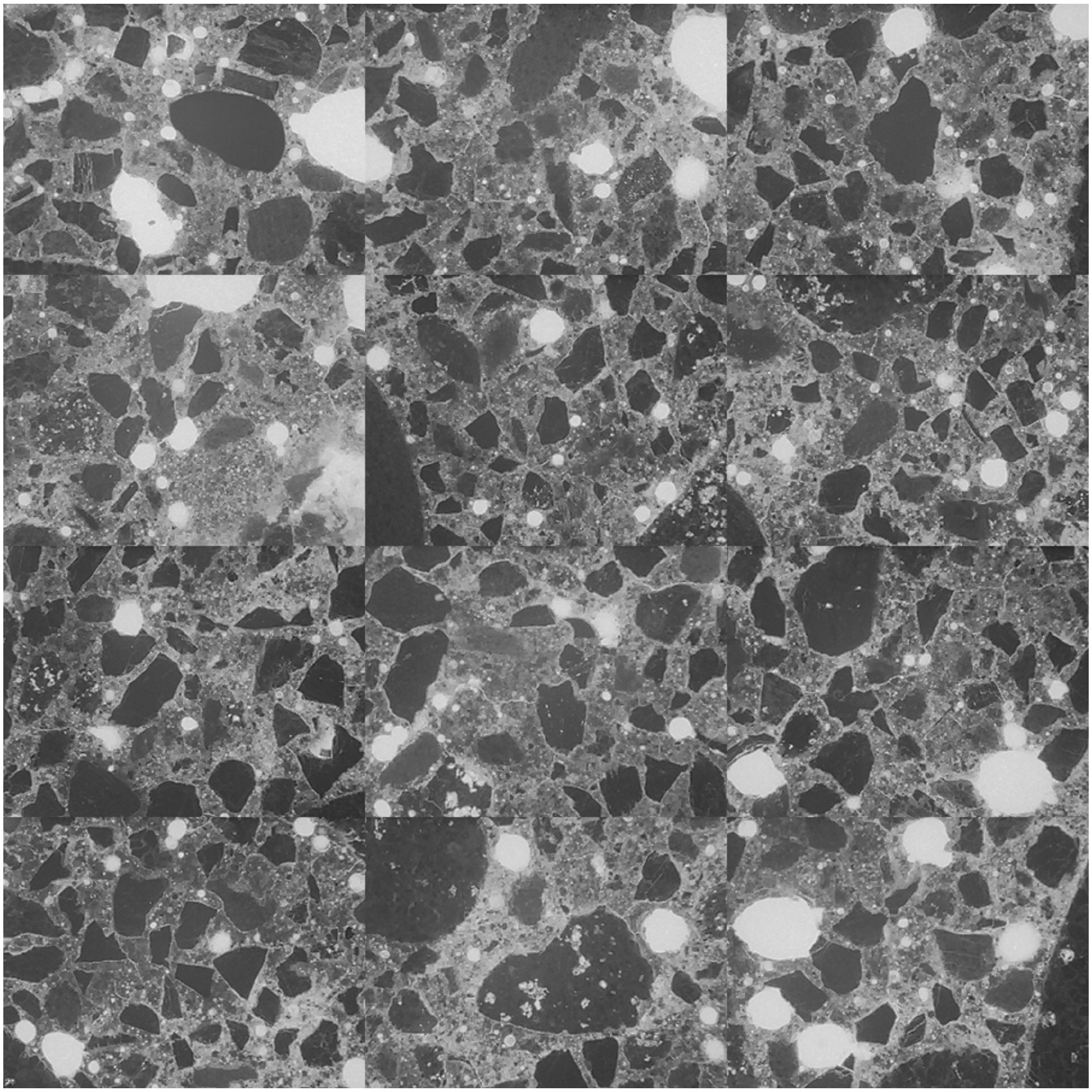

Figure S-8: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core S-2 (each individual frame measures 2.612 x 1.959 mm).

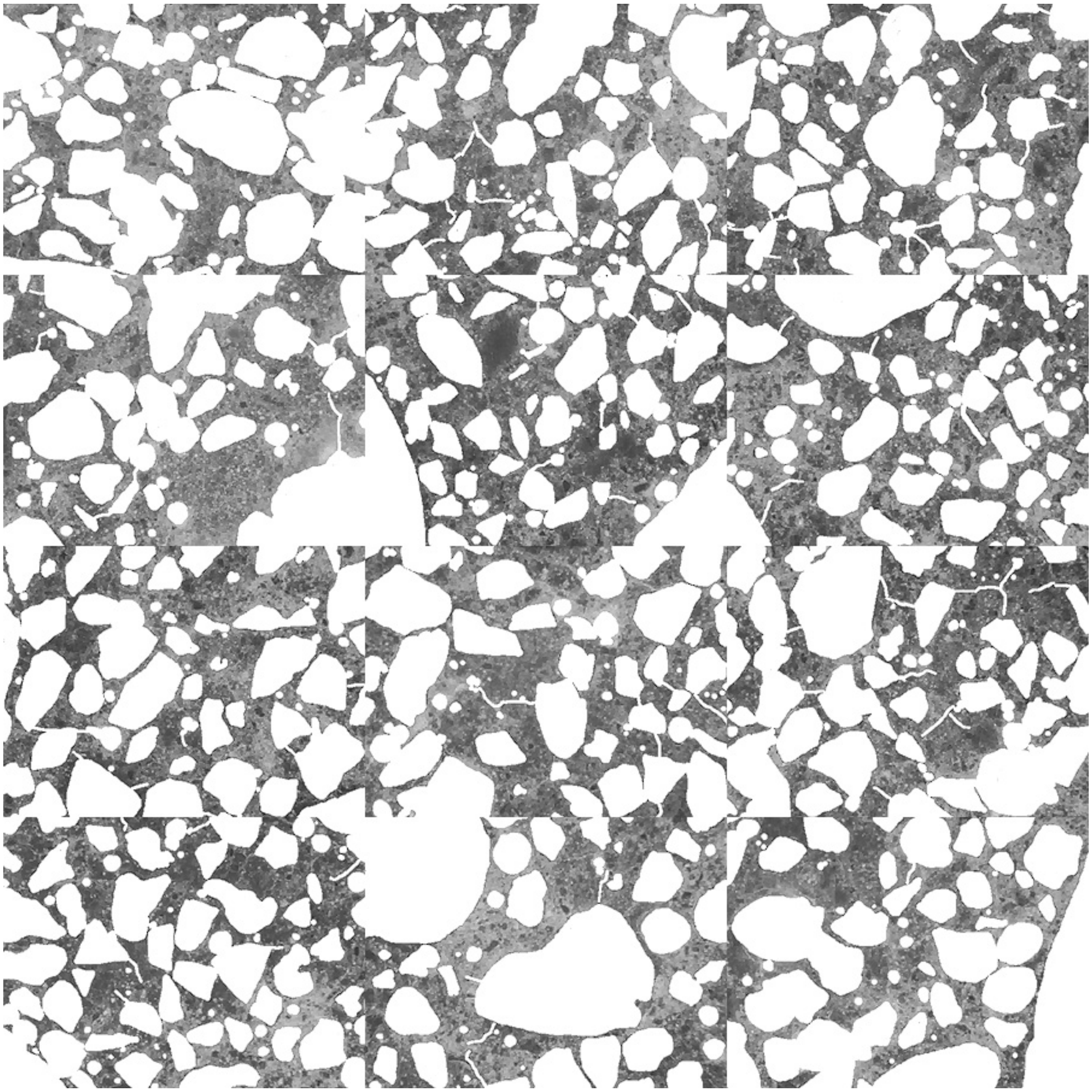
Figure S-9: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core S-2 after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table S-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples).

cement paste pixel fluorescence measurements (average intensity per frame)			
78	73	64	78
57	66	60	68
59	58	75	73
equivalent w/c (y = 0.0044x + 0.0329)			
0.37	0.35	0.31	0.37
0.28	0.32	0.30	0.33
0.29	0.28	0.36	0.35

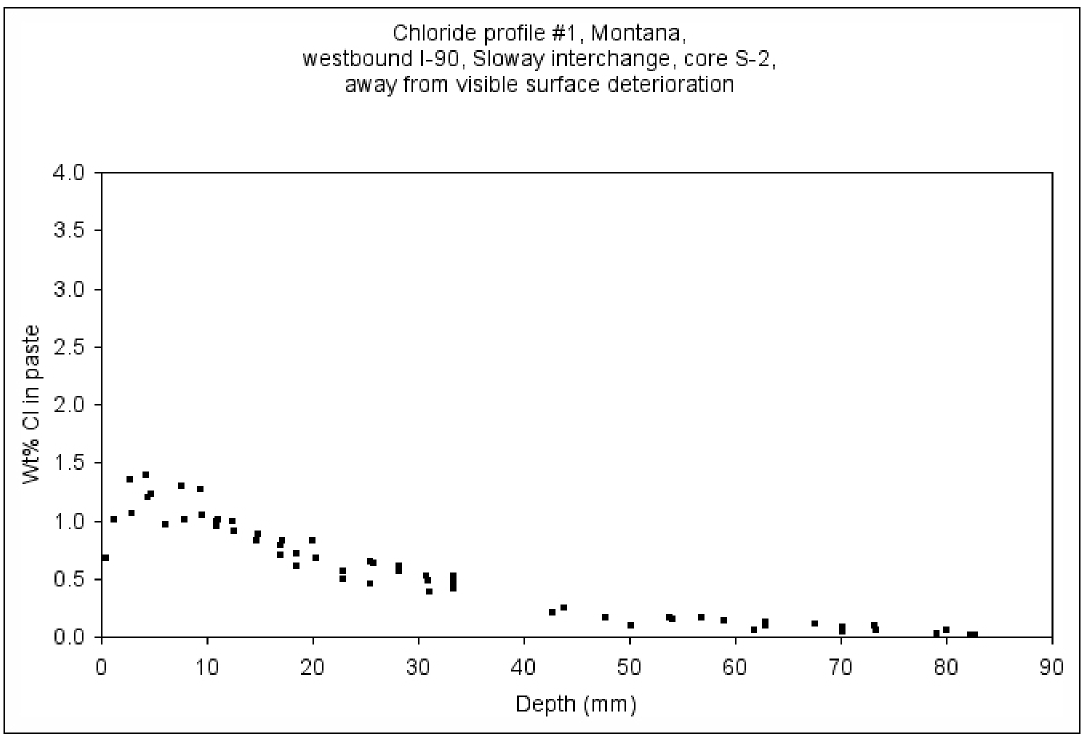

Figure S-10: Chloride profile through cement paste, from billet prepared from core S-2.

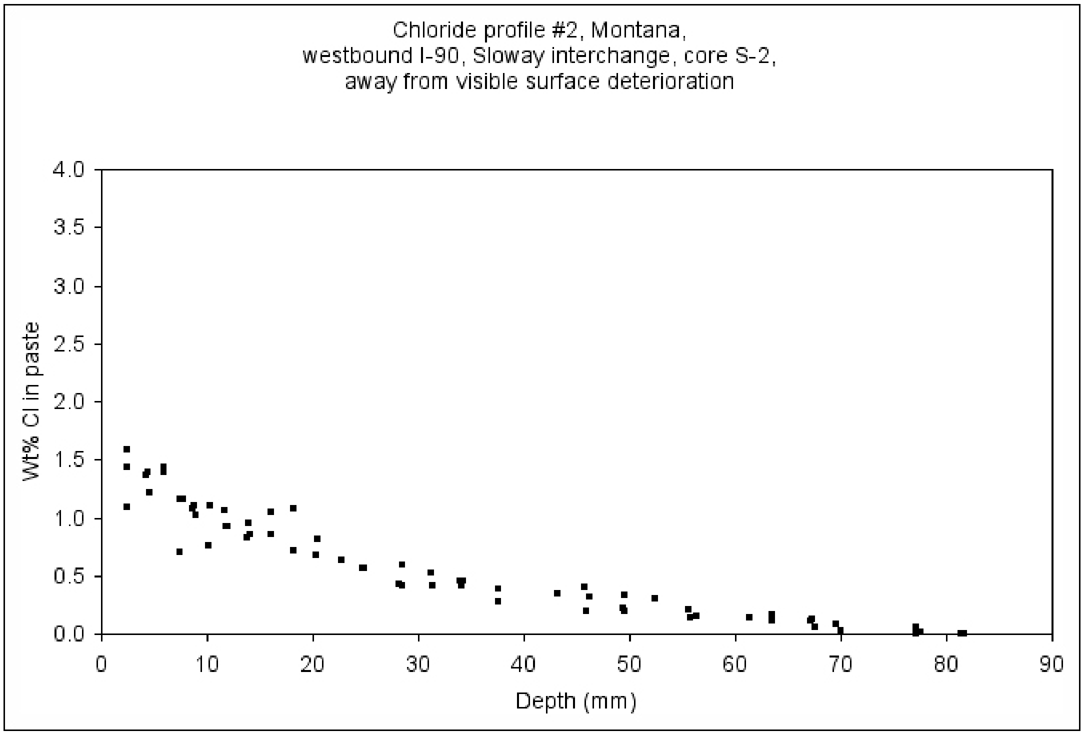

Figure S-11: Chloride profile through cement paste, from billet prepared from core S-2.

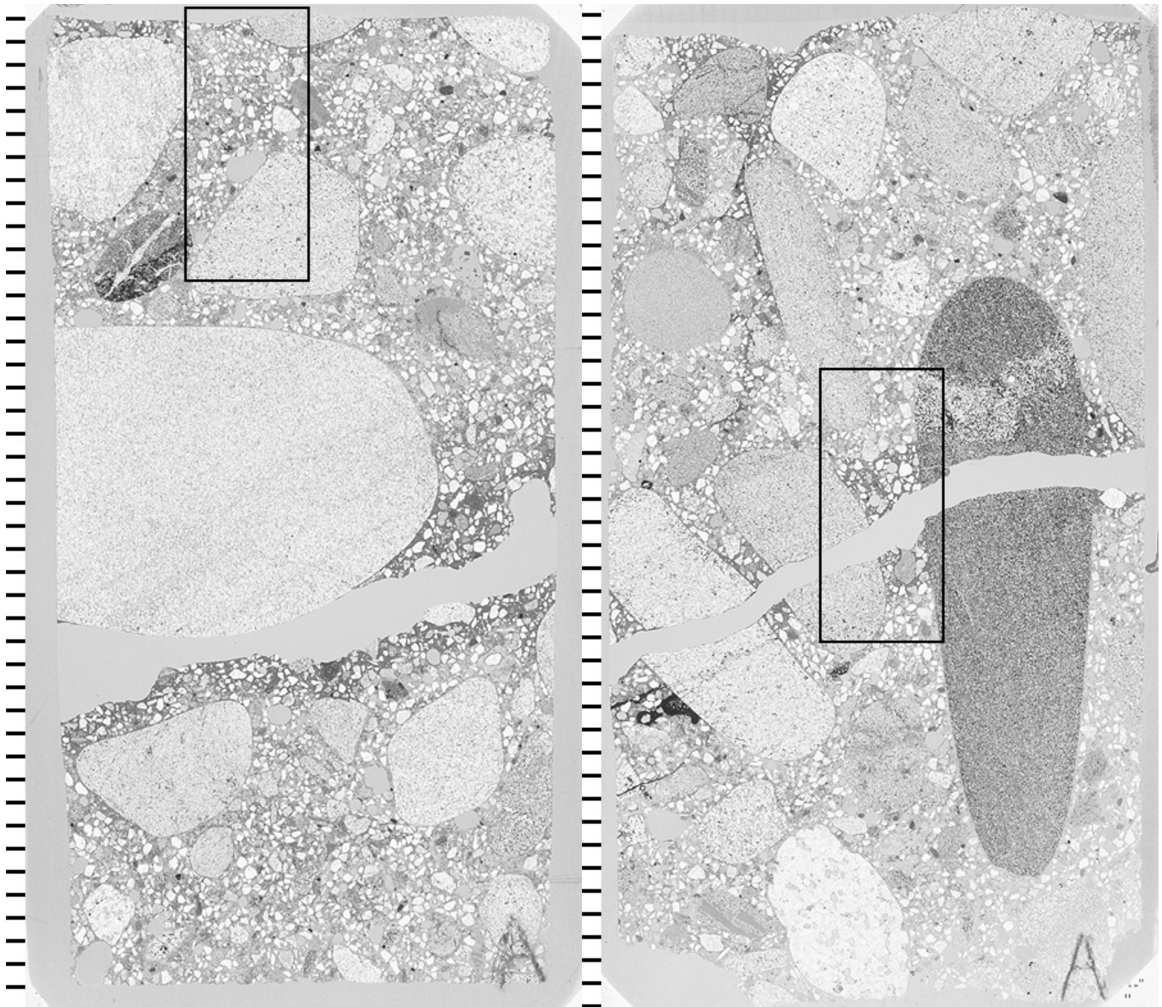

Figure S-12: Transmitted light scanned images of thin sections to show locations of elemental maps. The top of each thin section represents the wear surface of the pavement, the large cracks, sub-parallel to the surface, are at a depth of about 25 mm, (tic marks every mm).

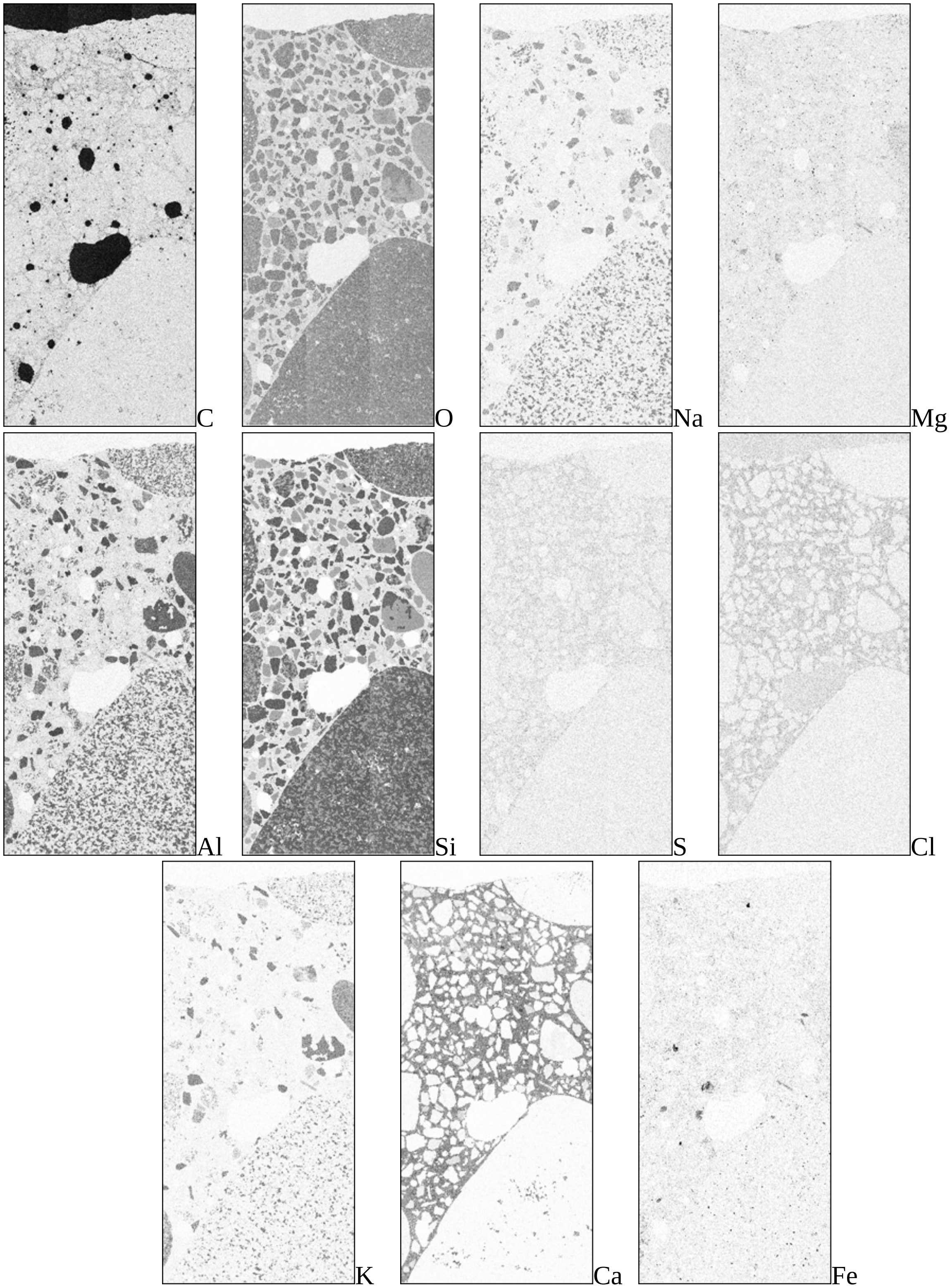

Figure S-13: Elemental maps from pavement surface, darker regions indicate higher concentrations.

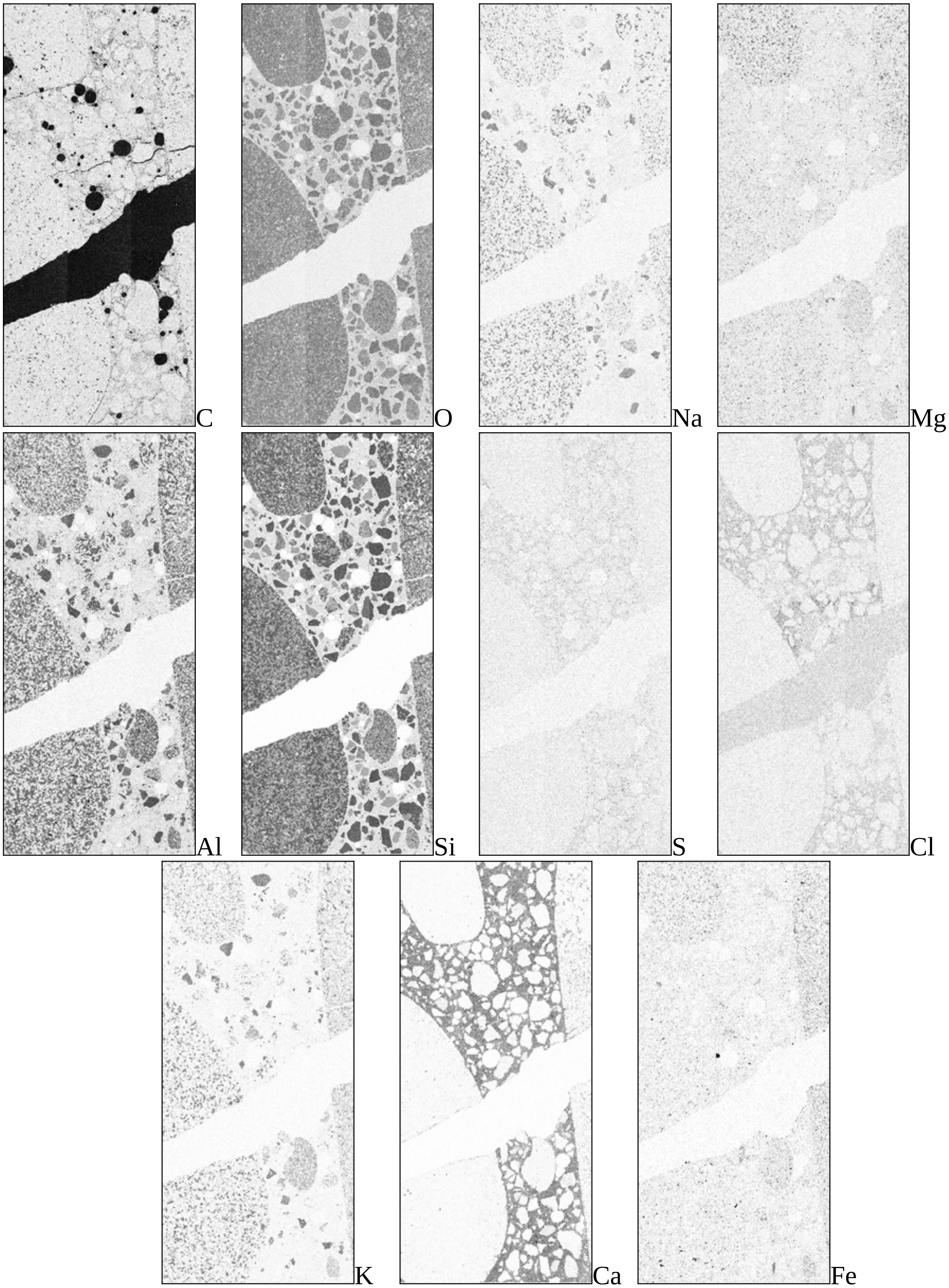

Figure S-14: Elemental maps from crack at depth, darker regions indicate higher concentrations.

South Dakota, eastbound 26th Street left-turn lane onto northbound
Interstate Highway 29

This pavement was placed on November 1, 1996, and exposed to $MgCl_2$ brine shortly thereafter on November 15, 1996. A letter came with the cores which described the pavement surface to be in good condition, but stated that the cores taken near the joint looked like they had been eaten away. Figure SD-1 shows the locations of the cores, and Figure SD-2 shows an overview of the turn lane. Figure SD-3 shows the core holes from near the joint. What had been interpreted in the letter as deterioration was just the normal appearance of a concrete joint as exposed in cross section. Figures SD-4 and SD-5 show photographs of the individual cores. Two of the cores were cut into slabs and polished: core SD-1 (at a joint), and core SD-4 (mid-panel). Figures SD-6 through SD-9 show the slabs as polished, after staining with phenolphthalein, and after treatment to enhance air voids and cracks. The phenolphthalein stain showed normal carbonation depths. The black and white treatment did not reveal any macro-cracking in either of the cores. Table SD-1 summarizes the air void parameters. Both sets of slabs showed adequate entrained air, with spacing factors of 0.158 mm and 0.176 mm for cores SD-1 and SD-4 respectively. Figure SD-10 shows an example stereomicroscope image of the air void structure. Water to cement ratio estimations were performed on thin sections prepared from cores taken at the joint, and on thin sections prepared from cores taken at mid-panel. Figures SD-11 and SD-12 show the images used to make the measurements from a thin section prepared from the top of core SD-1 (at a joint). The results of the w/c estimation are summarized in Table SD-2, with an average w/c value of 0.47 as compared to the 28-day moist cured mortar sample standards. A second thin section was prepared from the top of core SD-1, and images recorded, as shown in Figure SD-13. These images were not masked and used for w/c measurement, but provided as a visual check on the first thin section. Figures SD-14 and SD-15 show the images used to make the measurements from a thin section prepared from the top of core SD-7 (at a joint). The results of the w/c estimation are summarized in Table SD-3, with an average w/c value of 0.45. Figures SD-16 and SD-17 show the images used to make the measurements from a thin section prepared from the top of core SD-4 (mid-panel). The results of the w/c estimation are summarized in Table SD-4, with an average w/c value of 0.38. A second thin section was prepared from the top of core SD-4, and images recorded, as shown in Figure SD-18. These images were not masked and used for w/c measurement, but provided as a visual check on the first thin section. Figures SD-19 and SD-20 show the images used to make the measurements from a thin section prepared from the top of core SD-5 (mid-panel). The results of the w/c estimation are summarized in Table SD-5, with an average w/c value of 0.35. Figure 21 compares cement paste fluorescence histograms from the four cores. The samples prepared from the joint fluoresced consistently brighter than the samples prepared from mid-panel. Figures SD-22 through SD-25 show chloride profiles from cores SD-3 and SD-7.

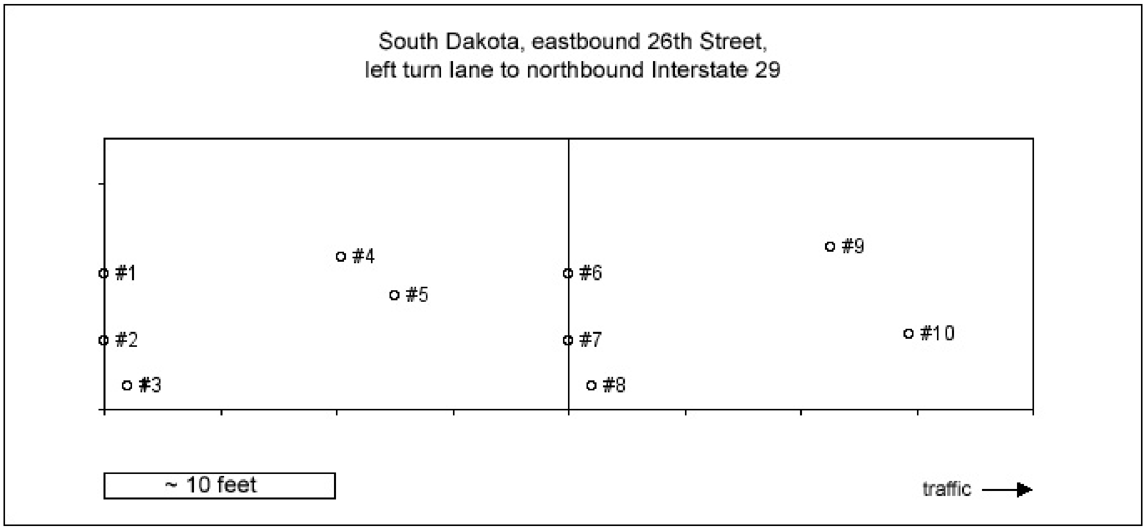

Figure SD-1: Diagram to show core locations based on submitted field information.

Figure SD-2: Photograph of core site.

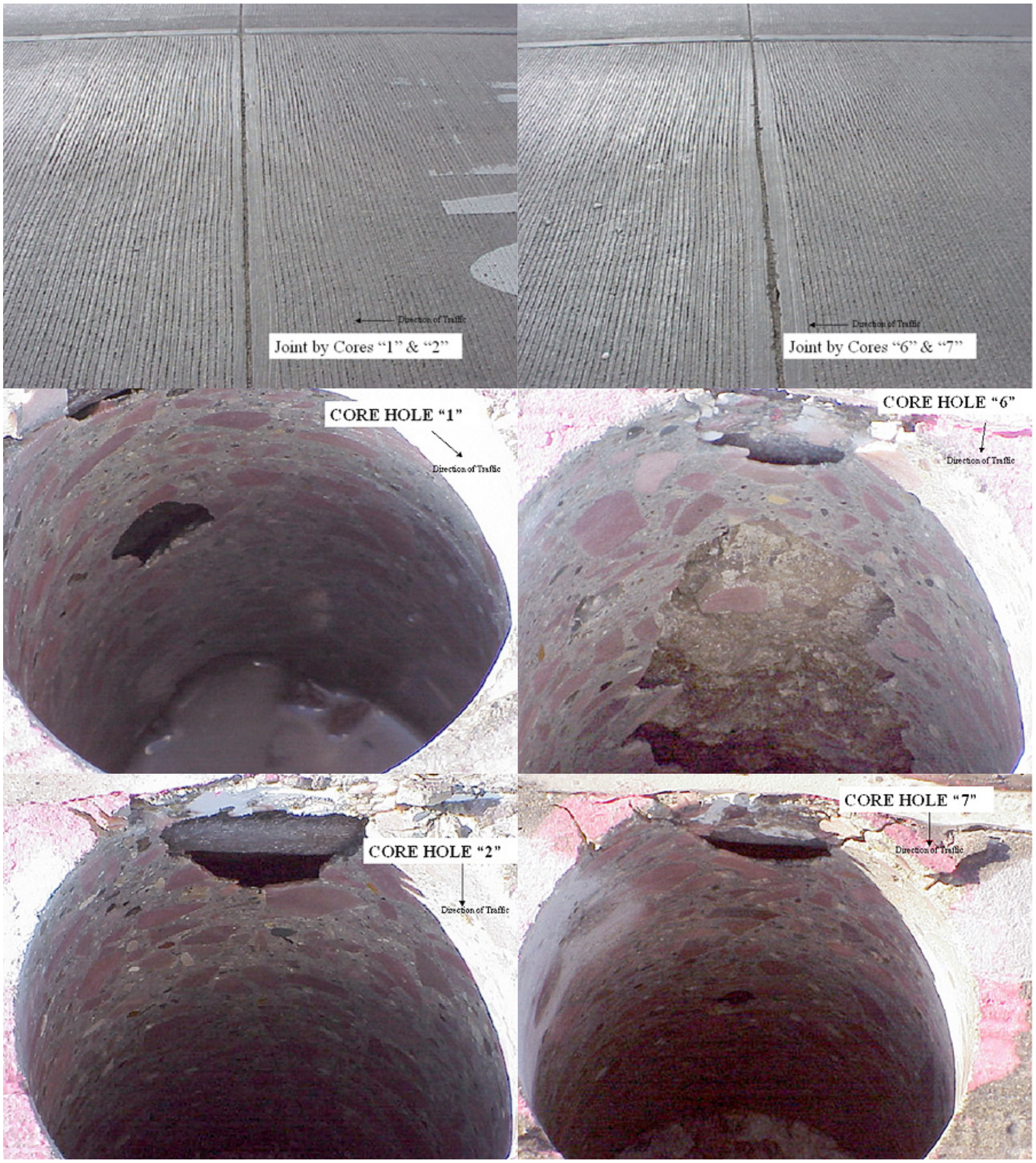

Figure SD-3: Photographs of the joints sampled, and of the holes after the coring operation.

Figure SD-4: Cores taken at joint.

Figure SD-5: Cores taken away from joint.

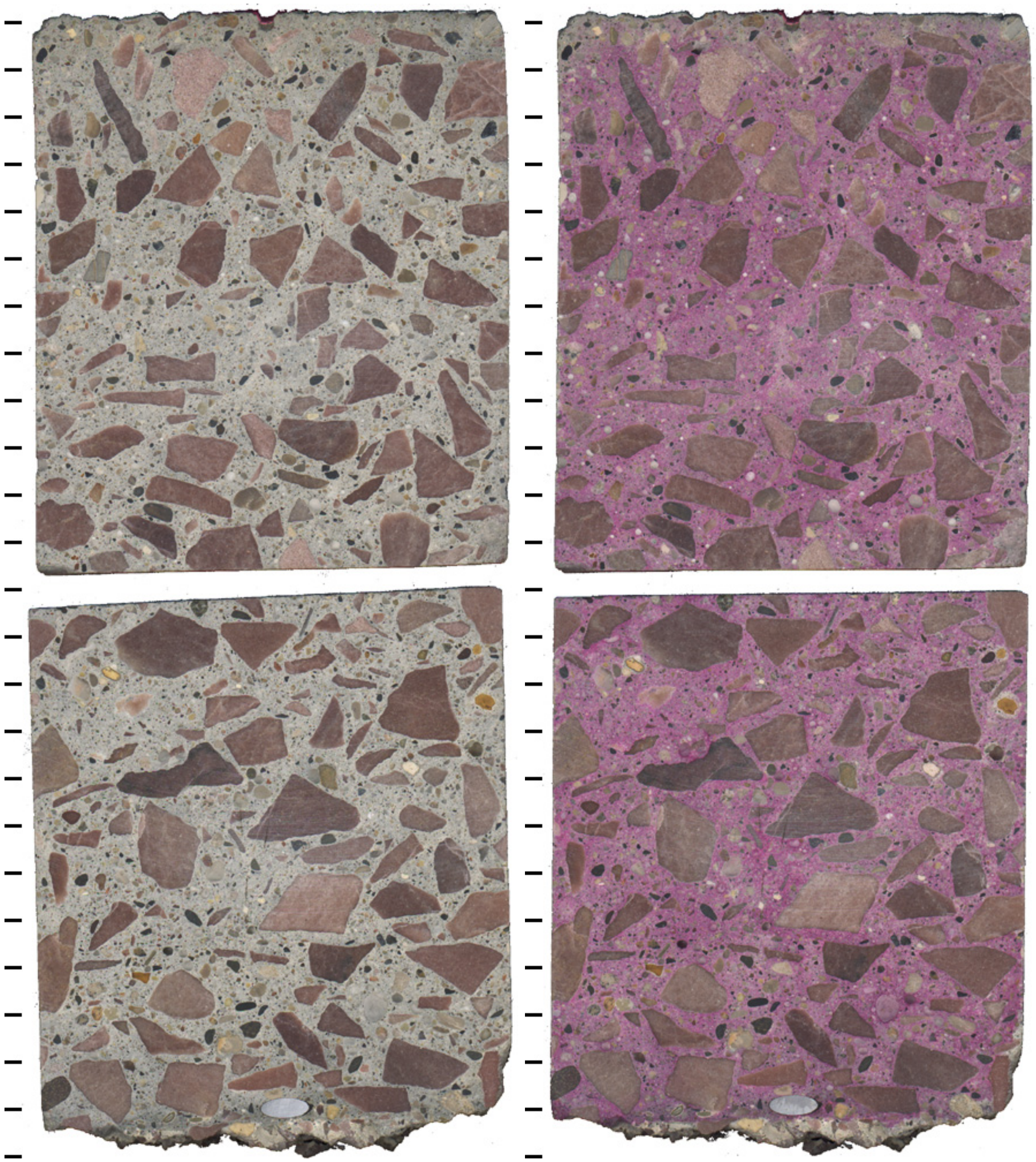

Figure SD-6: Polished slabs to show complete cross-section through core SD-1 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

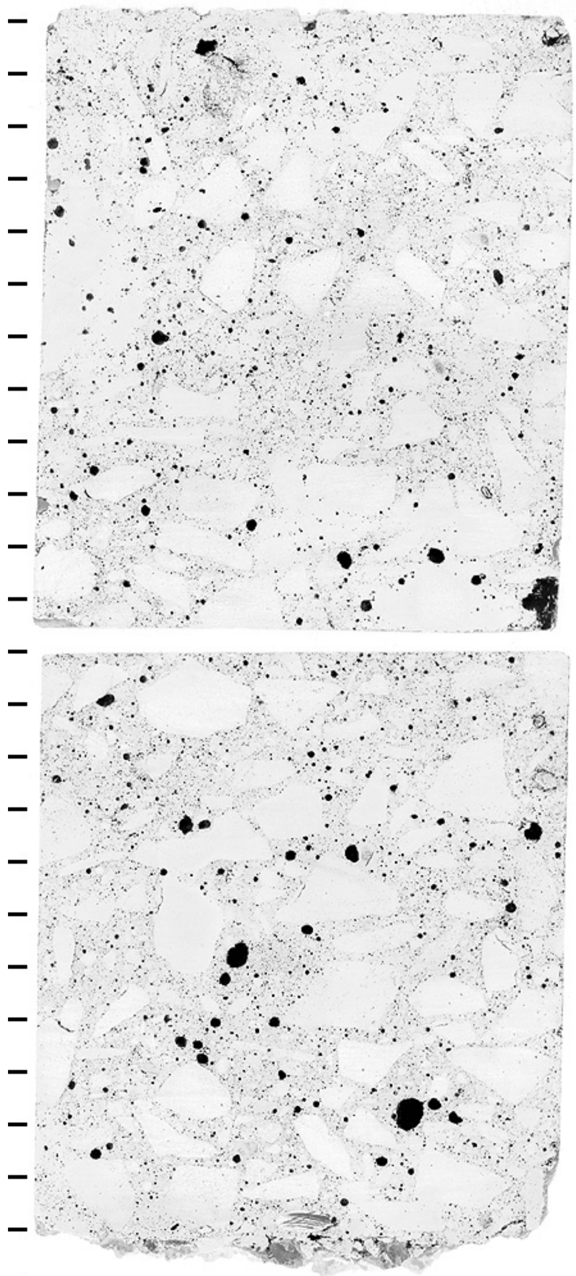

Figure SD-7: Polished slabs to show complete cross-section through core SD-1 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

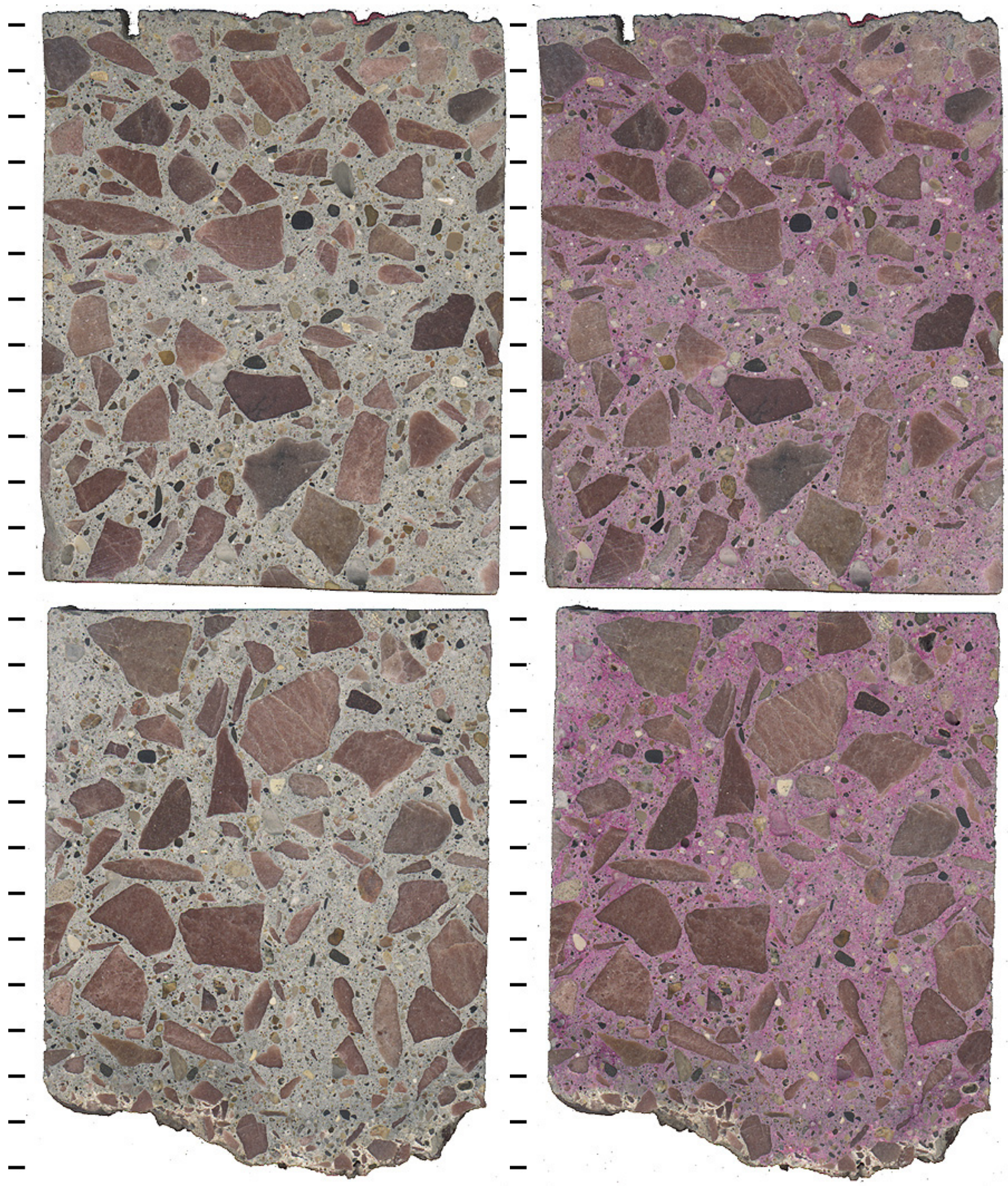

Figure SD-8: Polished slabs to show complete cross-section through core SD-4 both before (left) and after application of phenolphthalein stain (right) tic marks every cm.

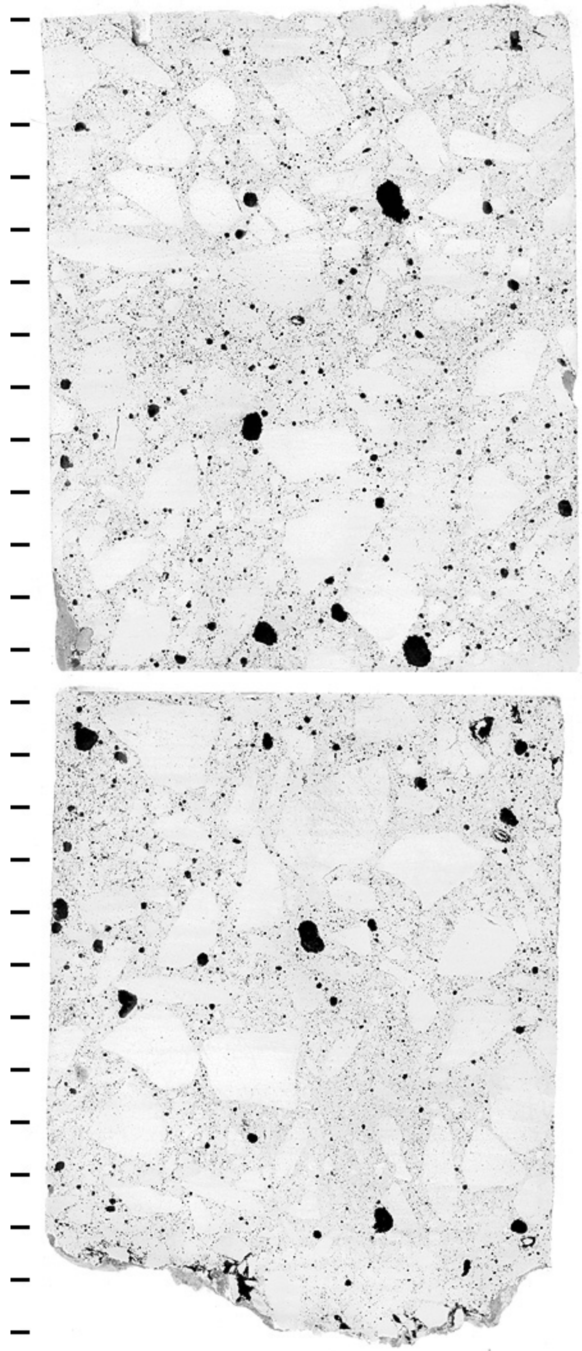

Figure SD-9: Polished slabs to show complete cross-section through core SD-4 after treatment to enhance appearance of air voids and cracks, tic marks every cm.

Table SD-1: Air void parameters

Sample ID	SD_01	SD_04
Location	at joint	away from joint
Raw data		
Total traverse length (mm)	3625.456	3625.456
Area analyzed (cm^2)	71.0	71.0
Air stops	85	91
Paste stops	396	382
Aggregate stops	907	915
Secondary deposit stops	0	0
Total stops	1388	1388
Number of air intercepts	1577	1420
Number of filled void intercepts	2	0
Results		
Air vol%	6.1	6.6
Paste vol%	28.5	27.5
Aggregate vol%	65.3	65.9
Secondary deposit vol%	0.0	0.0
Existing average chord length (mm)	0.141	0.167
Existing paste/air ratio	4.7	4.2
Existing air void specific surface (mm^{-1})	28.4	23.9
Existing air void frequency (voids/m)	435	392
Existing spacing factor (mm)	0.158	0.176
Original average chord length (mm)	0.141	0.167
Original paste/air ratio	4.7	4.2
Original air void specific surface (mm^{-1})	28.4	23.9
Original air void frequency (voids/m)	436	392
Original spacing factor (mm)	0.158	0.176

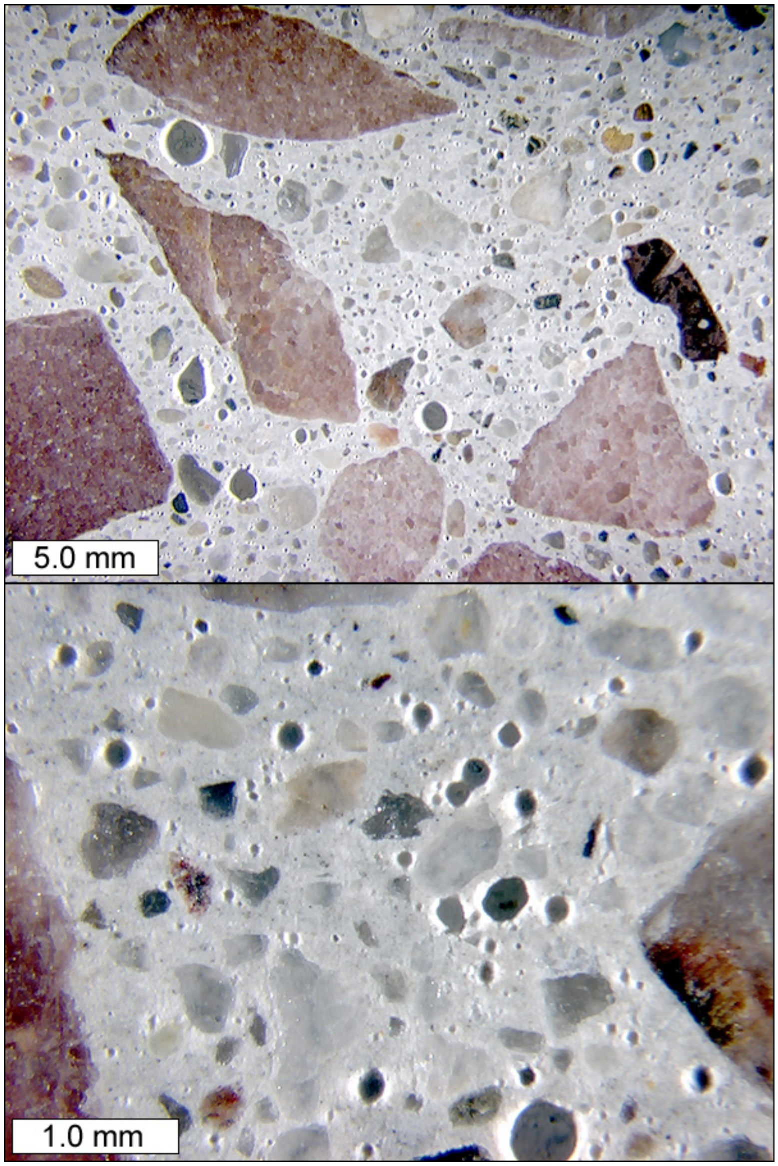

Figure SD-10: Stereo microscope images to show air void structure on polished slab from core SD-4.

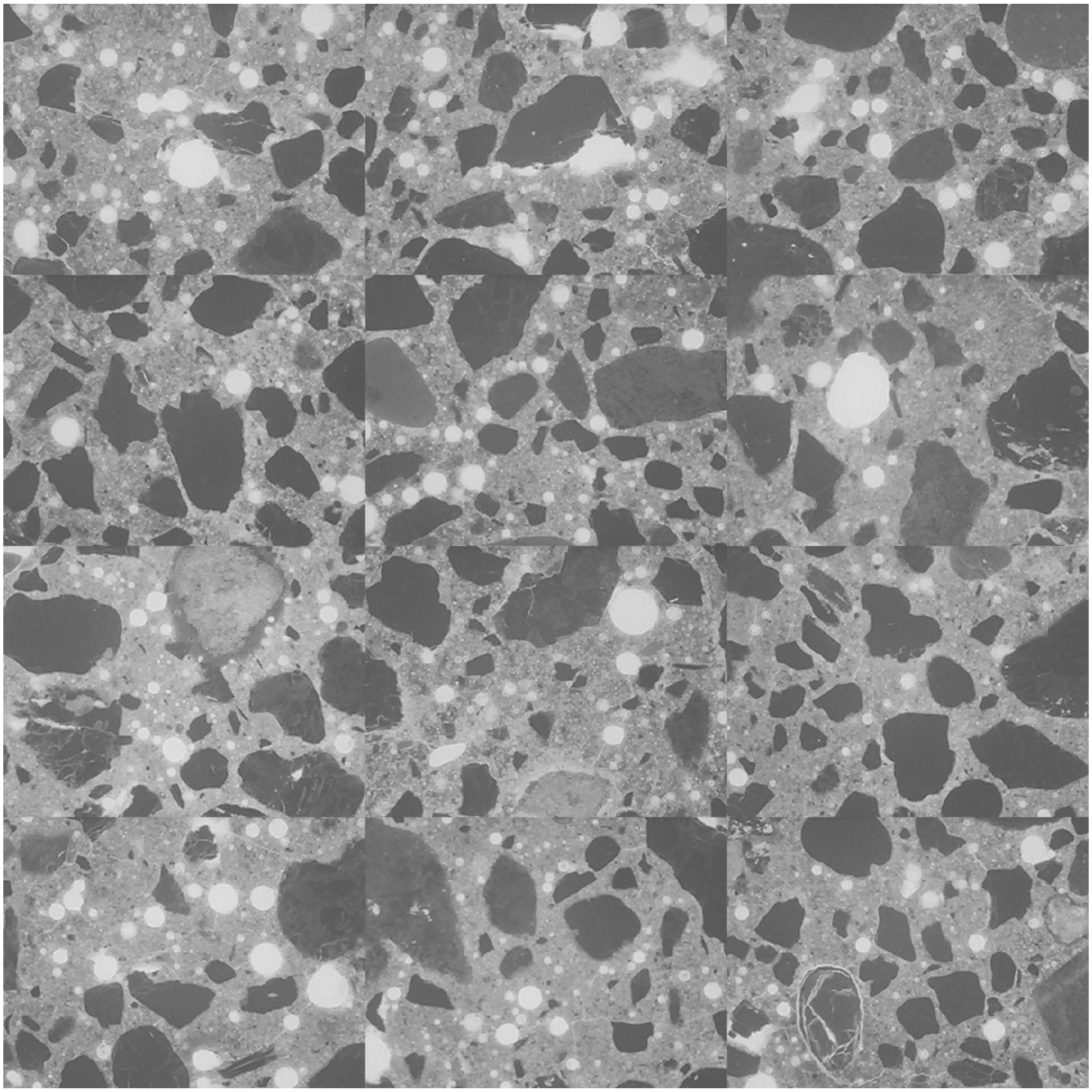

Figure SD-11: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-1 (each individual frame measures 2.612 x 1.959 mm).

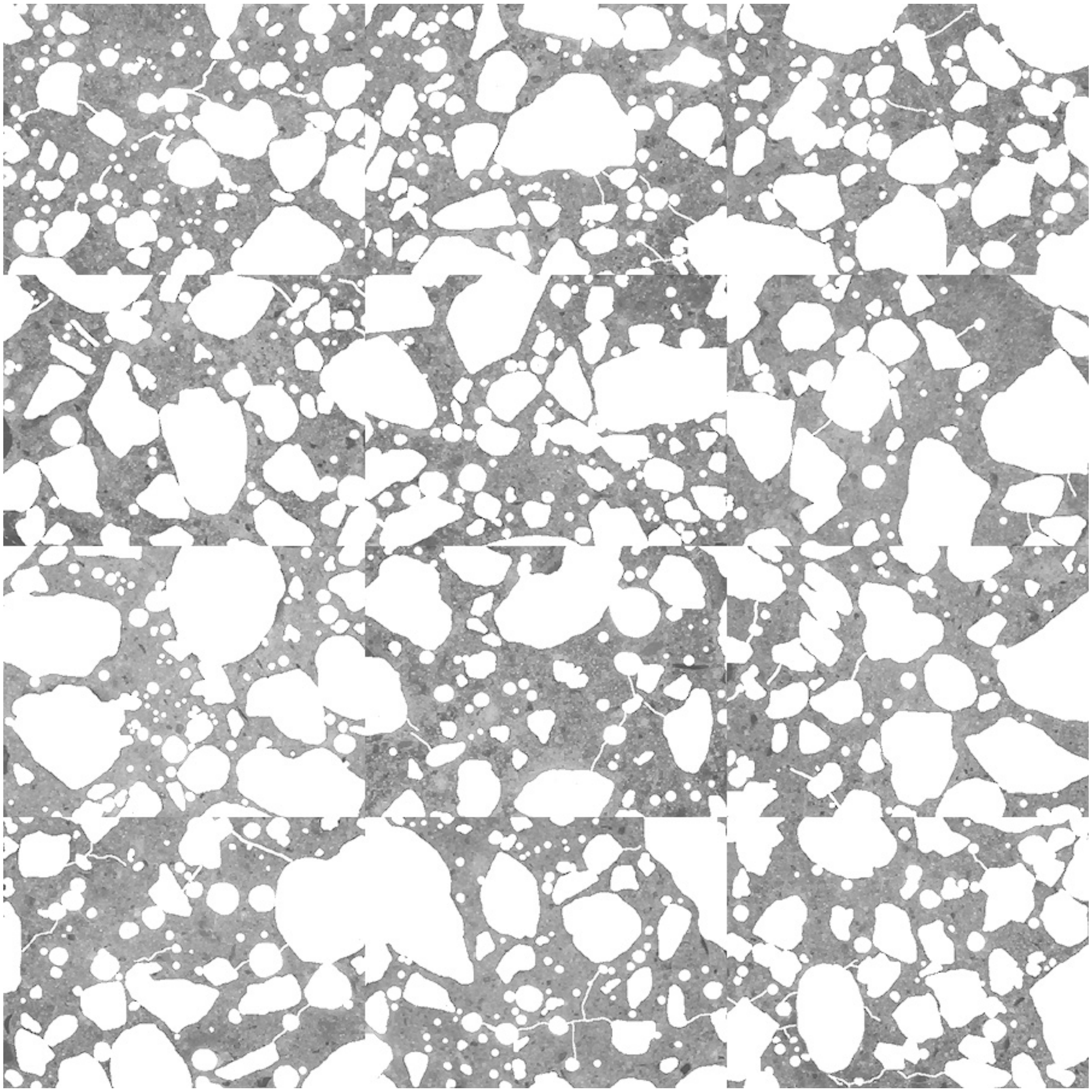

Figure SD-12: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-1 after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table SD-2: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) for core SD-1.

cement paste pixel fluorescence measurements (average intensity per frame)			
101	101	95	95
93	98	120	97
101	102	101	97
equivalent *w/c* ($y = 0.0044x + 0.0329$)			
0.47	0.47	0.45	0.45
0.44	0.46	0.56	0.46
0.47	0.48	0.47	0.46

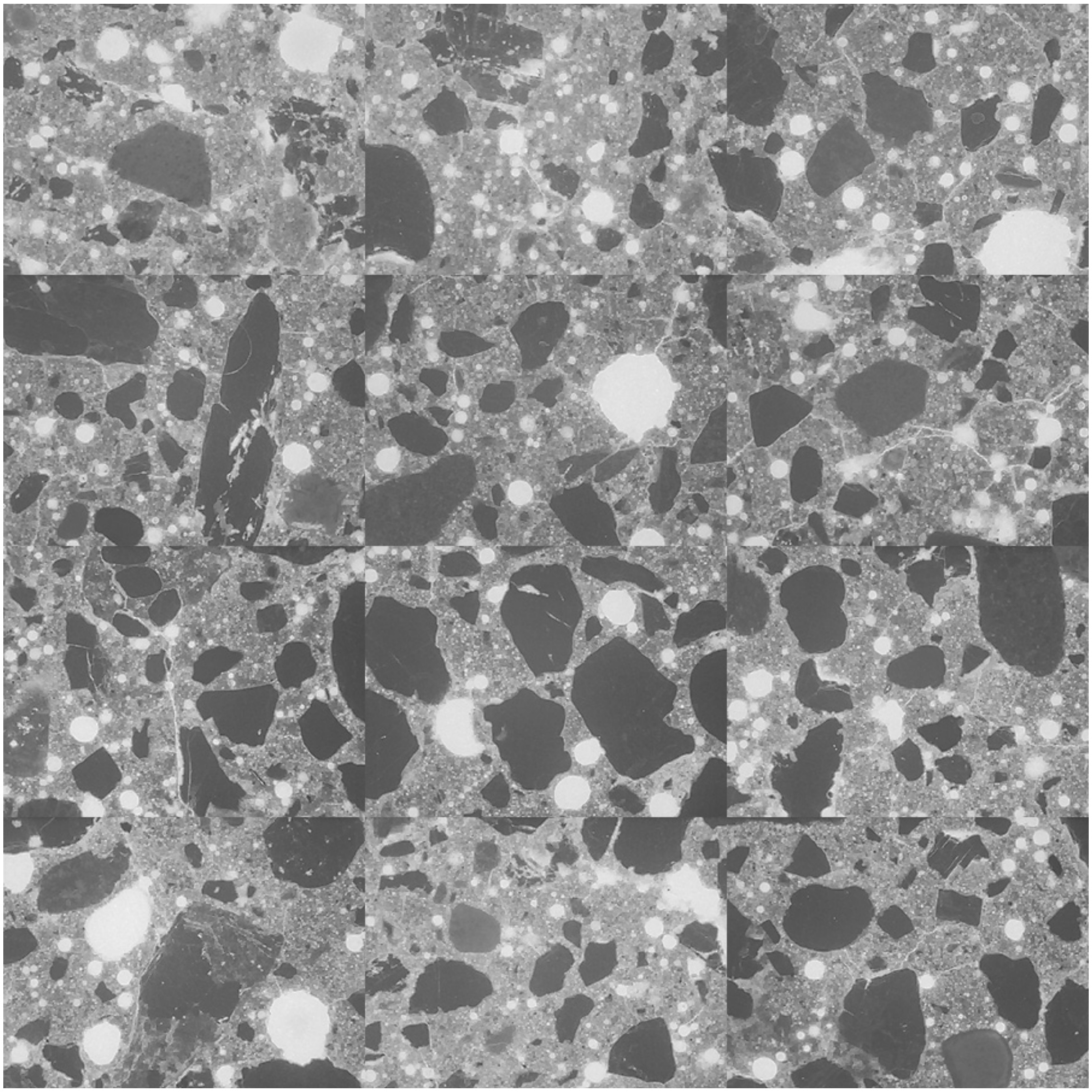

Figure SD-13: Mosaic of 12 frames collected from thin section prepared from a second billet cut from top portion of core SD-1 (each individual frame measures 2.612 x 1.959 mm). These frames were not masked and used for w/c determination, but recorded as visual check against the first section prepared from core SD-1.

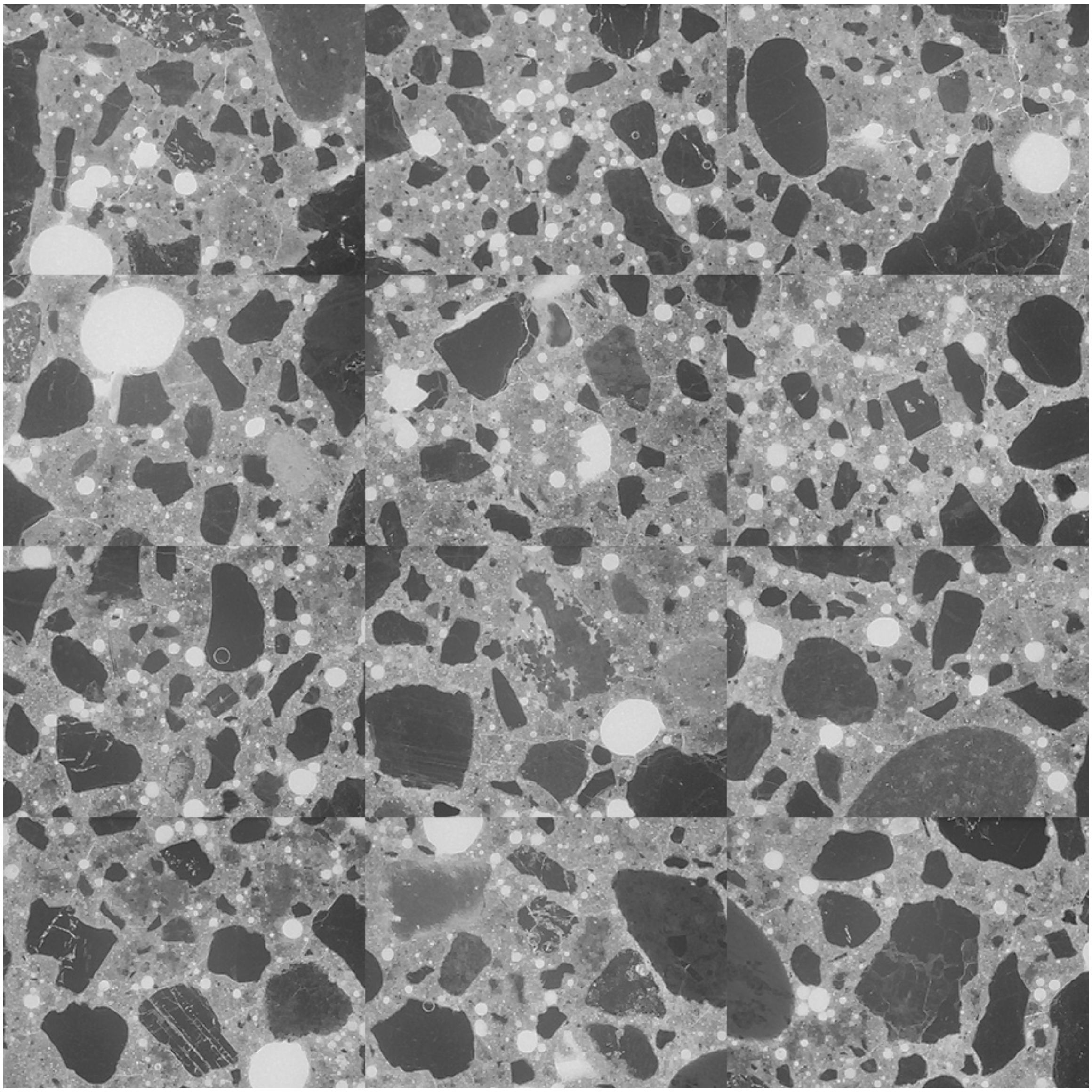
Figure SD-14: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-7 (each individual frame measures 2.612 x 1.959 mm).

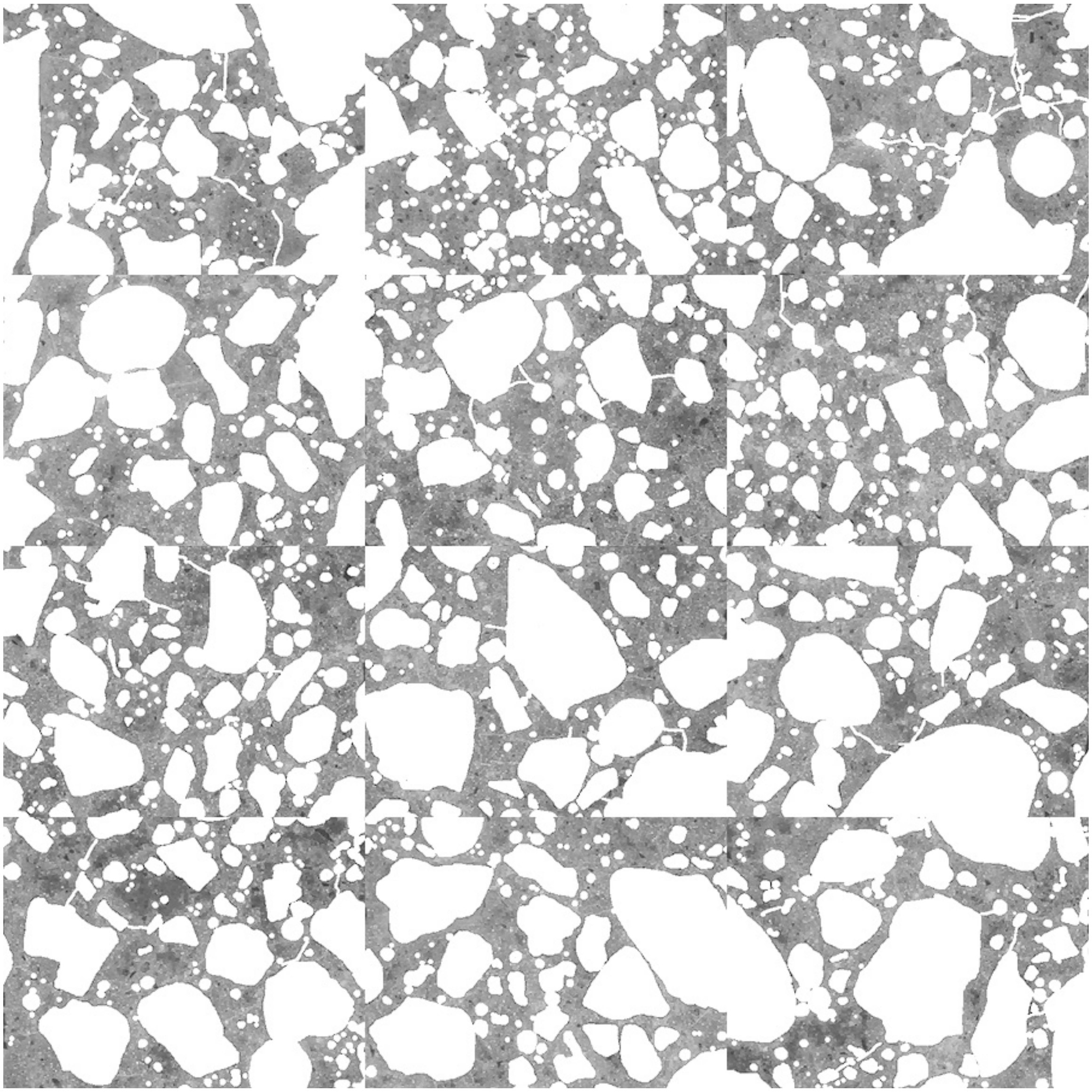

Figure SD-15: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-7 after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table SD-3: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) for core SD-7.

cement paste pixel fluorescence measurements (average intensity per frame)			
97	97	96	103
92	102	91	95
95	89	103	95
equivalent w/c ($y = 0.0044x + 0.0329$)			
0.46	0.45	0.45	0.48
0.44	0.48	0.43	0.45
0.45	0.42	0.48	0.45

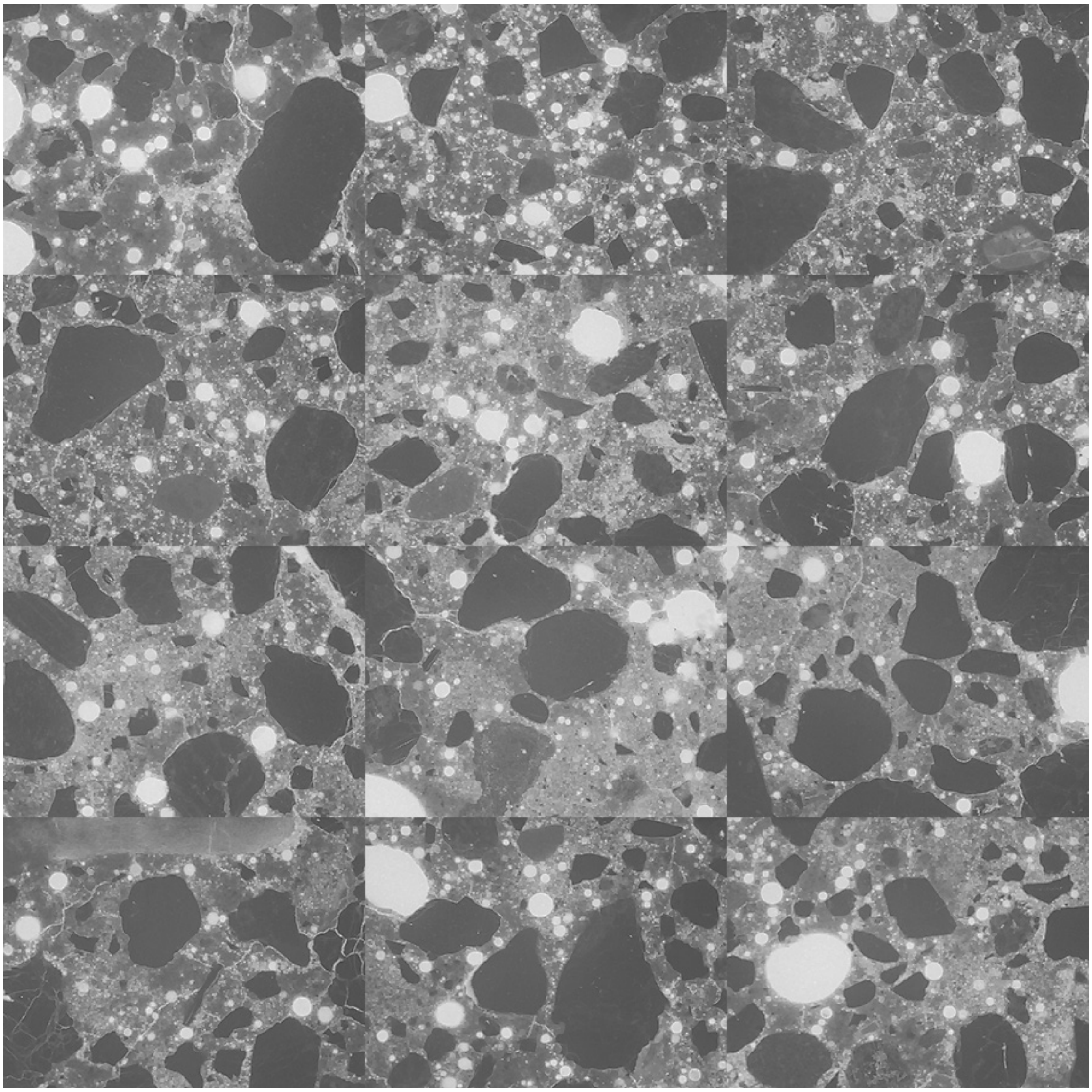

Figure SD-16: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-4 (each individual frame measures 2.612 x 1.959 mm).

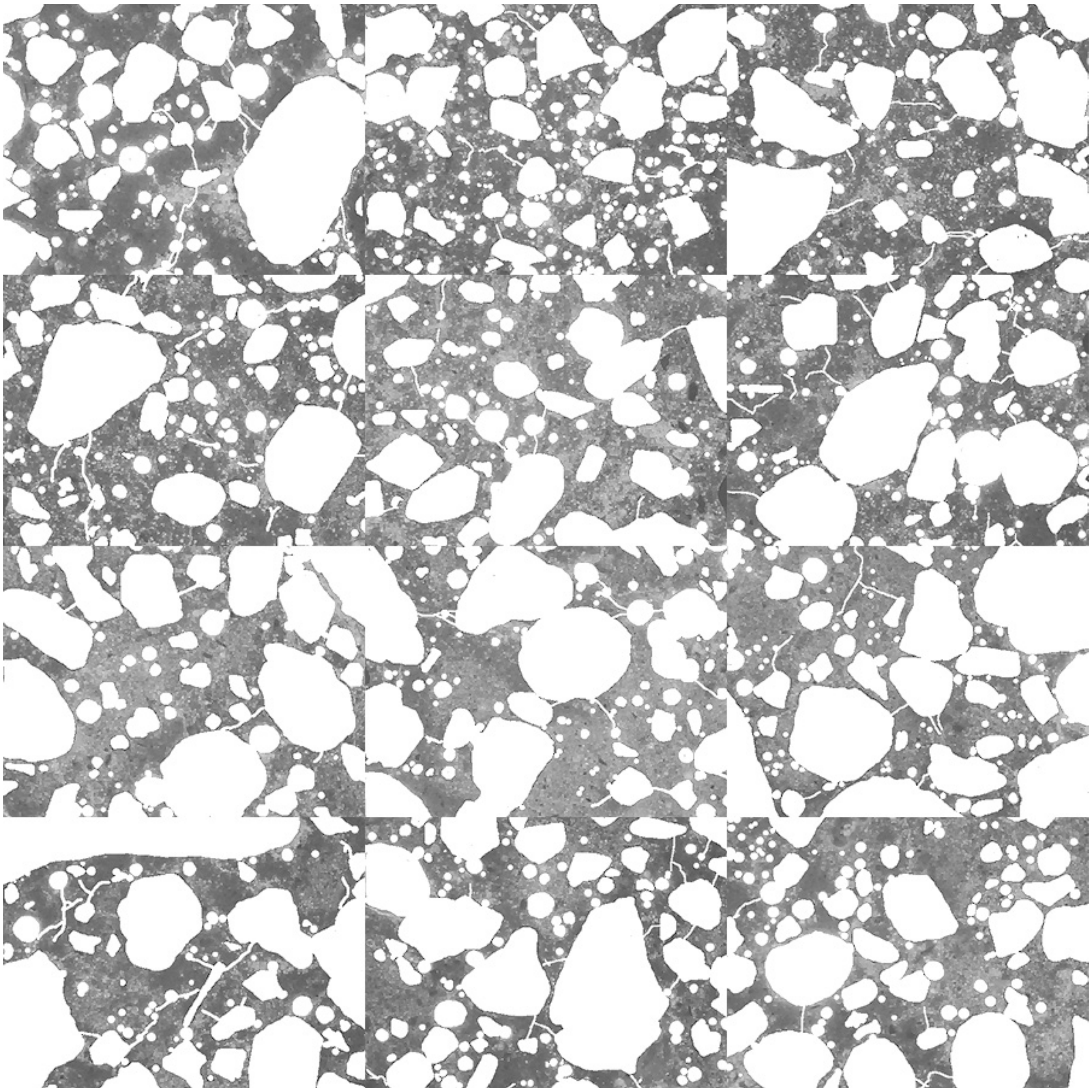

Figure SD-17: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-4 after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table SD-4: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) from core SD-4.

cement paste pixel fluorescence measurements (average intensity per frame)			
78	78	71	76
93	90	94	85
85	68	70	70
equivalent w/c (y = 0.0044x + 0.0329)			
0.37	0.37	0.34	0.37
0.44	0.35	0.43	0.44
0.40	0.33	0.34	0.34

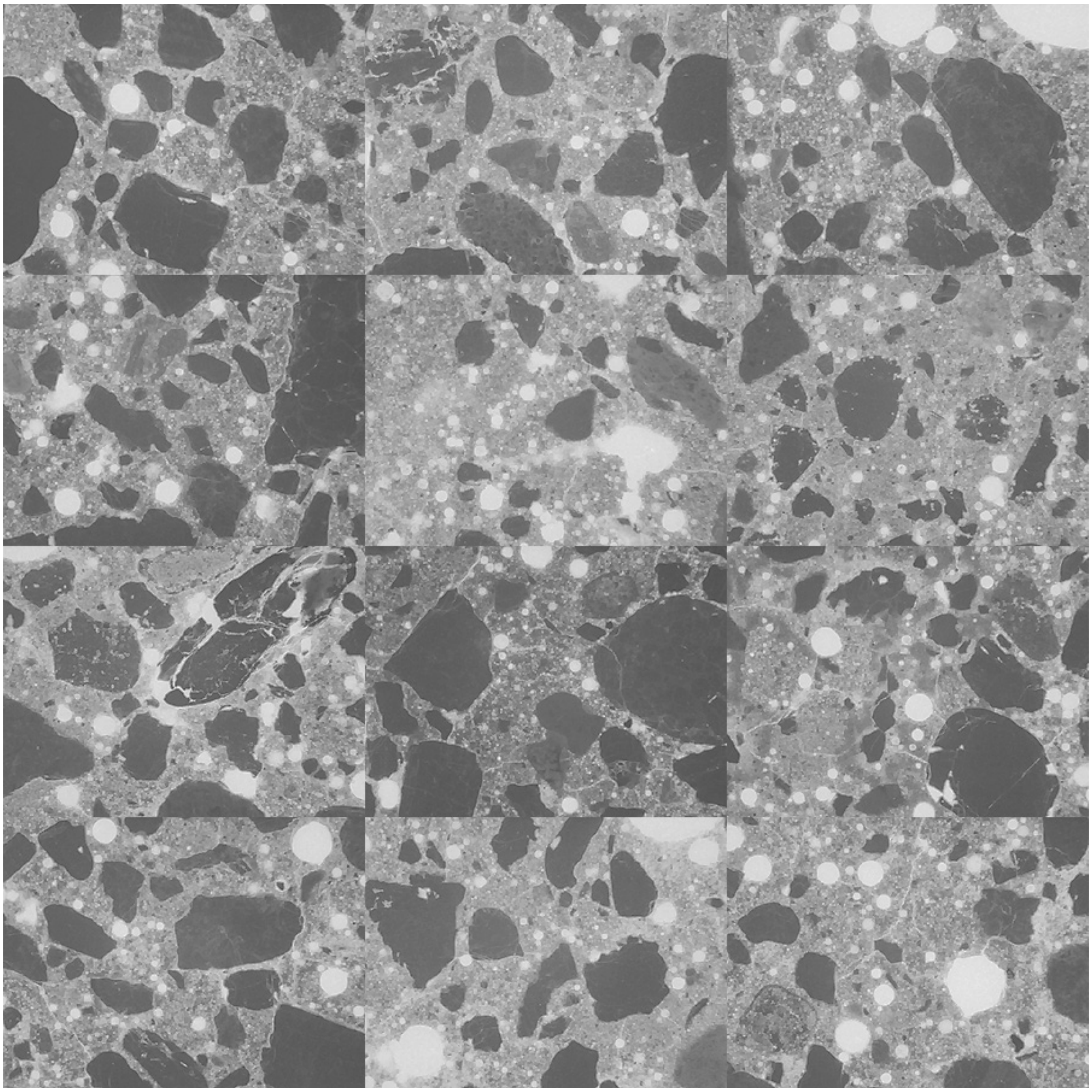

Figure SD-18: Mosaic of 12 frames collected from thin section prepared from a second billet cut from top portion of core SD-4 (each individual frame measures 2.612 x 1.959 mm). These frames were not masked and used for w/c determination, but recorded as visual check against the first section prepared from core SD-4.

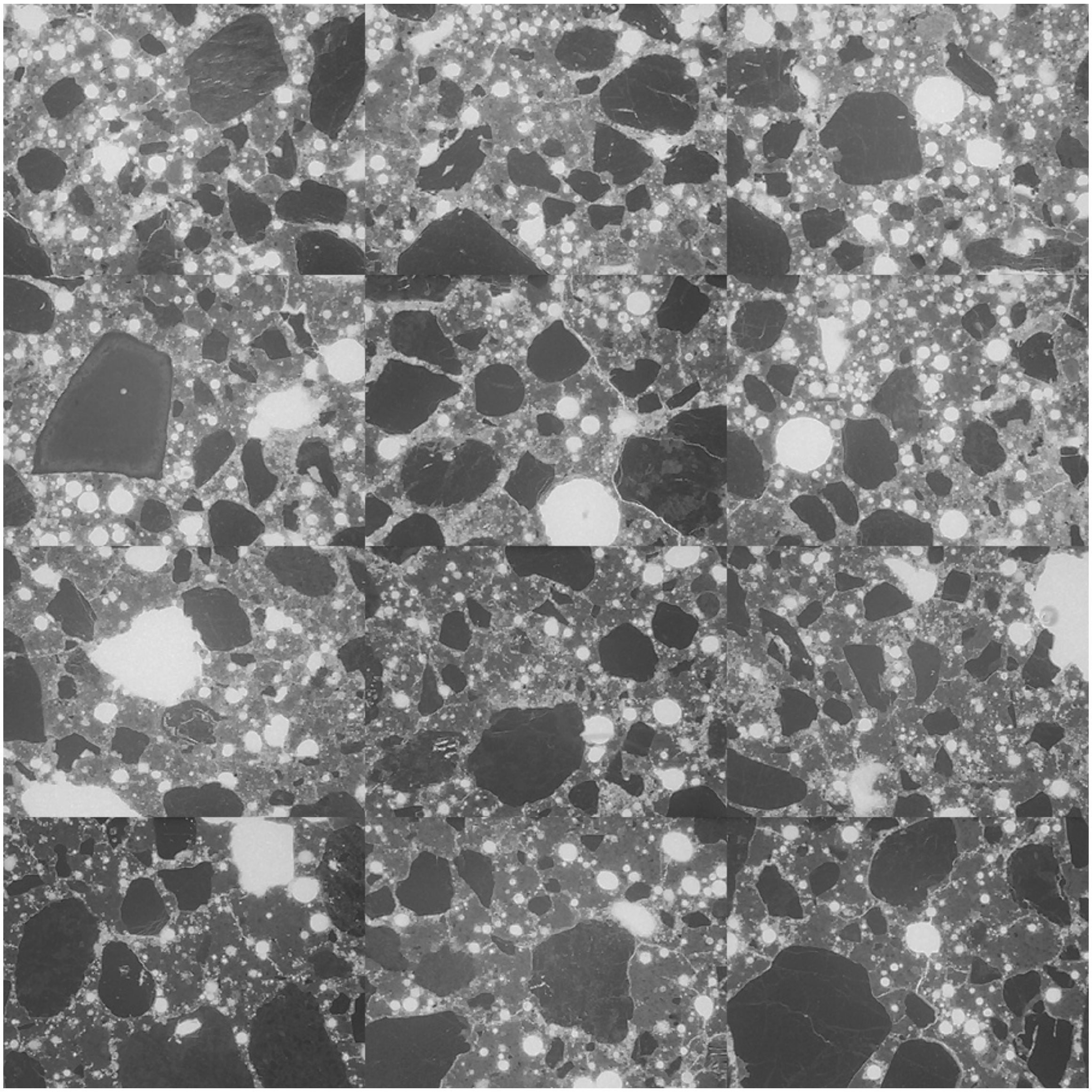

Figure SD-19: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-5 (each individual frame measures 2.612 x 1.959 mm).

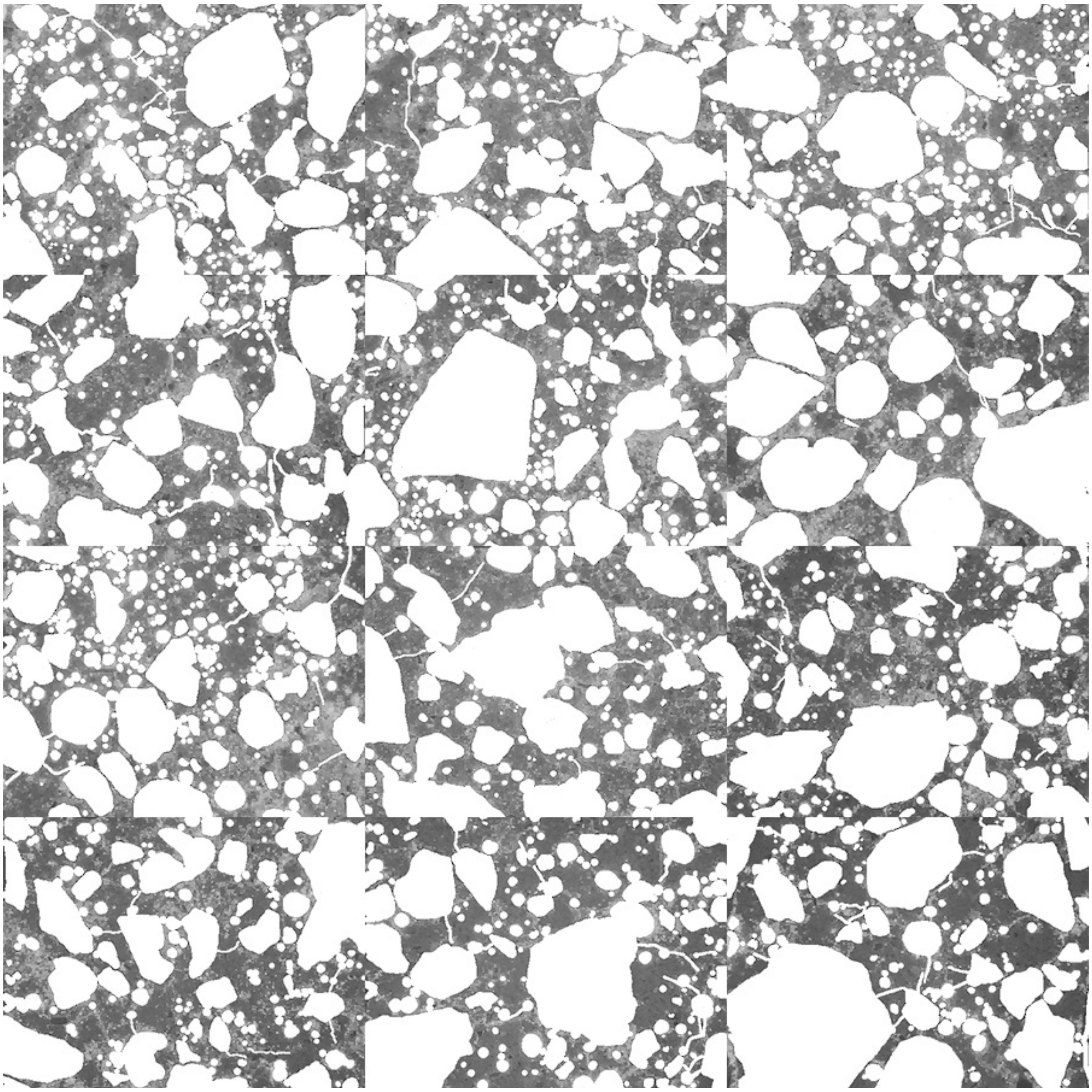

Figure SD-20: Mosaic of 12 frames collected from thin section prepared from billet cut from top portion of core SD-5 after masking out air voids, fine aggregate, and micro-cracks to isolate cement paste (each individual frame measures 2.612 x 1.959 mm).

Table SD-5: Average cement paste pixel intensities per frame, and equivalent w/c values (as compared to 28-day moist cured mortar samples) core SD-5.

cement paste pixel fluorescence measurements (average intensity per frame)			
86	84	86	74
82	74	83	75
58	64	62	52
equivalent *w/c* ($y = 0.0044x + 0.0329$)			
0.41	0.40	0.41	0.36
0.39	0.36	0.39	0.36
0.29	0.31	0.30	0.26

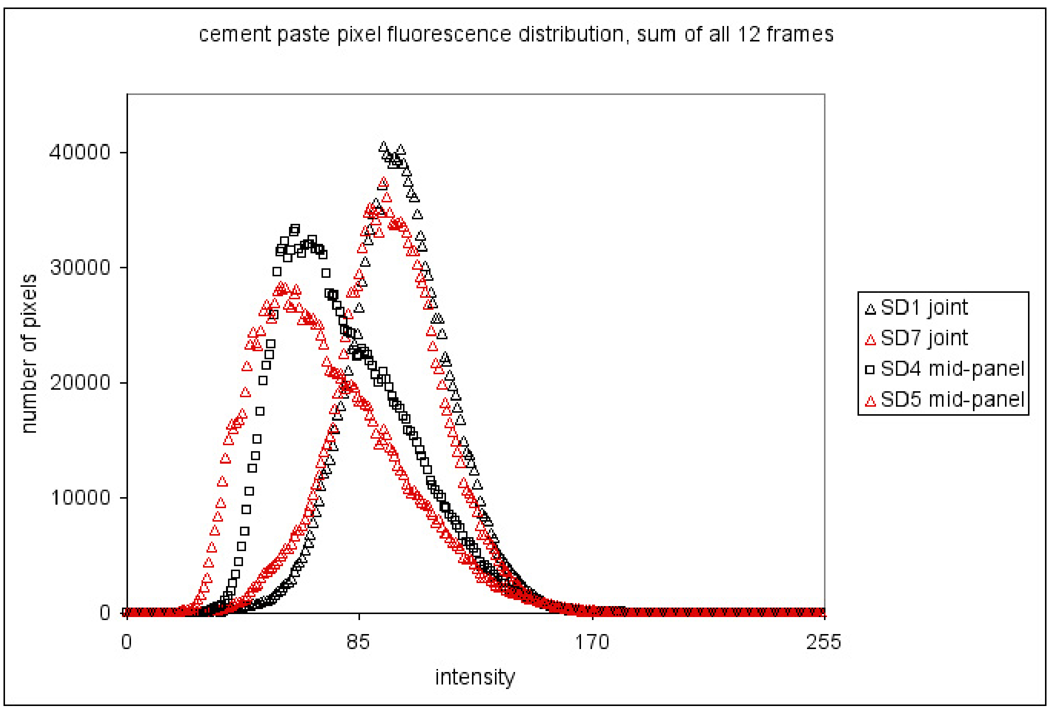

Figure SD-21: Histogram comparing cement paste pixel intensities using all 12 frames as collected from thin sections prepared from cores taken at the joint versus cores taken mid-panel

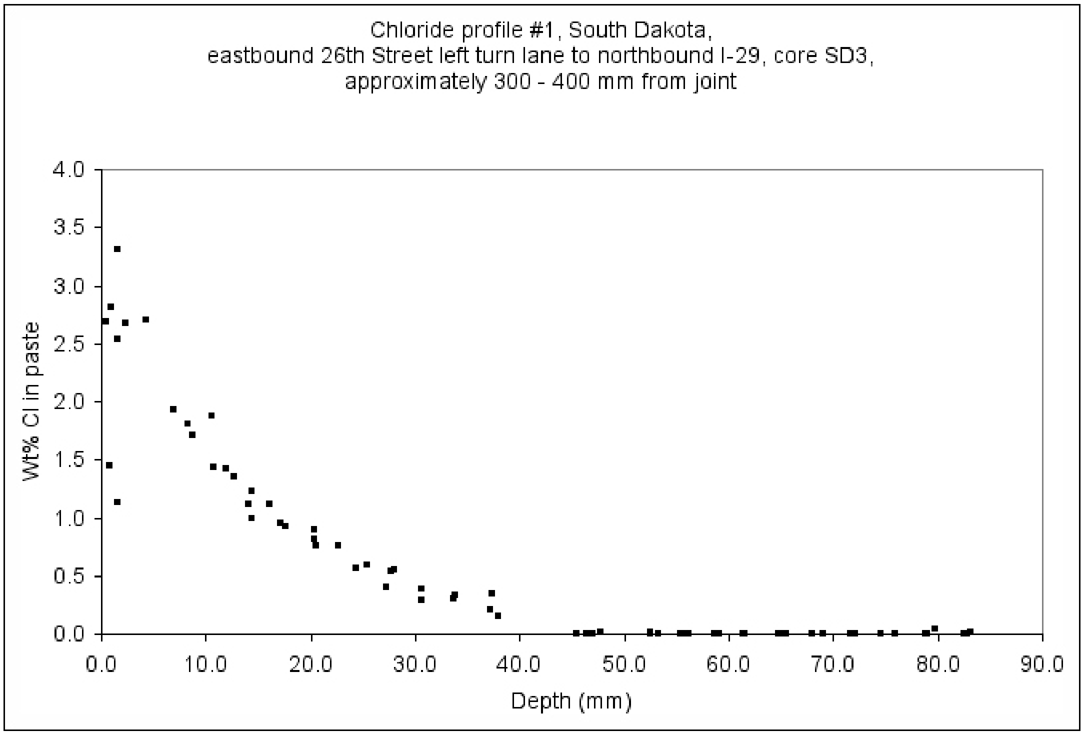

Figure SD-22: Chloride profile through cement paste, from billet prepared from core SD-3.

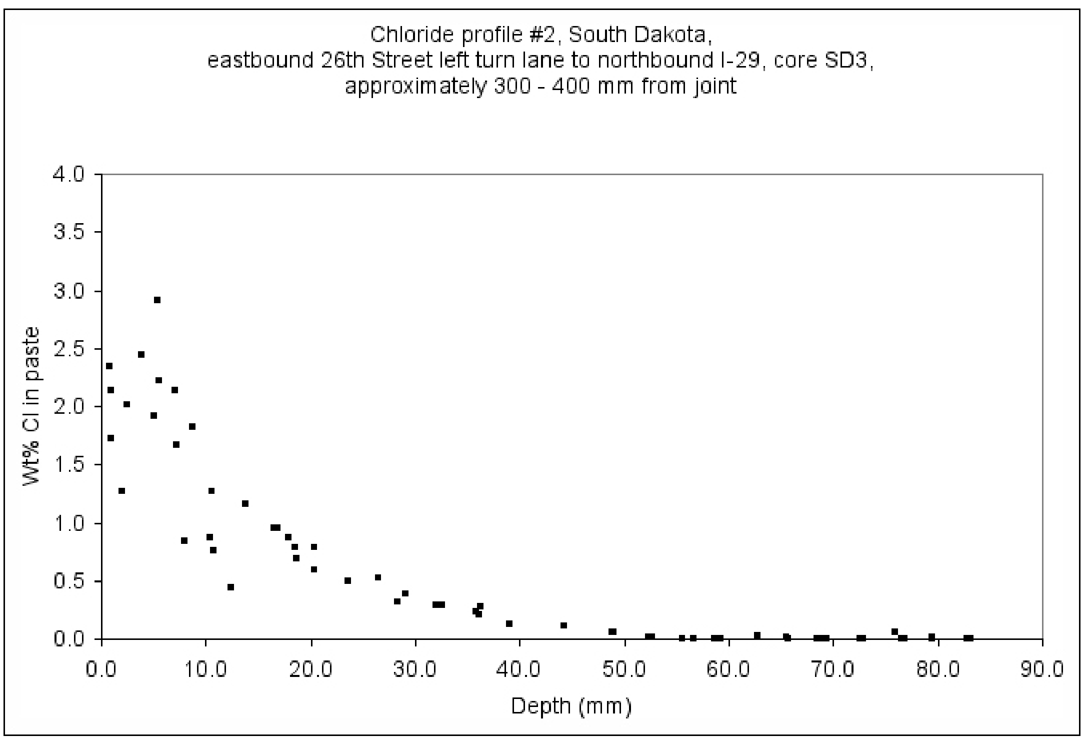

Figure SD-23: Chloride profile through cement paste, from billet prepared from core SD-3.

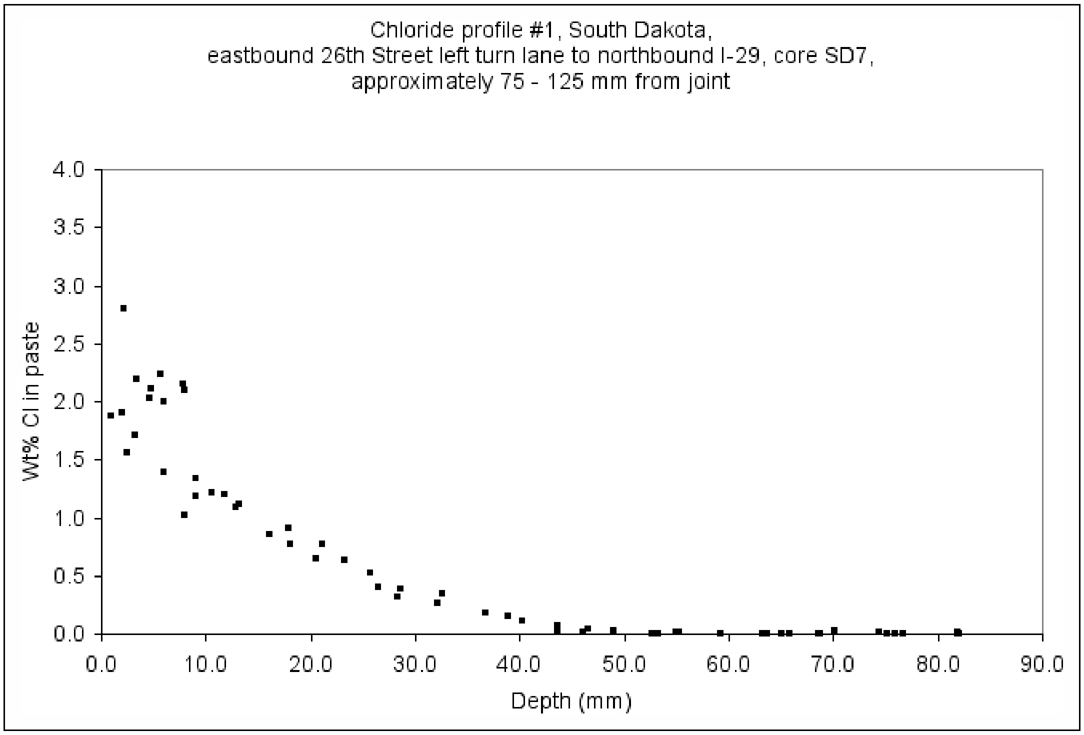

Figure SD-24: Chloride profile through cement paste, from billet prepared from core SD-7.

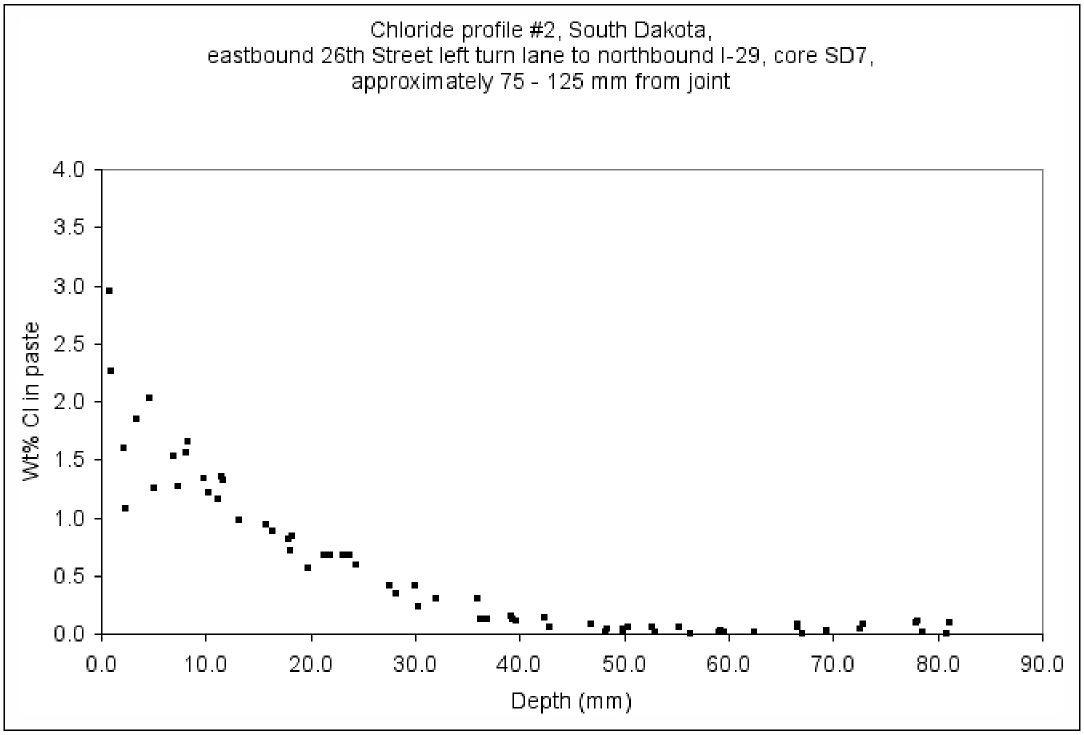

Figure SD-16: Chloride profile through cement paste, from billet prepared from core SD-7.

Task 5 Problems and/or Deviations from Work Plan

There were no problems for Task 5 incurred during the reporting period.

Task 5 Completion -100%

Task 6: Laboratory Experiment

Work Conducted at Michigan Tech

<u>*Paste Hardness Measurements*</u>

Researchers at Michigan Tech have been investigating different ways to measure deterioration of the concrete specimens other than by means of microscopy. During this reporting period, micro-hardness measuring techniques have been evaluated for their suitability. The Vickers hardness test was first evaluated but was not readily applicable. Recent work has focused on the Rockwell test method. A brief summary is provided below.

A series of previously prepared, 50mm diameter portland cement mortar cylinders were sectioned and prepared for hardness testing. Pairs of cylinders were prepared with water/cement ratios of 0.4, 0.5 and 0.6. One cylinder from each pair was soaked for 84 days in limewater while the second cylinder received an 84 day $MgCl_2$ solution soak. Circular billets were sectioned from the center of the cylinder on a kerosene-cooled diamond saw. These billets were then trimmed to facilitate grinding and polishing such that one edge of the billets was from the outside surface of the original cylinder. The dimensions of each billet were approximately 25mm width x 45mm length and 15mm thickness. The billets were then ground to parallel on a mineral oil cooled diamond grinder and polished using 1000 grit SiC powder. The polished billets were then hardness tested in a manner similar to ASTM E 18 – *Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials*. ASTM E 18 calls for a tungsten carbide indenter, which was not available at testing. A stainless steel indenter was used. The HR15W Rockwell hardness scale was used for these materials. This is a superficial hardness test that uses a 1/8 inch indenter with a total test force of 15kg. Fifteen indentations were made in each sample and measured. Several of each set of data were culled for various reasons ranging from shifting of the surrounding material to the obvious damage caused when then indenter was inadvertently placed on a pore in the paste. These data are plotted in Figure 1.

The data shows a decrease in hardness with increasing water/cement ratio. These numbers are somewhat suspect as the standard deviations for the data are rather large. The data are shown in Table 1. There are varying numbers of data points in each set because different numbers of data points were culled from each set. It is believed that a larger indenter (either ¼ or ½ inch) may give a more reliable measurement of the overall hardness of the mortar. A smaller indenter (1/16 inch) may be used to more accurately measure the hardness of the paste.

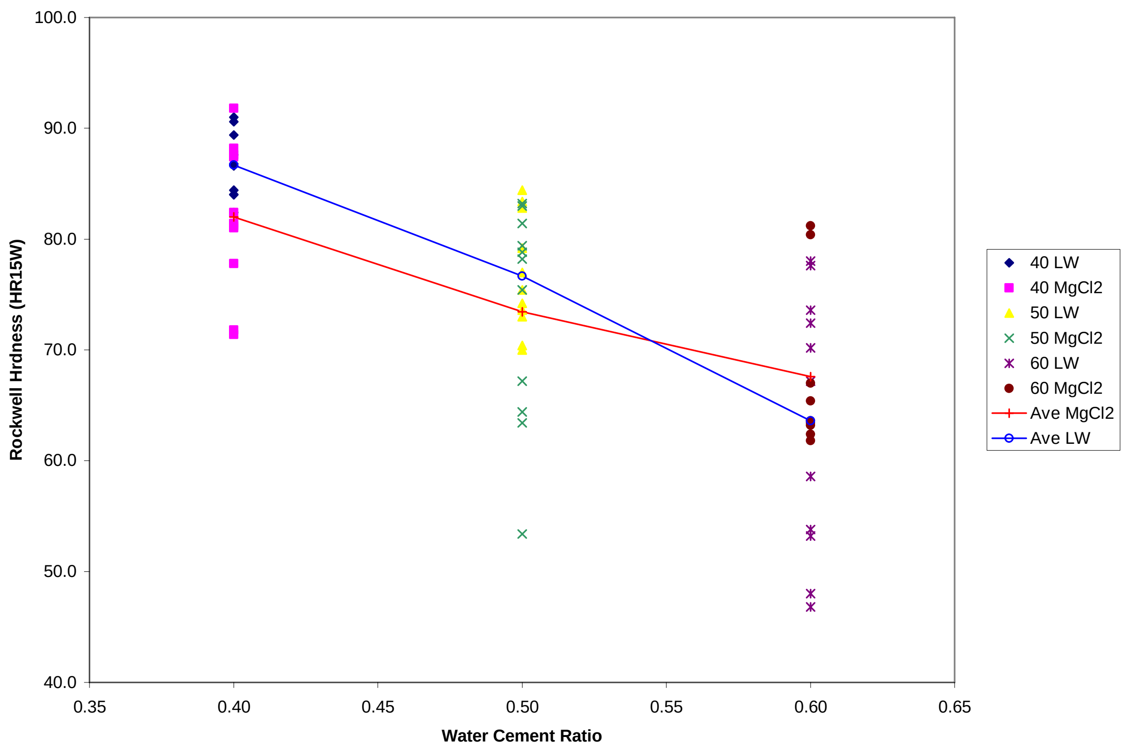

Figure 1. Rockwell Hardness of various Portland cement mortar samples.

Table 1. HR15W data from tested mortar cylinders.

	40LW	40MgCl2	50LW	50MgCl2	60LW	60MgCl2
	91.0	81.2	70.0	53.4	48.0	67.0
	84.4	71.4	70.4	75.4	53.2	80.4
	82.4	77.8	82.8	63.4	53.8	63.4
	87.6	81.0	77.0	67.2	58.6	61.8
	90.6	82.4	74.2	64.4	73.6	62.4
	89.4	81.4	73.0	81.4	70.2	65.4
	84.0	71.8	83.4	83.0	72.4	63.2
	86.8	91.8	79.2	78.2	67.2	63.6
	84.0	87.6	84.4	83.2	78.0	81.2
	86.6	88.2	75.4	79.4	46.8	
		87.4	73.6	78.8	77.6	
Average	86.7	82.0	76.7	73.4	63.6	67.6
Std Dev	3.0	6.6	5.1	9.8	11.8	7.6

Chloride Profiling of Laboratory Specimens

Sets of 100mm diameter mortar and concrete cylinders were cast and moist-cured. The sets included cylinders made with 0.45 and 0.55 water/cement ratios as well as cylinders made with straight Portland cement, with additions of ground granulated blast furnace slag and with additions of fly ash. The cylinders were sectioned into approximately 60mm thick specimens. These specimens were then placed into solutions made with various deicers ($MgCl_2$, $CaCl_2$, NaCl, Caliber and CMA) at a high and low concentration for 60 days at a temperature of 5°C. The concentrations of the deicer solutions are given in Table 1 and a complete list of specimens is given in Table 2.

Table 1. Deicer solution concentrations.

	Concentration (wt%)	
Deicer	High	Low
MgCl2	15.0	6.2
CaCl2	17.0	7.0
NaCl	17.8	7.3
Caliber	51.6	29.8
CMA	20.0	8.2

Chloride profiling has been underway on specimens pulled from solutions at 60 days. Two profiles are collected per specimen: one profile from each of two billets cut from the specimen. To prepare the billets, a slab is cut from the middle of each specimen with a kerosene cooled diamond saw to obtain a rectangular cross-section. The pair of billets is cut from the center portion of each slab, such that the top of each billet represents the top surface of the specimen in cross-section. Each billet has dimensions of approximately 25mm width x 45mm depth x 15mm thick. The billet cross-sectional surfaces are ground flat with a mineral-oil cooled diamond grinder. Each billet is placed in the

Oxford/Horiba XGT 2000W x-ray analytical microscope and 54 spectra are collected from points in the cement paste to represent 18 depth horizons. The processing of collected spectra has been a limiting factor in the chloride profiling procedure. Each individual spectrum had to be opened individually with the Oxford/Horiba XGT-2000W software, processed, and the results cut and pasted into a spreadsheet. Faced with the task of analyzing nearly 8000 individual spectra, help was sought from the IT Services Department at Michigan Tech to write a program to extract the x-ray count data from the bin hex spectrum files and to report it in a spreadsheet-friendly text format. An Excel spreadsheet macro was also written to process the spectra text files and depth data into chloride profiles. The macro places the entire spectrum into an Excel spreadsheet, extracts the total x-ray counts in the range of 2.51 to 2.76 KeV (the chlorine K-alpha peak) and uses a routine to cull certain data points. The culling of data is dependant on the total x-ray counts of the entire spectrum. If the total counts for a particular spectrum falls outside the range of one standard deviation from the average of all 54 spectra collected from a billet, the data from that spectrum are culled from the profile. Calibration curves plotting wt% Cl in paste versus total Cl K-alpha counts were constructed using mixes spiked with known chlorine addition. A further description of the calibration procedure is included in the write up for the field samples. With these improvements, the process of constructing a chloride profile from the collected spectra has gone from an hour to a few minutes.

Table 2. List of specimens with deicer solutions.

Specimen ID	Specimen ID
Hi MgCl2 0.45 w/c PC	Hi NaCl 0.45 w/c PC
Hi MgCl2 0.55 w/c PC	Hi NaCl 0.55 w/c PC
Hi MgCl2 0.55 w/c PC SILANE SEAL	Hi NaCl 0.55 w/c PC SILANE SEAL
Hi MgCl2 0.55 w/c PC SILOXANE SEAL	Hi NaCl 0.55 w/c PC SILOXANE SEAL
Hi MgCl2 0.45 w/c FLY ASH	Hi NaCl 0.45 w/c FLY ASH
Hi MgCl2 0.55 w/c FLY ASH	Hi NaCl 0.55 w/c FLY ASH
Hi MgCl2 0.45 w/c SLAG	Hi NaCl 0.45 w/c SLAG
Hi MgCl2 0.55 w/c SLAG	Hi NaCl 0.55 w/c SLAG
Hi MgCl2 0.45 w/c PC MORTAR	Hi NaCl 0.45 w/c PC MORTAR
Hi MgCl2 0.55 w/c PC MORTAR	Hi NaCl 0.55 w/c PC MORTAR
Hi MgCl2 0.45 w/c FLY ASH MORTAR	Hi NaCl 0.45 w/c FLY ASH MORTAR
Hi MgCl2 0.55 w/c FLY ASH MORTAR	Hi NaCl 0.55 w/c FLY ASH MORTAR
Hi MgCl2 0.45 w/c SLAG MORTAR	Hi NaCl 0.45 w/c SLAG MORTAR
Hi MgCl2 0.55 w/c SLAG MORTAR	Hi NaCl 0.55 w/c SLAG MORTAR
Lo MgCl2 0.45 w/c PC	Lo NaCl 0.45 w/c PC
Lo MgCl2 0.55 w/c PC	Lo NaCl 0.55 w/c PC
Lo MgCl2 0.45 w/c PC MORTAR	Lo NaCl 0.45 w/c PC MORTAR
Lo MgCl2 0.55 w/c PC MORTAR	Lo NaCl 0.55 w/c PC MORTAR
Hi CaCl2 0.45 w/c PC	Hi Caliber 0.45 w/c PC
Hi CaCl2 0.55 w/c PC	Hi Caliber 0.55 w/c PC
Hi CaCl2 0.55 w/c PC SILANE SEAL	Hi Caliber 0.55 w/c PC SILANE SEAL
Hi CaCl2 0.55 w/c PC SILOXANE SEAL	Hi Caliber 0.55 w/c PC SILOXANE SEAL
Hi CaCl2 0.45 w/c FLY ASH	Hi Caliber 0.45 w/c FLY ASH
Hi CaCl2 0.55 w/c FLY ASH	Hi Caliber 0.55 w/c FLY ASH
Hi CaCl2 0.45 w/c SLAG	Hi Caliber 0.45 w/c SLAG
Hi CaCl2 0.55 w/c SLAG	Hi Caliber 0.55 w/c SLAG
Hi CaCl2 0.45 w/c PC MORTAR	Hi Caliber 0.45 w/c PC MORTAR
Hi CaCl2 0.55 w/c PC MORTAR	Hi Caliber 0.55 w/c PC MORTAR
Hi CaCl2 0.45 w/c FLY ASH MORTAR	Hi Caliber 0.45 w/c FLY ASH MORTAR
Hi CaCl2 0.55 w/c FLY ASH MORTAR	Hi Caliber 0.55 w/c FLY ASH MORTAR
Hi CaCl2 0.45 w/c SLAG MORTAR	Hi Caliber 0.45 w/c SLAG MORTAR
Hi CaCl2 0.55 w/c SLAG MORTAR	Hi Caliber 0.55 w/c SLAG MORTAR
Lo CaCl2 0.45 w/c PC	Lo Caliber 0.45 w/c PC
Lo CaCl2 0.55 w/c PC	Lo Caliber 0.55 w/c PC
Lo CaCl2 0.45 w/c PC MORTAR	Lo Caliber 0.45 w/c PC MORTAR
Lo CaCl2 0.55 w/c PC MORTAR	Lo Caliber 0.55 w/c PC MORTAR
Hi CMA 0.45 w/c PC	Hi CMA 0.45 w/c FLY ASH MORTAR
Hi CMA 0.55 w/c PC	Hi CMA 0.55 w/c FLY ASH MORTAR
Hi CMA 0.55 w/c PC SILANE SEAL	Hi CMA 0.45 w/c SLAG MORTAR
Hi CMA 0.55 w/c PC SILOXANE SEAL	Hi CMA 0.55 w/c SLAG MORTAR
Hi CMA 0.45 w/c FLY ASH	Lo CMA 0.45 w/c PC
Hi CMA 0.55 w/c FLY ASH	Lo CMA 0.55 w/c PC
Hi CMA 0.45 w/c SLAG	Lo CMA 0.45 w/c PC MORTAR
Hi CMA 0.55 w/c SLAG	Lo CMA 0.55 w/c PC MORTAR
Hi CMA 0.45 w/c PC MORTAR	Hi CMA 0.55 w/c PC MORTAR

A selection from the chloride profiles produced thus far is given in Figures 1-9. Figure 1 shows profiles of 0.45w/c Portland cement concrete billets in high concentration deicer solutions of $MgCl_2$, $CaCl_2$ and NaCl. Figure 2 shows profiles of 0.55w/c Portland cement concrete billets in high concentration deicer solutions of $MgCl_2$, $CaCl_2$ and NaCl. Figure 3 shows profiles of 0.45w/c Portland cement concrete billets in low concentration deicer solutions of $MgCl_2$, $CaCl_2$ and NaCl. Figure 4 shows profiles of 0.55w/c Portland cement concrete billets in low concentration deicer solutions of $MgCl_2$, $CaCl_2$ and NaCl. Figure 5 shows profiles of 0.45w/c Portland cement mortar billets in high concentration deicer solutions of $MgCl_2$, $CaCl_2$ and NaCl. Figure 6 shows profiles of 0.55w/c Portland cement mortar billets in high concentration deicer solutions of $MgCl_2$, $CaCl_2$ and NaCl. Figure 7 shows profiles of 0.45w/c Portland cement mortar, Portland cement mortar with fly ash addition and Portland cement mortar with ground granulated blast furnace slag addition billets in high concentration $MgCl_2$ deicer solutions. Figure 8 shows profiles of 0.55w/c Portland cement mortar, Portland cement mortar with fly ash addition and Portland cement mortar with ground granulated blast furnace slag addition billets in high concentration $MgCl_2$ deicer solutions. Figure 9 shows profiles of 0.55w/c Portland cement mortar in high concentration $MgCl_2$ deicer solution, Portland cement mortar with siloxane sealant in high concentration $MgCl_2$ deicer solution and Portland cement mortar in high concentration Caliber deicer solution.

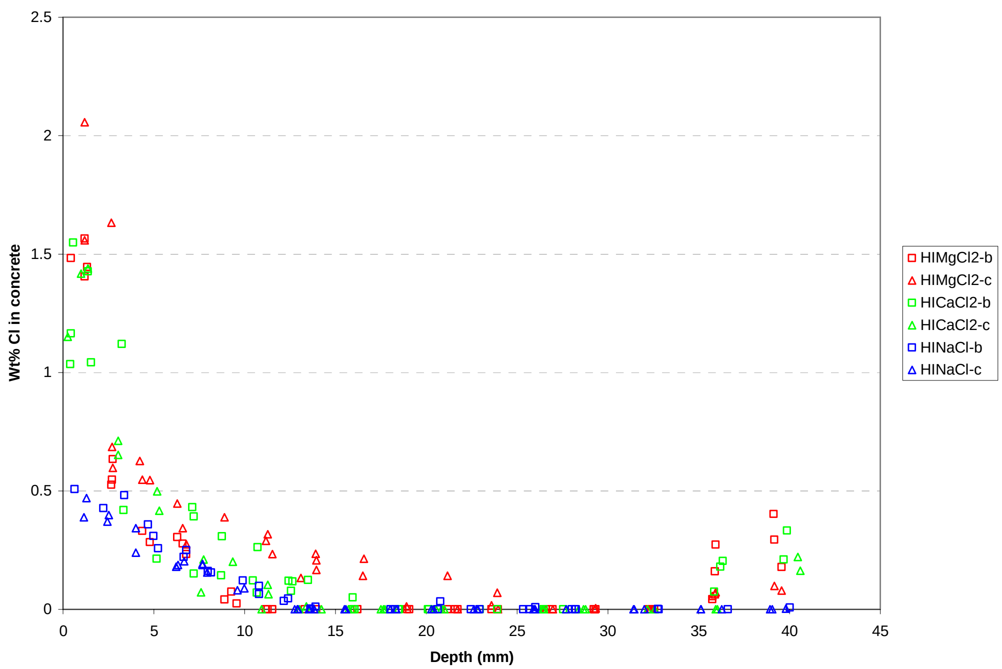

Figure 1. Chloride profiles of 0.45w/c PCC billets in three high concentration deicer solutions.

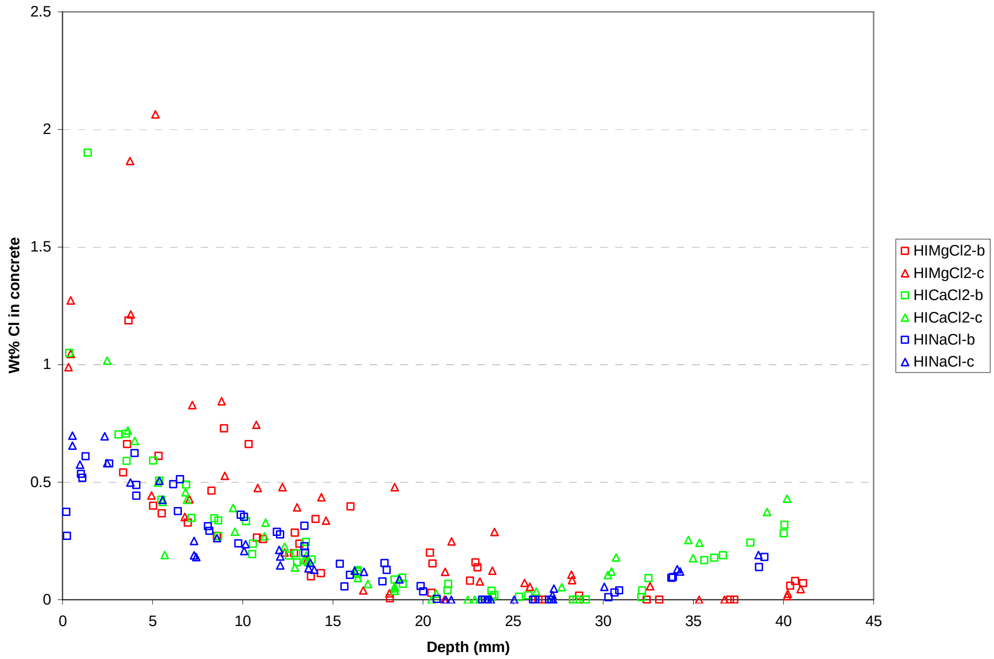

Figure 2. Chloride profiles of 0.55w/c PCC billets in three high concentration deicer solutions.

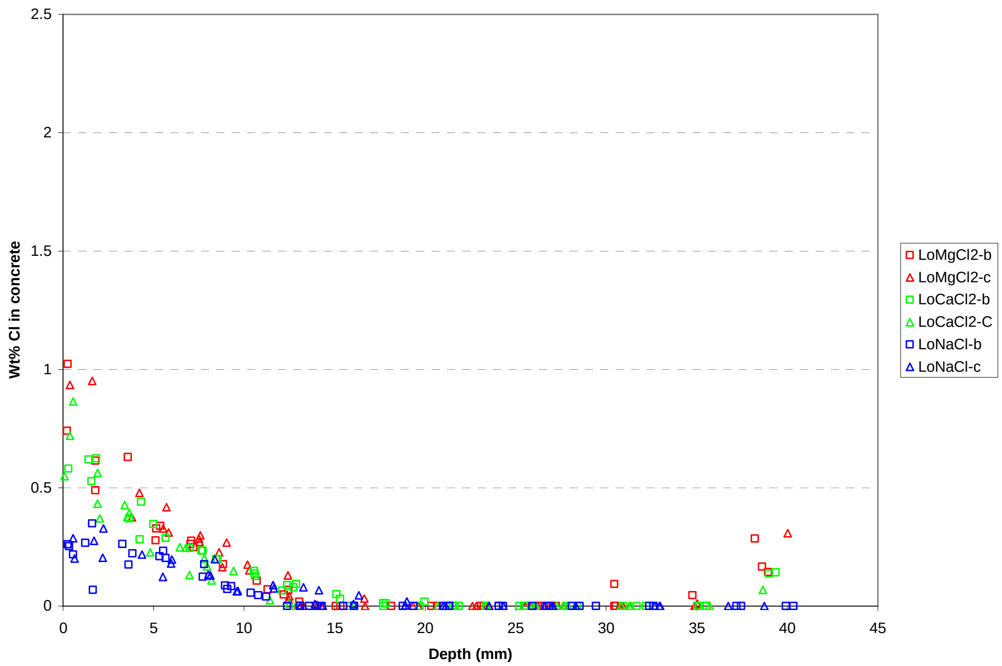

Figure 3. Chloride profiles of 0.45w/c PCC billets in three low concentration deicer solutions.

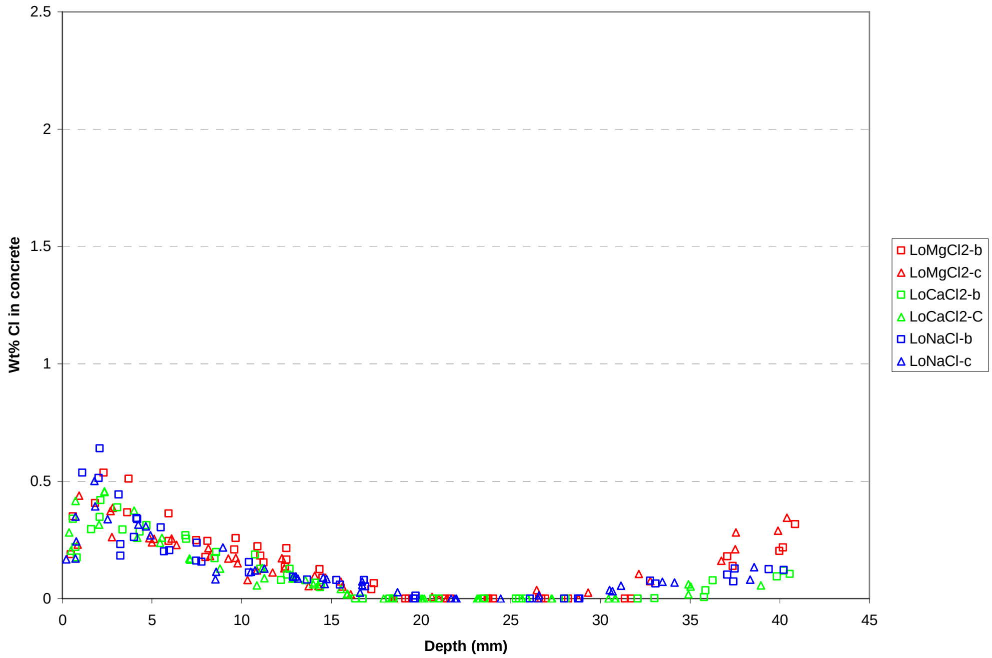

Figure 4. Chloride profiles of 0.55w/c PCC billets in three low concentration deicer solutions.

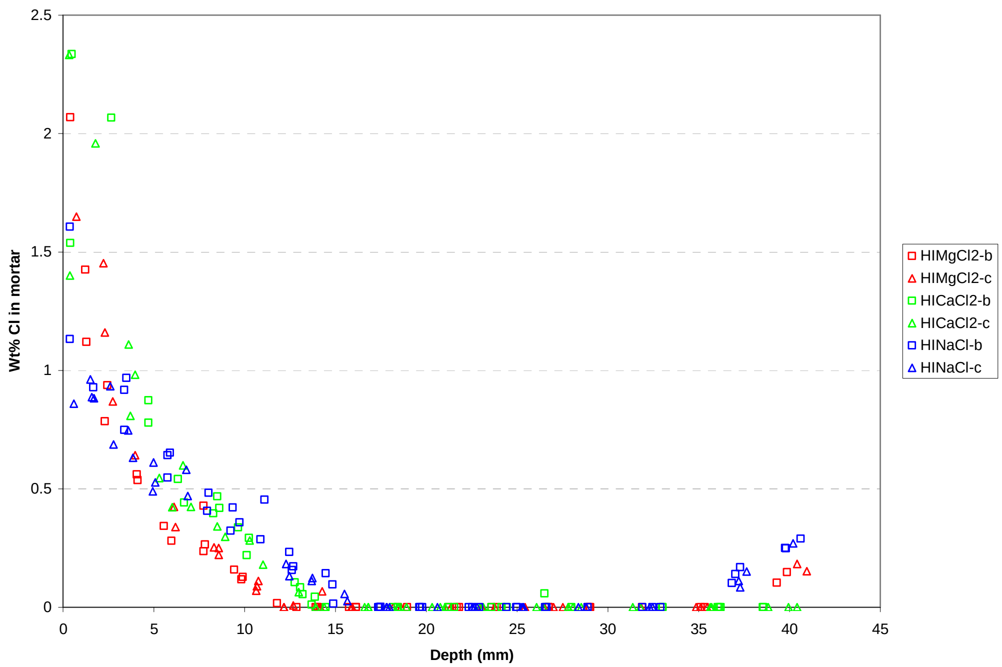

Figure 5. Chloride profiles of 0.45w/c PC mortar billets in three high concentration deicer solutions.

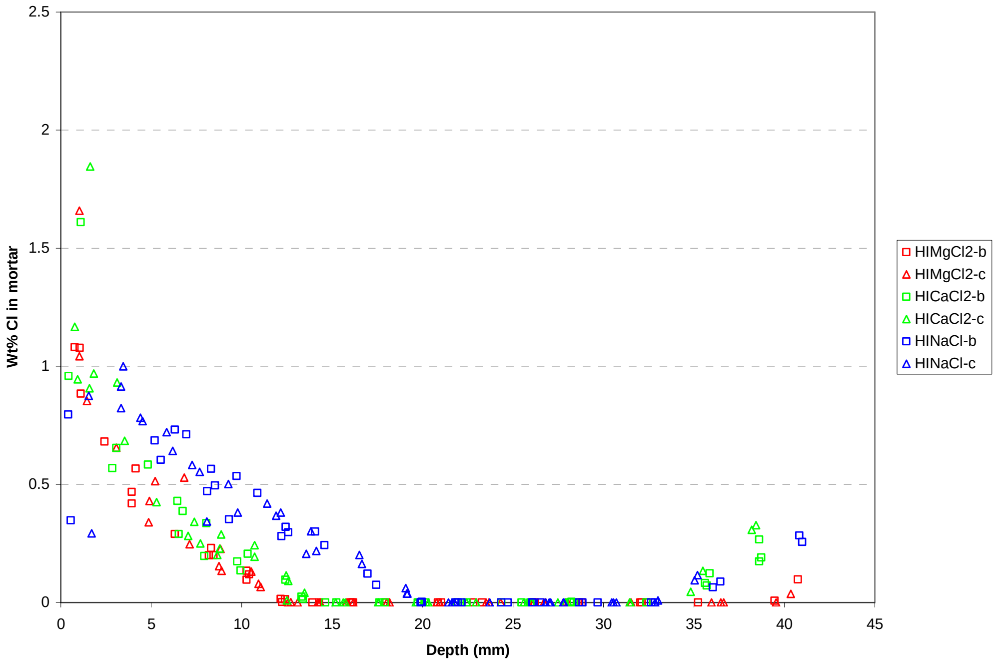

Figure 6. Chloride profiles of 0.55w/c PC mortar billets in three high concentration deicer solutions.

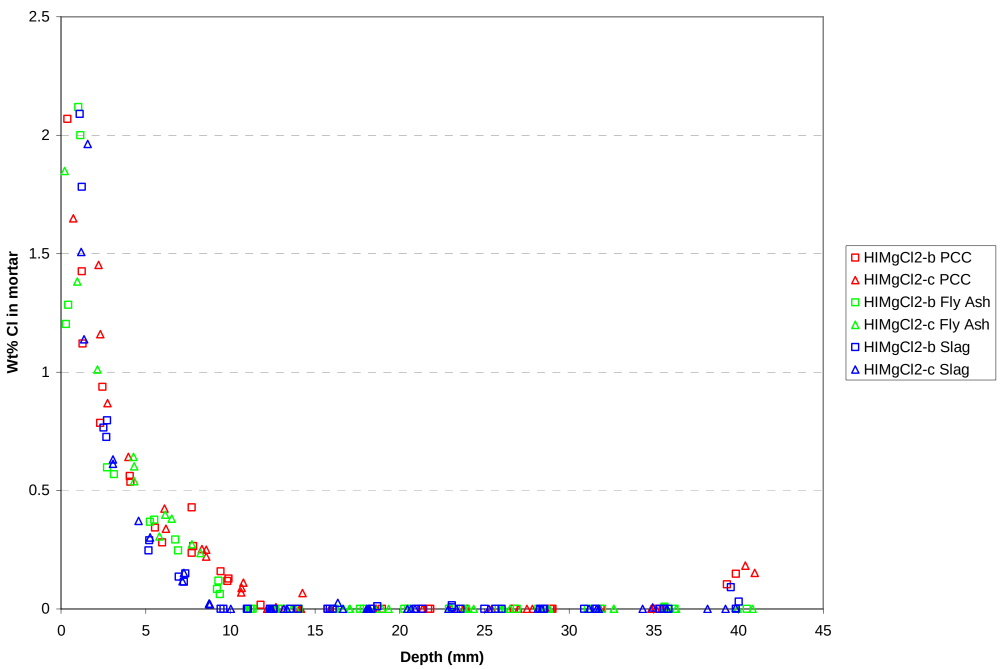

Figure 7. Chloride profiles of 0.45w/c PC mortar, mortar with fly ash and mortar with slag billets in high concentration $MgCl_2$ deicer solution.

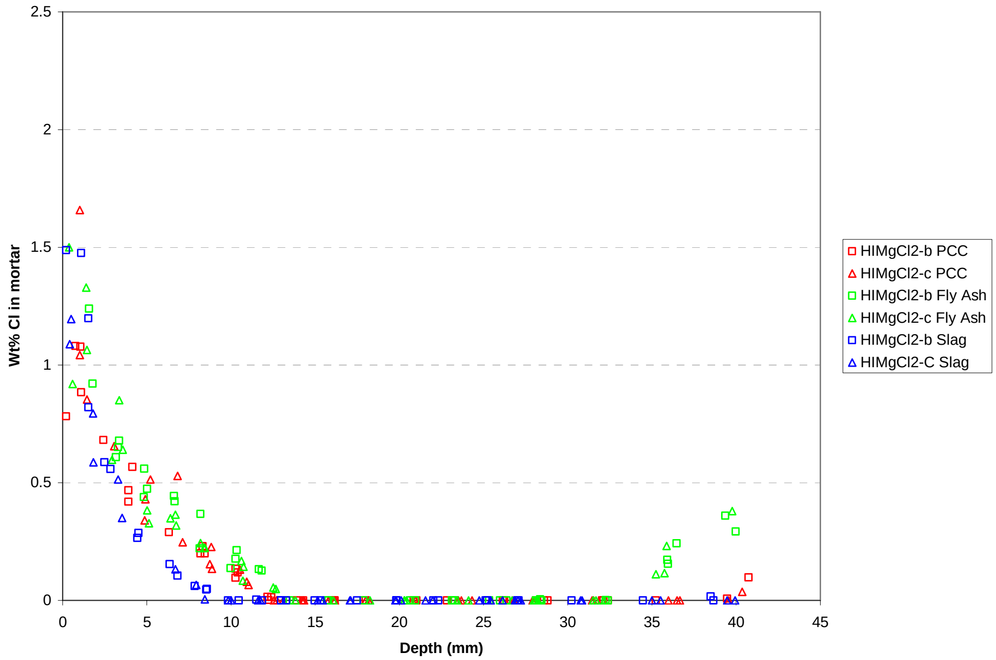

Figure 8. Chloride profiles of 0.55w/c PC mortar, mortar with fly ash and mortar with slag billets in high concentration $MgCl_2$ deicer solution.

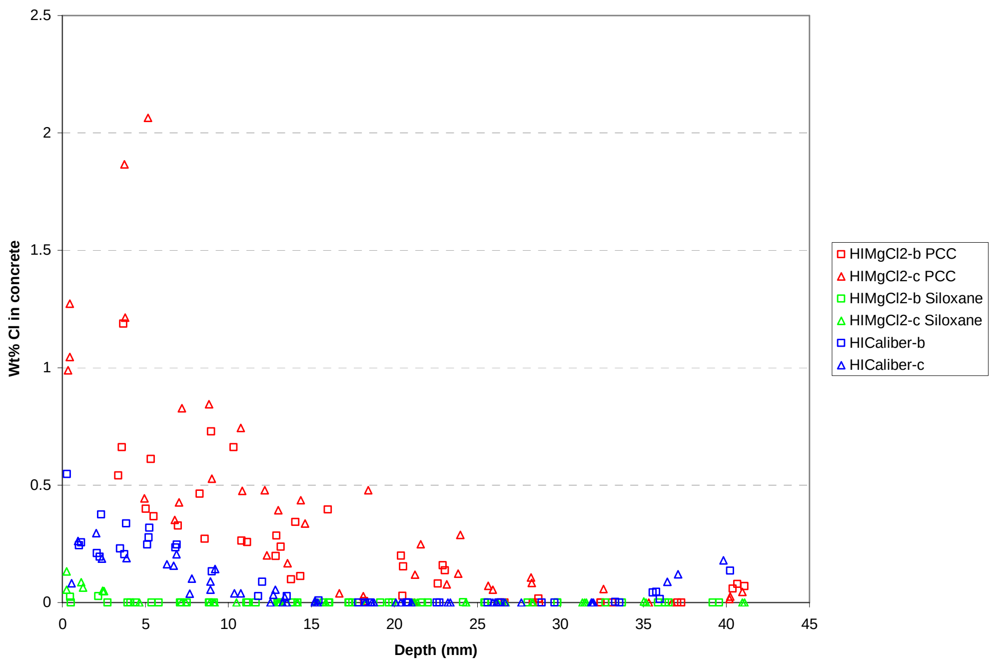

Figure 9. Chloride profiles of 0.55w/c PCC and PCC-siloxane sealed in high concentration $MgCl_2$ solution with PCC in high concentration Caliber solution.

Work Conducted at University of Toronto

Diffusion and Permeability Assessment

Concrete and mortar specimens cast at Michigan Tech and sent to the University of Toronto for an assessment of their penetrability were tested. Preliminary results are presented below.

Bulk diffusion test **(ASTM C 1556-03)**

In previous quarterly reports, a summary of results for mortar and concrete samples exposed to calcium chloride and magnesium chloride at approximately 5^{o}C were presented. At this time the results for the concrete and mortar samples exposed to sodium chloride are shown in Tables 1 and 2. The chloride profiles relative to each salt used are compared relative to each other for the same type of concrete in Figures 1 to 6. In addition, results from concrete samples tested after their surfaces were coated with two types of sealers, either sealer 1(S1) or sealer 2 (S2), are shown in Figures 7 to 9 and Tables 3.

Exposure Conditions: 18% Sodium Chloride at 5^{o}C for 35 days (Tables 1 and 2)
17% Calcium and15 % Magnesium Chloride at 5^{o}C for 35 days (Table 3)

Table 1. Summary of Results - Concrete samples – 18% NaCl

	w/cm=0.45			w/cm=0.55		
Code	PCC	FCC	SGC	PCC	FCC	SGC
Concrete Samples						
Da (m^2/s)	24.9e-12	39.1e-12	10.1e-12	28.2e-12	45.6e-12	12.5e-12
Cs (%)	0.69	0.65	1.05	0.74	0.54	0.80
P [0.1%] (mm)	18.45	22.66	13.36	20.17	22.75	13.77
r^2	0.9920	0.9693	0.9964	0.9810	0.9920	0.9810

Table 2. Summary of Results - Mortar samples – 18% NaCl

	w/cm=0.45			w/cm=0.55		
Code	PCC	FCC	SGC	PCC	FCC	SGC
Concrete Samples						
Da (m^2/s)	17.1e-2	21.9e-12	19.2e-12	-	32.6e-12	22.8e-12
Cs (%)	1.14	1.08	1.16	-	1.10	1.18
P [0.1%] (mm)	17.79	19.91	18.98	-	24.35	20.76
r^2	0.9707	0.9826	0.9838	-	0.9787	0.9859

Da: Apparent Diffusion Coefficient
Cs: Surface Concentration
P (0.1%): Penetration depth for 0.1% chloride concentration
r^2: r-squared from fitting Fick's 2nd law equation to experimental data

PCC: Portland cement concrete
FCC: Portland cement + 15% fly ash concrete
SGC: GGBFS blended cement concrete

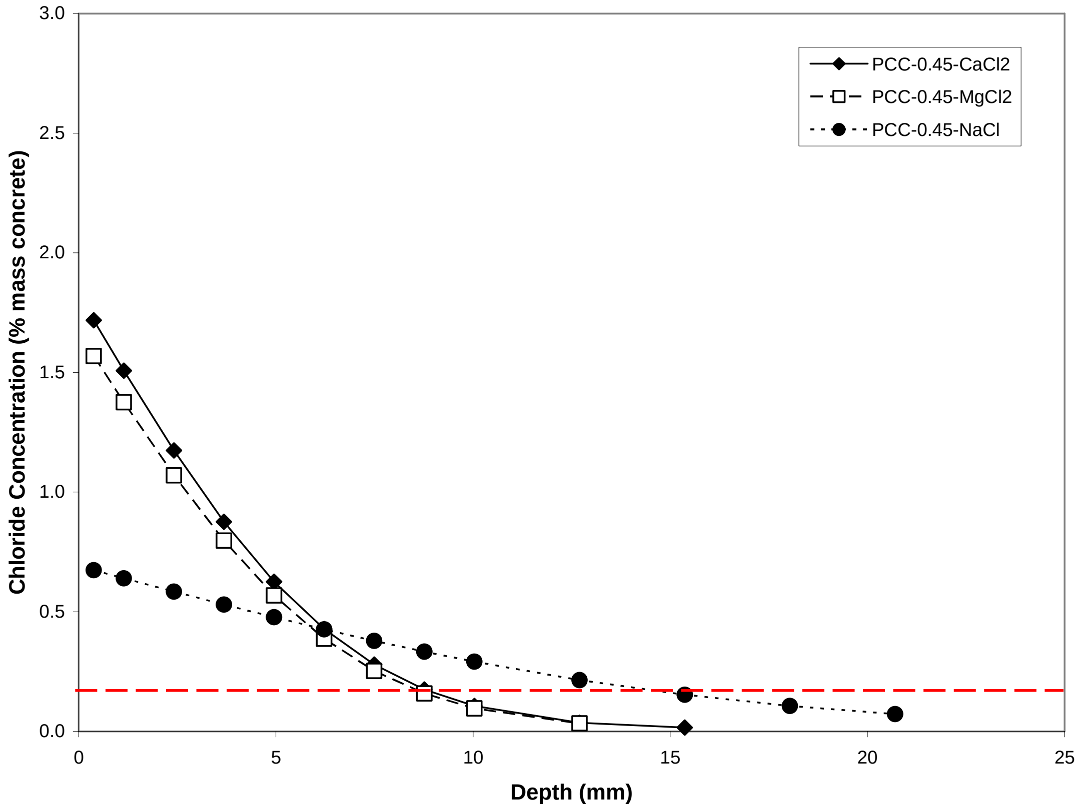

Figure 1. Portland cement concrete samples (w/c=0.45) - chloride profiles for different salts

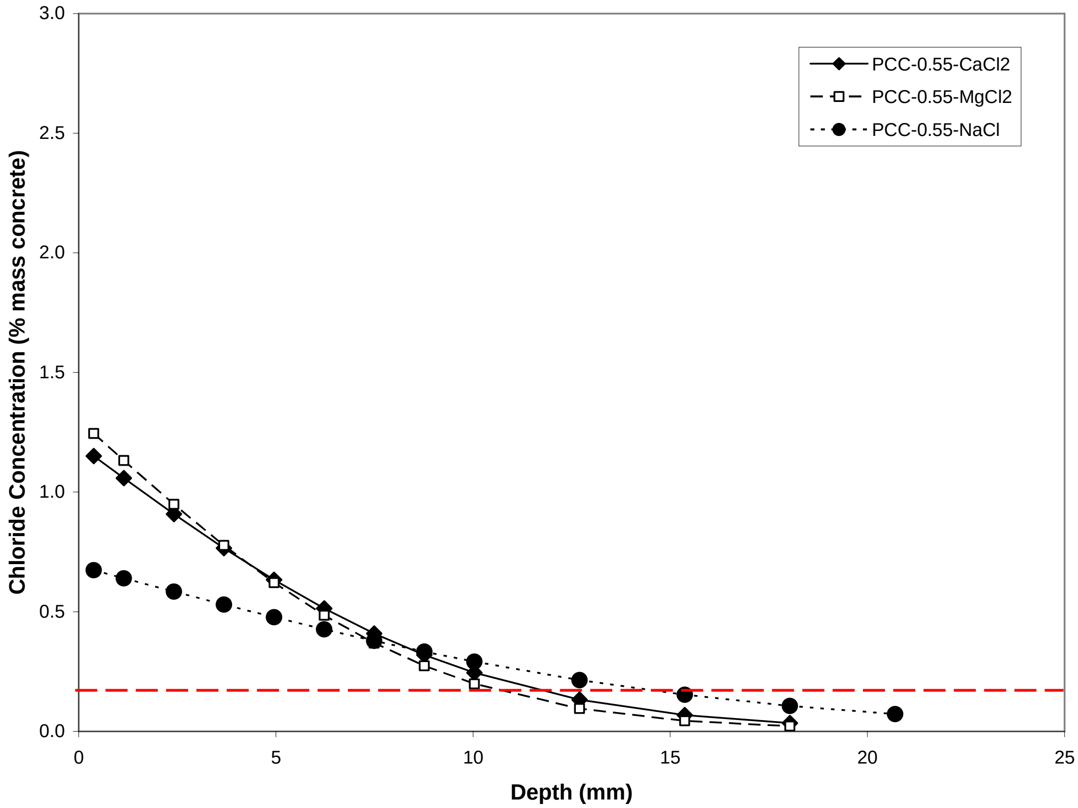

Figure 2. Portland cement concrete samples (w/c=0.55) - chloride profiles for different salts

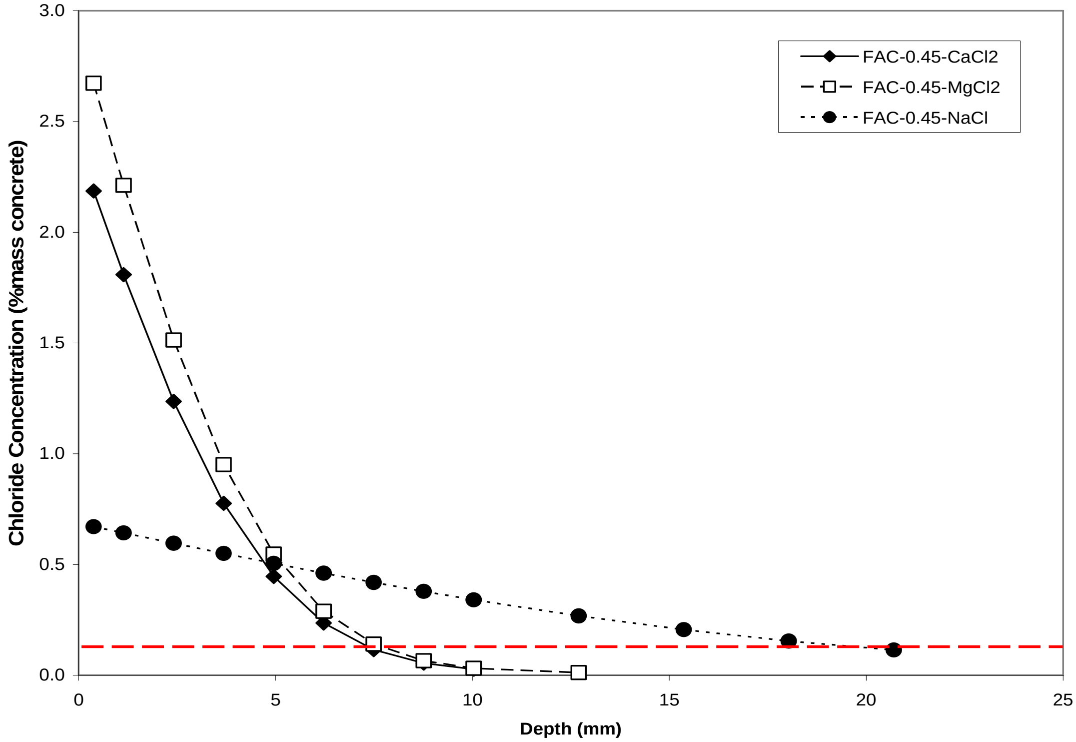

Figure 3. Portland cement + 15% fly ash concrete samples (w/cm=0.45) - chloride profiles for different salts

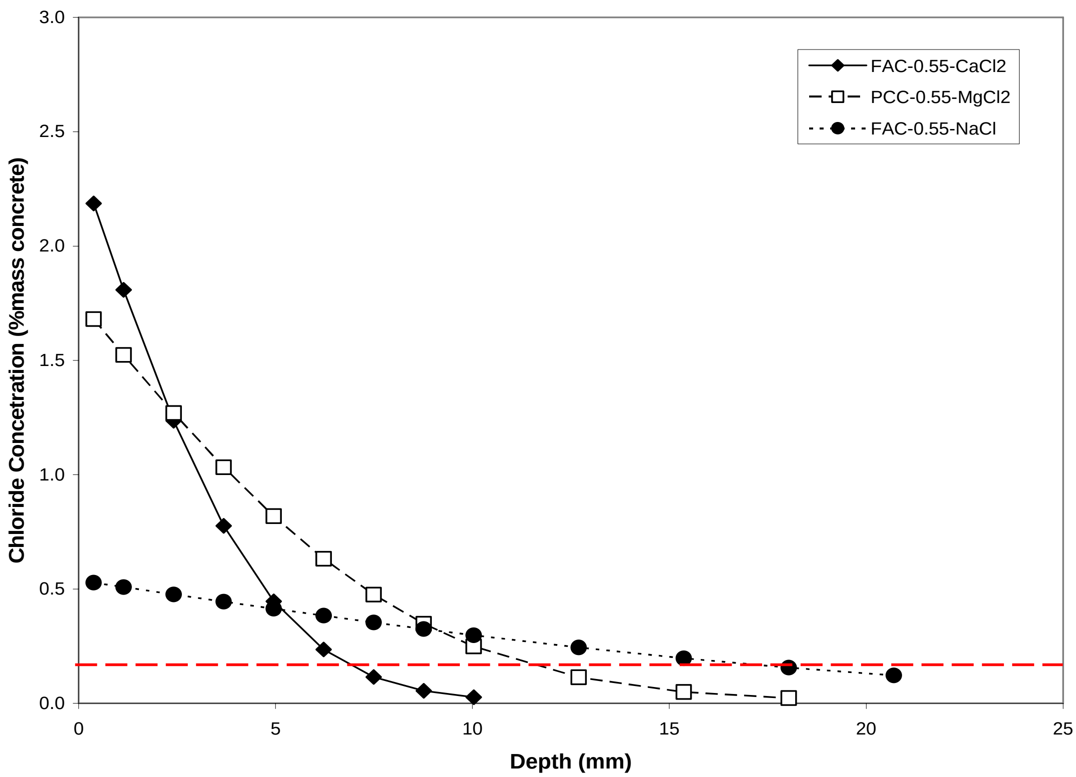

Figure 4. Portland cement + 15% fly ash concrete samples (w/cm=0.55) - chloride profiles for different salts

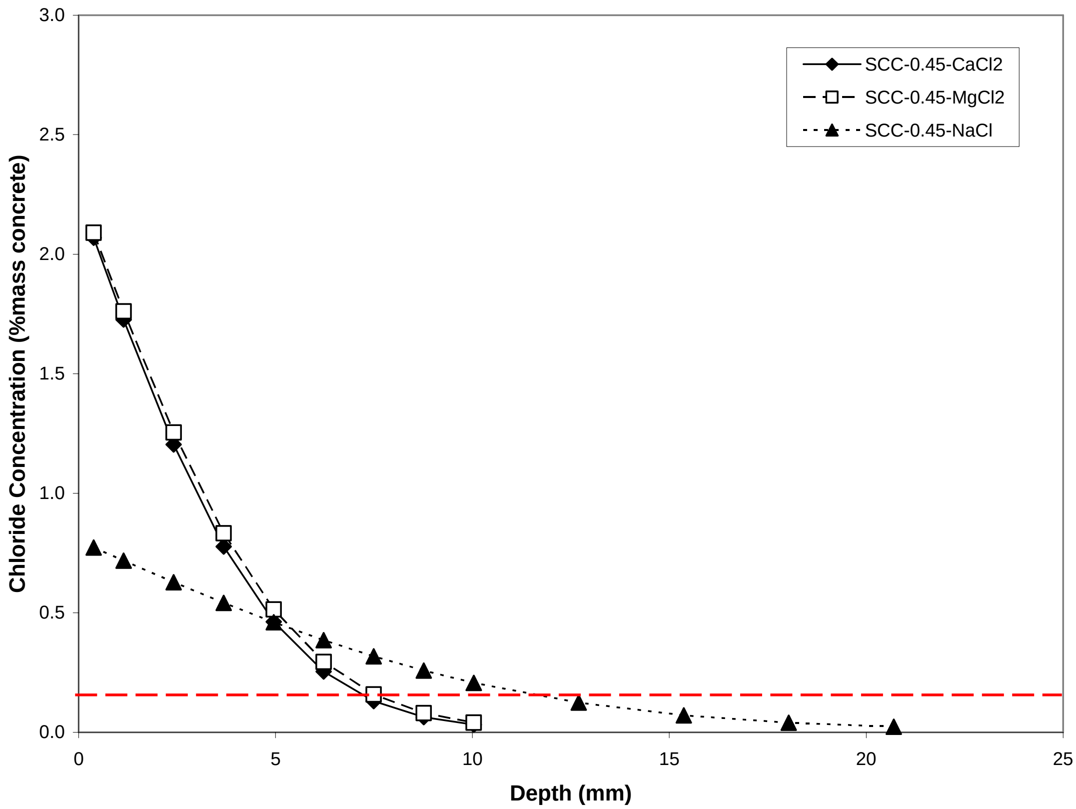

Figure 5. GGBFS blended cement concrete samples (w/cm=0.45) - chloride profiles for different salts

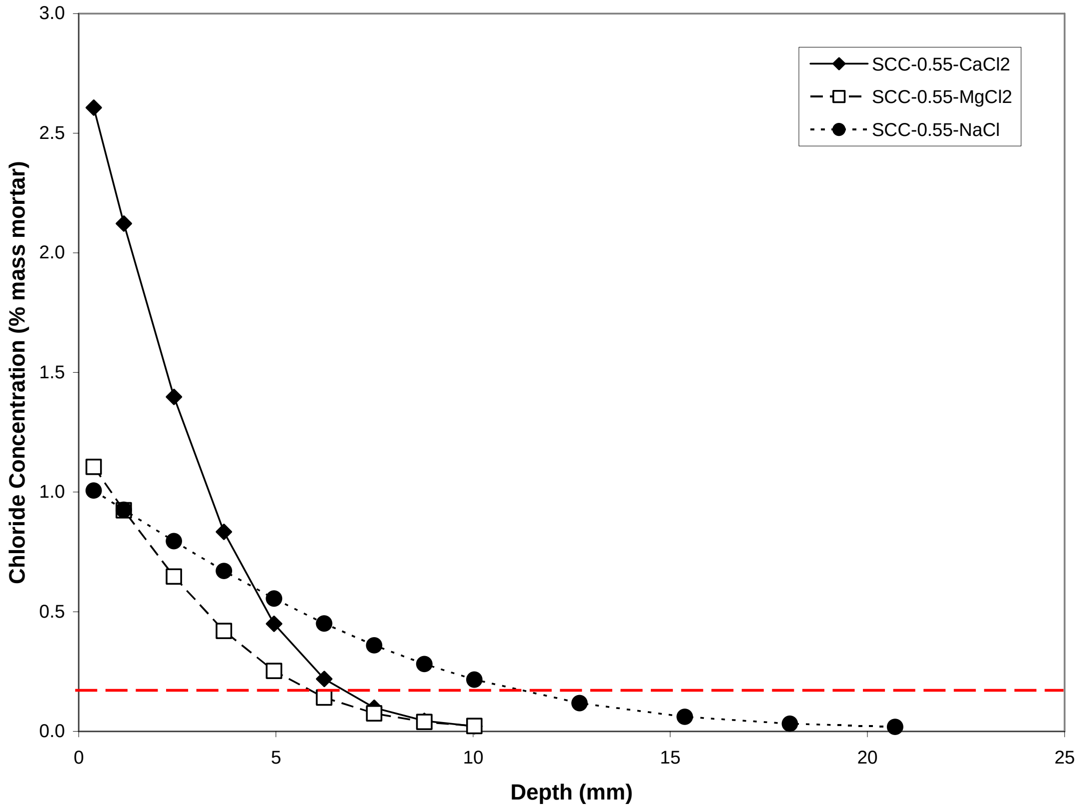

Figure 6. GGBFS blended cement concrete samples (w/cm=0.55) - chloride profiles for different salts

Concrete samples coated with sealer 1 (S1) did not allow the penetration of chloride ions; therefore, the experimental data cannot be fitted with Fick's 2nd law equation. Instead, the following graphs are added for comparison purposes.

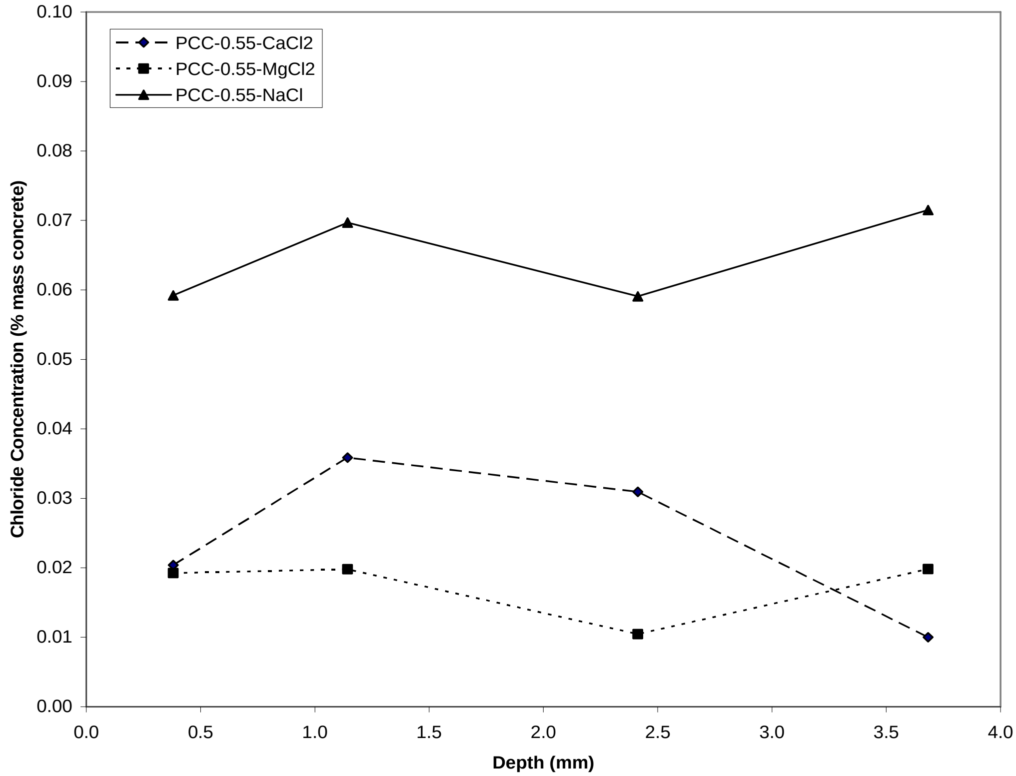

Figure 7. Portland cement concrete samples (sealer 1) - chloride profiles

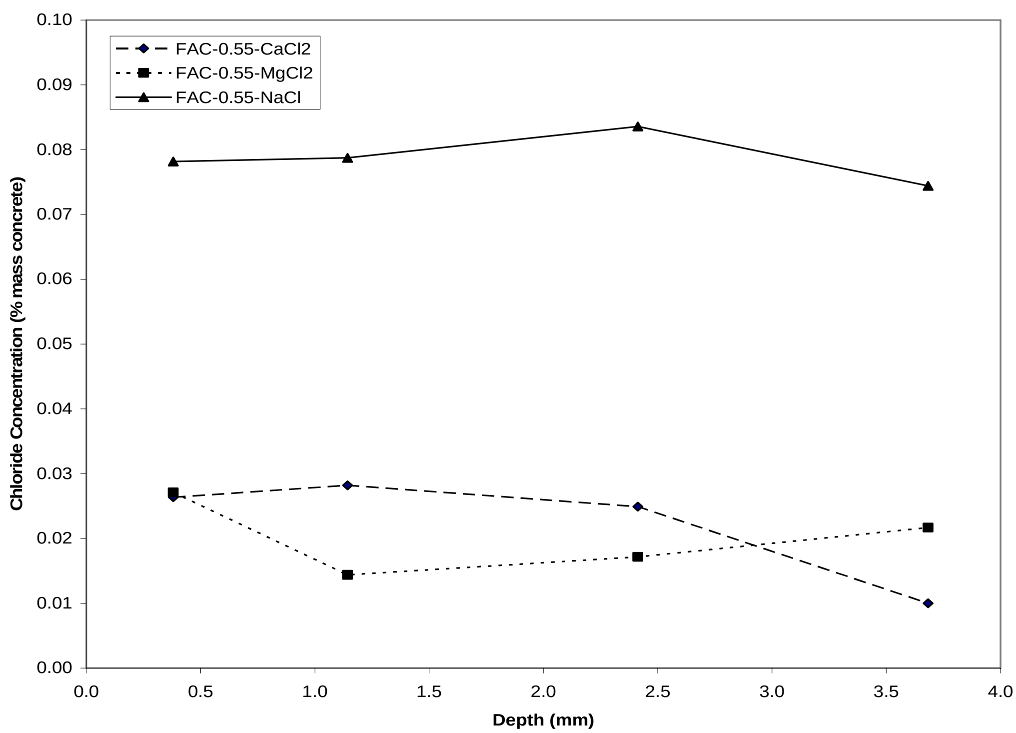

Figure 8. Portland cement + 15% fly ash concrete samples (sealer 1) - chloride profiles

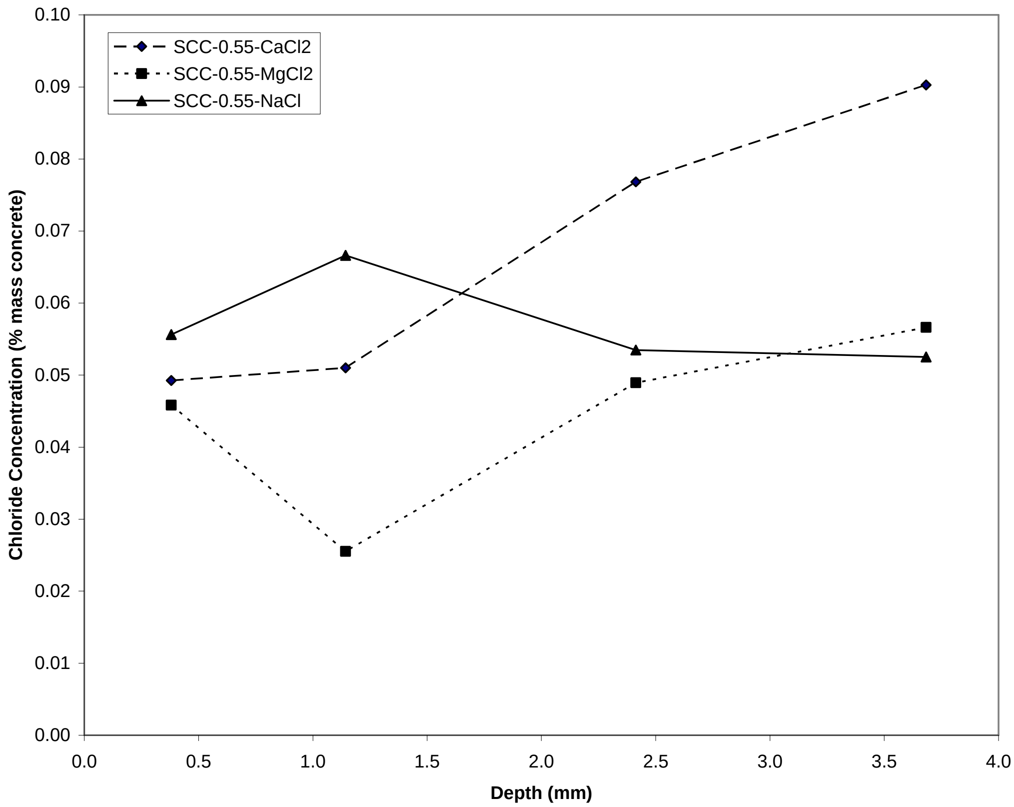

Figure 9. GGBFS blended cement concrete samples (sealer 1) - chloride profile

Concrete samples coated with sealer 2 (S2) did not perform as well as sealer 1 (S1), so although it slow down the chloride penetration, it did allow the penetration of chloride ions in considerable quantities.

Table 3. Summary of Results - Concrete samples – S2

	w/cm=0.55 (17% $CaCl_2$)			w/cm=0.55 (15% $MgCl_2$)		
Code	PCC	FCC	SGC	PCC	FCC	SGC
Concrete Samples						
Da (m^2/s)	12.6e-12	11.7e-12	4.01e-12	8.91e-12	18.0e-12	7.24e-12
Cs (%)	0.25	0.26	0.71	0.24	0.31	0.70
P [0.1%] (mm)	7.78	7.81	7.49	6.34	10.91	9.99
r^2	0.9773	0.9702	0.9960	0.9812	0.9901	0.9972

Sorptivity test **(ASTM C 1585-04)**
This task has been completed and preliminary results were presented in previous quarterly reports.

Rapid chloride permeability test **(ASTM C1202-97)**

This task has been completed and preliminary results were presented in previous quarterly reports.

Task 6 Problems and/or Deviations from Work Plan

There were no problems for Task 6 incurred during the reporting period.

Task 6 Completion - 85%

Task 7: Assessing and Minimizing the Impact of Deicing/Anti-Icing Chemicals

Basic data to address this task is being obtained in the laboratory experiments involving various sealants, described above.

Task 7 Problems and/or Deviations from Work Plan

None

Task 7 Completion -20%

Task 8: Effects of Various Deicing/Anti-Icing Chemicals

Basic data to address this task is being obtained in the laboratory experiments described above.

Task 8 Completion -35%

Task 9: Life Cycle Cost Analysis

Task 9 Problems and/or Deviations from Work Plan

None

Task 9 Completion -0%

Task 10: Development of Guidelines

Task 10 Problems and/or Deviations from Work Plan

None

Task 10 Completion -0%

Task 13: Final report

Task 13 Problems and/or Deviations from Work Plan

None

Task 13 Completion -0%

Task 14: Present to Panel

Task 14 Problems and/or Deviations from Work Plan

None

Task 14 Completion -0%

Task 15: Present to Review Board

Task 15 Problems and/or Deviations from Work Plan

None

Task 15 Completion -0%