

Durability Study of the US-23 Aggregate Test Road and Recent JPCP Projects
with Premature Joint Deterioration

Final Report

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16. Abstract <p>Materials related distress (MRD) characterized by “starburst” type corner spalling at the longitudinal centerline joint, and occasional transverse joint spalling have developed at a rapid rate in a number of JPCP projects constructed since 1999. The main objective for this project was to isolate the major cause(s) for suspected freeze-thaw deterioration, and to provide recommendations for improved materials specifications in order to ensure long-term freeze-thaw resistance to severe surface exposure conditions (i.e. surface contact with either water or 3% NaCl) during repeated freezing and thawing. Four younger (<10 years) field projects with this type of MRD and four older field projects without MRD were selected for laboratory freeze-thaw testing for two different exposure conditions (water and 3% NaCl) during cyclic freeze-thaw. Rapid surface deterioration developed due to deicer salt exposure within a few freeze-thaw cycles for the concrete with MRD problems. The concrete without MRD had significantly improved deicer scaling resistance. Microscopic examination of the scaled surfaces demonstrated that excessive expansion and cracking had developed within the Portland cement paste consistent with inadequate air-void system. ASTM C457 test method was used to evaluate the air-void system in the hardened concrete. The four concrete projects which had not developed freeze-thaw problems at the joints also had higher air contents (>5.5%) while the concretes with low air had severe deterioration. A substantial improvement in deicer scaling resistance was obtained for MDOT’s low-cement concrete containing slag cement (328 lbs Type I, and 162 lbs slag cement). The improvement was attributed to a better quality paste-coarse aggregate interface (i.e. without air-void clustering) and air-void system (smaller sized bubbles), and lower paste permeability (i.e. lower water uptake rate).</p>			
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DISCLAIMER

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Executive Summary

The purpose of this study was to provide the understanding and necessary evidence to modify specifications practices to prevent future occurrences of premature (within 8 years) joint deterioration which caused starburst type deterioration at joint corners, joint staining and occasional spalling.

During the course of this project core samples were obtained from eight projects. Four had developed MRD joint distress within 8 years, and four older projects were free of joint related MRD. These older projects were selected in order to determine which level of deicer scaling resistance is necessary in order to avoid field MRD as the laboratory test procedure is more severe than field exposure (i.e. critically saturated prior to freeze-thaw testing and exposed to a 3% NaCl solution during freeze-thaw). The potential for improvement in materials-related specifications was evaluated using MDOT's low cement mix design (P-1 MOD) which contains 490 lb cementitious blend of 326 lbs Portland Cement Type I and 164 lbs slag cement, Grade 100. Materials used for laboratory mixes were obtained from an ongoing overlay project.

The air-void system in the hardened concrete (entrained air, entrapped air, air-void in-filling) was conducted according to ASTM C457, "Standard Practice for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete".

Freeze-thaw testing followed a German standard test procedure. The specimen size was slightly modified in order to obtain prisms from 6 inch diameter core samples. Also, the moisture conditioning was modified to account for differences in moisture content of the field concrete and assure a near critical saturation level for all test specimens prior to freeze-thaw testing. A unique feature of the German test procedure is that the bottom concrete surface is in contact with the test liquid, consisting of either water or a 3% NaCl solution. Further, the bottom surface undergoes a controlled temperature profile during each freeze-thaw cycle. Freeze-thaw deterioration is quantified by collecting and weighing the dried surface-scaled material at regular freeze-thaw cycle intervals. Lab-concretes were obtained

by cutting prisms from molded specimens. To assure similar water-saturation levels prior to freeze-thaw testing, the field and lab concretes were dried at 113 °F (45 °C) for two weeks in order to remove capillary pore water, then re-saturated for about a week at room temperature by placing the test surface in contact with the liquid.

The major findings of this study are:

Core samples of the deteriorated joint concrete showed that MRD had developed in the top surface region. Laboratory freeze-thaw testing on core samples from the projects with MRD showed that surface scaling rate was pronounced in the presence of a deicer salt solution (3% NaCl solution). Based on microscopic evaluation of the scaled material and the concrete surface exposed to freezing and thawing it was concluded that deterioration developed within the portland cement binder, originating in a narrow mortar zone around the coarse aggregate. Air-void agglomeration was pronounced in this zone.

The air-void system was found to be in-adequate for a severe exposure condition which exists at poorly draining joints when a concrete surface is exposed to deicer salt solution during freeze-thaw.

Concretes containing slag cement had improved deicer frost resistance as slag cement improves the paste-aggregate interface zone and distributes the air better than in concrete without slag cement.

The major recommendations are:

The results here suggest that if the minimum recommended fresh air content is slightly over 7%, the net remaining air content after about 10 years in service, when taking into account that infilling of air-voids over time can be expected in the joint area, is sufficient for field resistance to deicer salt and freeze-thaw.

Ensure that the base and subsurface is sufficiently drained so that water and deicer solutions are not permitted to accumulate at or beneath joints or other discontinuities in the concrete pavement surface. Ensuring adequate drainage will reduce the likelihood that the

surrounding concrete at joints will become critically saturated, thus, reducing the risk for MRD and premature deicer-related freeze-thaw deterioration.

Further benefits can be achieved by using slag cement. This was demonstrated for a MDOT P-I MOD slag cement concrete mix. Freeze-thaw results show that this concrete has improved deicer scaling resistance compared to the control concrete without slag cement for same air content. The improved laboratory performance is attributed to better distribution of air void system absent of air-void agglomeration around the coarse aggregate and a reduction in paste permeability as seen from a reduction water uptake rate during a suction test.

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1. Introduction

Problem Statement

Deicer salts are used extensively in Michigan for melting snow and ice to avoid hazardous and impassible driving conditions on roads and bridges. Some recent (since 1999) JPCP projects have developed Materials Related Distress (MRD) characterized by spalling along the longitudinal joint between the outer and inner lane. The spalling deterioration is pronounced in the corner area where the saw-cut surface area is greatest, and occasionally, joint spalling has developed in the transverse joint. Joint staining is another characteristic feature of this type of MRD, but the staining is without any visible radial cracking, typical for D-cracking. Materials Related Distress (MRD) in the joint concrete is consistent with freeze-thaw deterioration in poorly drained areas where the deicer salt solution is retained on the surface during freezing and thawing (PCA Bulletin, 2003). This type of localized deterioration can lead to costly rehabilitation or reconstruction.

The presence of a deicer salt solution on a concrete surface during a freeze-thaw cycle is considered severe exposure condition, while water on the surface represents a moderate exposure level. This is reflected in specification recommendations for total air content in fresh concrete (PCA Bulletin, 2003, ACPA, 1996). The recommended total air content for moderate exposure conditions (i.e. water on the surface) is 4.5% for a 1 inch maximum aggregate size, while a severe exposure condition has recommended air content of 6%. Although the basic freeze-thaw damage mechanisms are yet incompletely understood, it is generally accepted, that closely spaced air-voids from air entrainment prevent hydraulic pressures within the portland cement paste from building up to a level sufficient to cause mortar spalling (PCA, 2003). Other recommendations for field scale resistance include limiting the water-cementitious ratio to 0.45 and providing proper finishing after bleed water has evaporated (ACI Committee 201,1992). During fall construction a minimum moist curing period of 7 days is recommended for strength development of the surface layer and a minimum one month surface drying following moist curing is recommended in order to reduce excess surface moisture prior to onset of the first freeze-thaw cycle. When supplementary cementitious materials like slag cement

or flyash are incorporated into the cementitious blend, the recommended limits for replacement levels are 50% for slag cement and 25% for flyash by mass of total cementitious (PCA Bulletin, 2003).

Purpose and Scope

The purpose of the project is to conduct a comprehensive investigation to identify major factors for the varied freeze-thaw performance, and determine quantitative relations, if possible, between air-void system and freeze-thaw performance associated with deicer scaling resistance. Also, the influence of slag-cement on freeze-thaw resistance will be evaluated for the low cement content, MDOT P-1 MOD mix.

The project scope includes a laboratory freeze-thaw study of core samples from distressed younger pavements (< 8 years) in the vicinity of the distressed areas and older pavements without the joint distress in order to determine threshold values for the air-void system (total air and spacing factor) characteristic for good longer-term (>10 years) field performance.

The air-void system in the hardened concrete (entrained air, entrapped air, air-void infilling) will be determined following ASTM C457 procedures, while freeze-thaw testing is based on a German freeze-thaw test procedure for two different surface exposure conditions (water versus 3% NaCl solution).

The cause of surface scaling and specimen cracking is investigated by digital stereo microscope.

Project Benefit/Implementation

The expected findings from this study will provide the understanding and necessary evidence to modify specifications and construction practices to prevent future occurrences of similar premature deterioration caused by the durability factors discovered during this study.

Report Outline

The research methodology is presented in chapter 2. Results and major findings are presented in chapter 3. In chapter 4 conclusions and recommendations are presented. Chapter 5 has an implementation plan. References are in chapter 6. Appendix A contains additional test results and Appendix B contains the P-1 MOD mix composition for the US-131 overlay project.

2. Methodology

2.1 Field Projects

The field projects selected for laboratory testing are briefly summarized in table 2.1. Four projects had developed MRD at joints within 8 years, while four older projects, including two from the Aggregate Test Road, were without MRD. In addition, materials were obtained from an on-going overlay project on US-131 in order to isolate specific concrete material variables such as air content and slag cement on freeze-thaw resistance.

2.2 Specimen Conditioning prior to Freeze-Thaw Testing

Prismatic freeze-thaw specimens of dimensions 4 inch (100 mm) by 4 inch (100 mm) and 2.76 inch (70 mm) in height were cut from the middle portions of 6 inch diameter field cores. Two specimens were obtained for each freeze-thaw exposure type (water versus 3% NaCl solution). Frost exposure condition is strongly affected by pore-saturation levels while the resistance to exposure is strongly affected by air content. Therefore, to ensure similar saturation level for the different field core samples prior to freeze-thaw testing, specimens were dried in an oven at $113\text{ }^{\circ}\text{F} \pm 10\text{ }^{\circ}\text{F}$ ($45 \pm 5\text{ }^{\circ}\text{C}$) for two weeks until its weight loss was insignificant. After drying, freeze-thaw specimens were undergoing re-saturation by capillary suction at room temperature, $70\text{ }^{\circ}\text{F}$, ($21\text{ }^{\circ}\text{C}$) for about one week. The surface undergoing capillary suction was also subjected to liquid suction during a freeze-thaw test. Once the continuous capillary pores has reached saturation by capillary suction an abrupt decrease in water uptake occurs. For this curve-section weight-gain is slow due to diffusion of water into the air-voids and discontinuous pores (Fagerlund, G., 2004). Figure 2.1 is a typical resaturation curve. The moisture uptake just beyond capillary suction point was chosen for freeze-thaw testing.

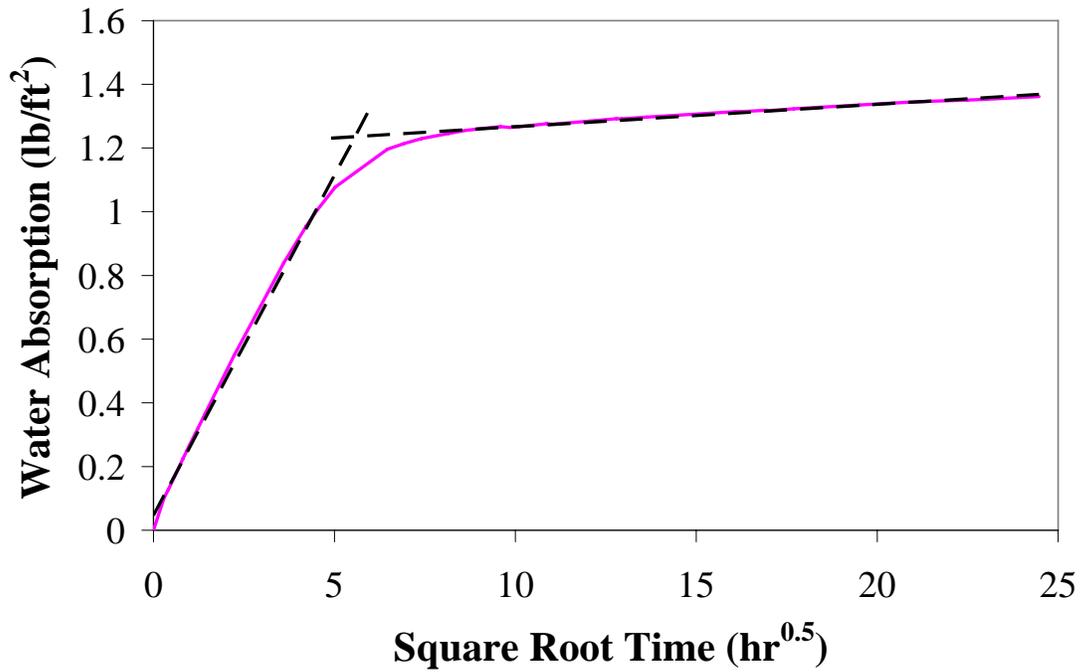


Figure 2.1 Typical saturation curve

Laboratory concrete specimens for the US-131 pavement were cast in teflon molds in accordance with the German test procedure. These specimens had slightly larger contact surface area than the field core samples (5.9 inch by 4.33 inch), but same thickness (2.76 inch). They were cured for 28 days, dried and re-saturated similar to the field specimens.

Table 2. 1 List of projects involved in the study

PROJECT			Location	Pavement Type		DESIGN PARAMETERS	Distress Description			
Route	CS	PN		Project Year	Length Opened		Slab	L	T	Coarse
				miles		(ft)	(in)	Agg. Type		
M-14 EB	81105	34962	I-94 to US-23 BR (Main Street)	3.48	2000	JPCP	15	11.0	Natural Gravel (81-84)	Long. Joint deterioration & joint spalling
M-46	74062	47172	Goetze Road to M-25	4.52	1999	Overlay	12	6.0	Dolomitic Limestone 6AA, (32-4)	starburst cracking with associated joint spalling
US-23 SB	58034	32750A	Agg Test Road Section A	1.09	1993	JRCP	27	10.5	Dolomite (93-03)	No staining or starburst condition
			Agg Test Road Section B	0.95	1993	JRCP	27	10.5	Blast-Furnace Slag (82-22)	No staining or starburst condition
I-69	19042& 7602	01978A	West of Peacock Rd. to East of Shaftburg Rd	4.98	1991	JRCP	41	9.0	Blast Furnace Slag (82-19)	No staining or starburst condition
I-94 WB	80023	45859	W of 62nd Street to W of M-51	8.50	2000	JPCP	15	11	Limestone (71-03)	Joint spalling, long. partial depth cracking; long joint deterioration
US-23 NB	58034	32750A	K-19sta 340+85 to sta 347+30	0.12	1993	JPCP	15	11	Dolomite (93-03)	Starburst cracking & associated spalling
US-23 NB	58034	32750A	Section #2 Sta 265+77 to 270+90 (513 ft)	0.20	1994	JPCP	15	10.5	Dolomite (93-03)	No staining or starburst condition
US-131	41132	50758	West River Drive North to 10 mile Rd.	6.43	2008	Overlay	12	6.5	Limestone (75-05)	No staining or starburst condition

2.3 Freeze-Thaw Testing

Laboratory tests based on the German CDF (Capillary suction, De-icing agent and Freeze-thaw test), and CIF (Capillary suction, Internal damage and Freeze-thaw test) procedure are described in detail in the Appendix. Additional moisture uptake associated with freeze-thaw damage was determined.

A freeze-thaw cycle has a 12 hour duration, consisting of a linear temperature lowering from 68 °F (20 °C) to – 4 °F (-20 °C) at a rate of 18 °F/hour (10 °C/hour), followed by a constant temperature of – 4 °F (-20°C) for 3 hours, then a heating rate of 18 °F/hour (10 °C/hour) for 4 hours. The specimen surface in contact with the liquid is subjected to this temperature profile. The temperature is kept at 68 °F (20 °C) for 1 hour before commencement of the next freeze-thaw cycle. During this time measurements are made. The freeze-thaw machine is shown in figure 2.2 with 10 stainless steel-bowls, each containing one specimen.



Figure 2.2 Freeze-Thaw Machine (www.schleibinger.com)

Each specimen is sitting on spacers so that the bottom test surface is in contact with the test liquid (either water or 3% NaCl solution) as shown in figure 2.3 a and b.

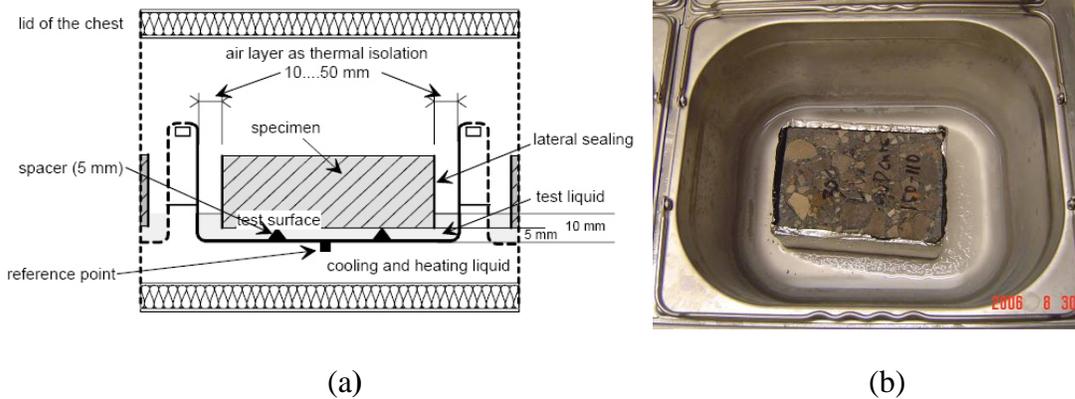


Figure 2.3 Close-up of specimen test (a) and actual test specimen with bottom test surface in contact with liquid, in this case in a frozen condition (b).

To prevent liquid uptake and scaling from the lateral surfaces the specimens are sealed using aluminum foil lined with butyl rubber (figure 2.3b) on the inside. Mass-loss from surface scaling and internal damage are determined after 4 to 6 consecutive freeze-thaw cycles.

At time of measurement each specimen is placed in an ultrasonic cleaning bath for removal of the scaled material, and the material is collected and dried at 212 °F (100 °C) for 24 hours, then allowed to cool to room temperature for one hour and weighed dry.

2.4 Examination of Specimen Surface and Scaled Particles by Digital Microscopy

In order to understand the damage mechanisms associated with freeze-thaw, the specimen surface and the scaled material were analyzed periodically in the digital microscope, figure 2.4.

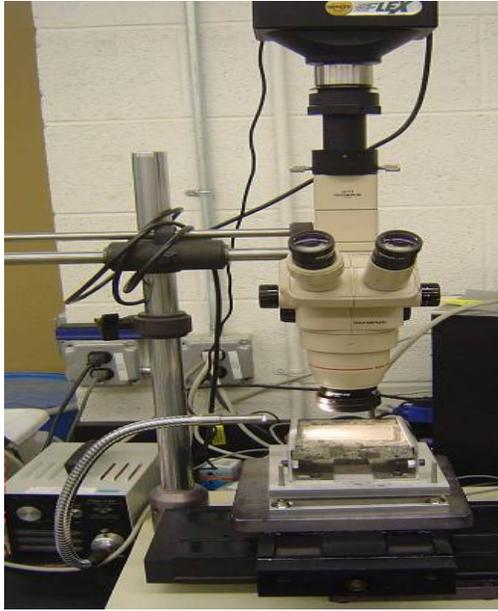


Figure 2.4 Digital microscope setup.

2.5 Air Void Analysis

Determination of the air-void content was conducted according to ASTM C 457 “Standard Practice for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete”, by methods A (linear traverse) and B (modified point-count).

Four by four inch by about 0.75 inch (20 mm) thick specimens were cut from the middle-portion of core samples with the measuring surface parallel to the top surface. This sectioning was selected based on preliminary test results showing substantial variations in air content and freeze-thaw test results between top and bottom for some test sections. Two samples were obtained for each pavement section and polished using a concrete polisher seen in figure 2.5.



Figure 2.5 Concrete polisher (www.concrete-experts.com)

Point count analysis for paste, total air and aggregate content and infilling of air was conducted on the polished concrete samples (Figure 2.7a). Air-void chord-size distribution was determined by an automated procedure (RapidAir 457 Air Void Analyzer) which required contrast enhancement. Air-voids were filled with white particles ($BaSO_4$) and the surface was colored with black ink (Figure 2.7b).

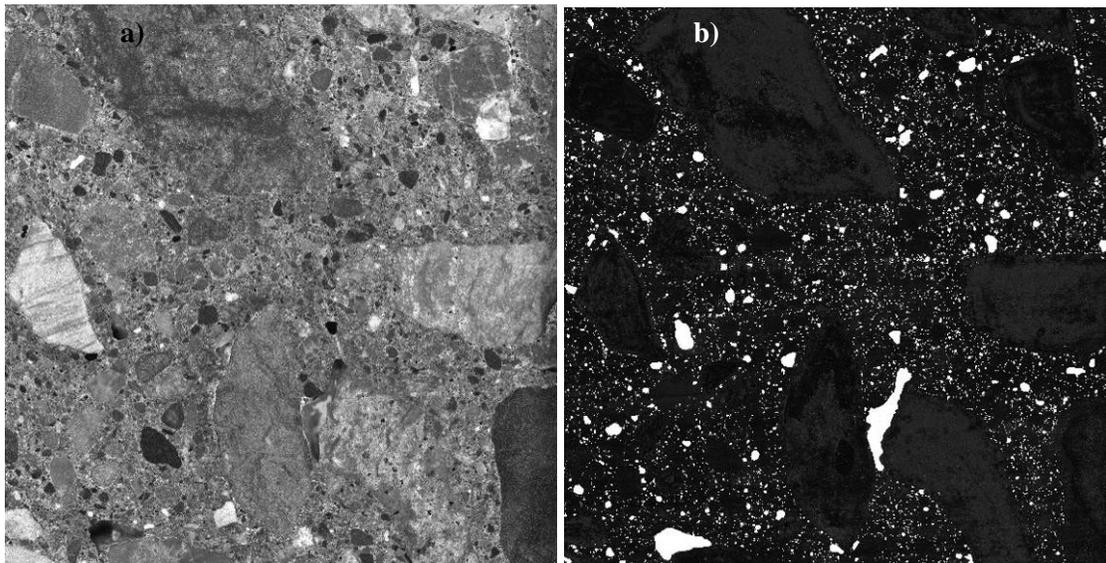


Figure 2.6 Sample surface after polishing (a), and the same surface after contrast enhancement (b).

3. Results and Discussion

3.1 Field Observations

Field observations show that joint associated distress is most pronounced at the joint corners and additional joint spalling develops in the longitudinal joints (figure 3.1). Transverse joint staining was found to be associated with this type of distress (figure 3.2). Occasional transverse joint spalling was found near the outside shoulder away from wheel-load area. This is likely a water accumulation problem due to the pavement cross slope (figure 3.2).



Figure 3.1 Joint associated distress (EB, M-14, Ann Arbor).



Figure 3.2 Transverse joint staining and spalling near outside shoulder (WB, I-94, Lawrence, MI).

A unique situation exists on WB, I-94, Lawrence, where a small part of the section at time of investigation (August, 2008) has no joint associated distress (i.e. no spalling and joint staining) while the remaining section has developed distress (figure 3.3). Additional transverse joint spalling was associated with longitudinal cracks running in a straight line between transverse joints. The crack pattern was typical for vibrator trails due to over-vibration of the concrete during paving operation. No vibrator trails were observed in the section without distress. These crack intercepts at the transverse joints were points of spall initiation just below the tined surface (figure 3.4 and 3.5). In figure 3.5 coring on one side of the joint spall show that joint deterioration has developed only in the top few inches. Figure 3.6 is another example of transverse joint deterioration outside the wheel-path, showing that concrete deterioration is due to erosion of the mortar. Extensive longitudinal joint associated distress has developed for both the M-14 and the I-94 projects. Coring on the I-94 project demonstrated that water was trapped in the joint due to tight crack opening (figure 3.7). Core samples were obtained from midslab and joint areas for freeze-thaw testing and air-void analysis.



Figure 3.3 WB I-94, Lawrence, MI, showing end of section without joint distress and the beginning of the section with distress.



Figure 3.4 Longitudinal cracks at transverse joints initiate joint associated distress just below the tined surface.



Figure 3.5 Close-up of joint deteriorated concrete (WB, I-94, Lawrence, MI).



(a)

(b)

Figure 3.6 (a) WB, I-94, transverse joint spalling deterioration at intercept of longitudinal crack from vibrator trails, and (b) deterioration initiation just below the tined surface from mortar erosion.



(a)

(b)

Figure 3.7 WB I-94, Lawrence, MI, with longitudinal joint deterioration (a), and (b) poorly draining joint.

3.2 Laboratory Freeze-Thaw Test Results

Results in figure 3.8 corroborate field observations for the WB, I-94, Lawrence, project, where one section has no distress while the adjoining section has extensive joint associated distress. The concrete from the distressed area failed quickly (< 10 cycles) in the deicer scaling test while the concrete without any field distress had substantially better deicer scaling resistance with 75% less surface scaling for same number of freeze-thaw cycles. Photos (figure 3.9) of the specimen exposure surfaces illustrate extensive erosion of the mortar phase after only 10 freeze-thaw cycles while the erosion is limited in the concrete without any field distress. The major factor for the poor laboratory frost resistance is insufficient air content. The concrete with poor freeze-thaw resistance and field distress has 3.8% total air content, while the field concrete with no distress has 5.9% air (ASTM C457).

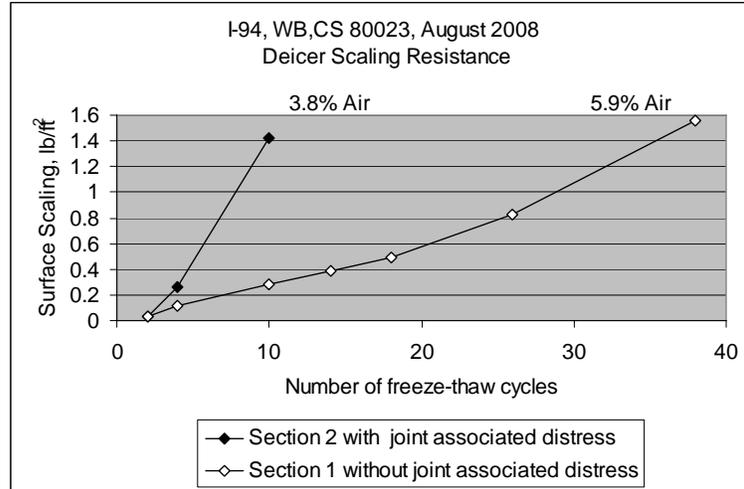


Figure 3.8 WB, I-94 test results for two different sections.

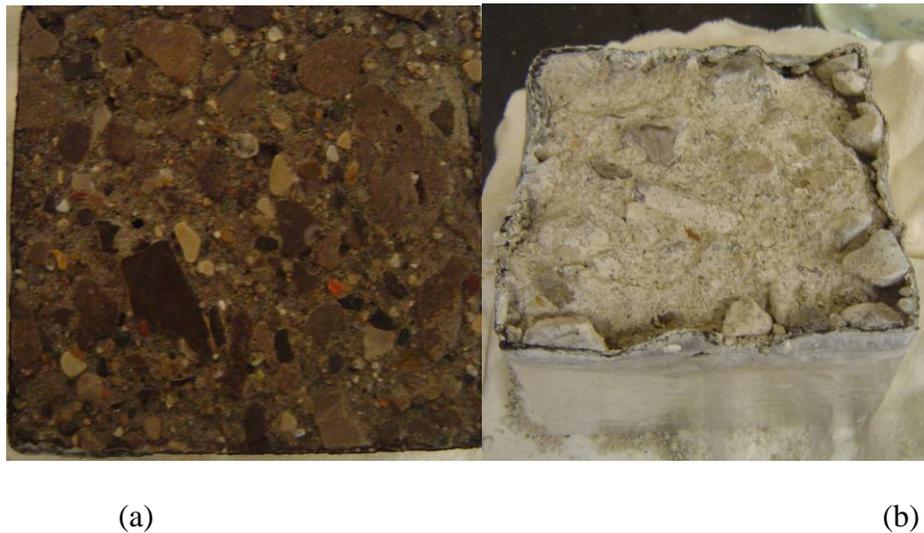
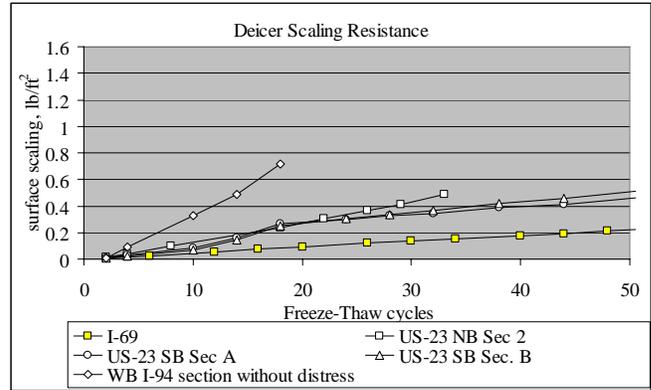
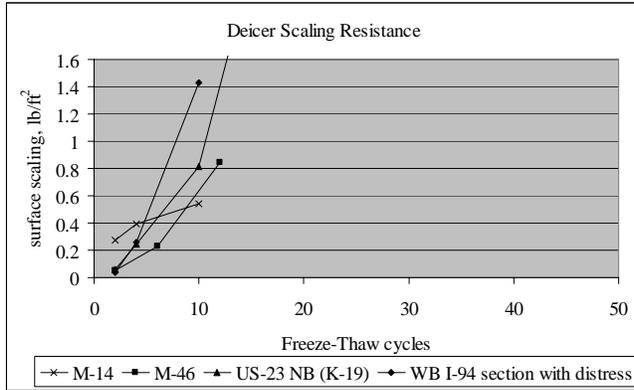


Figure 3.9 Concrete exposure surface from WB I-94, Lawrence, without associated joint distress (a) after 12 freeze-thaw cycles, and (b) from the distressed area after 10 freeze-thaw cycles.

Scaling resistance for the field concrete can be divided into two distinctly different groups as seen in figure 3.10. One group, consisting of the concrete pavements with distress (M-14, M-46, US-23 NB (K-19), I-94), has rapid scaling of the mortar and extensive mortar erosion within 5 to 10 freeze-thaw cycles (figure 3.10a), while the group without distress has 5 to 10 times lower scaling. These concrete projects include one section on WB I-94 discussed above which has no joint associated distress at time of this investigation (August 2008). Despite the higher air-content (5.8%) this concrete has twice the scaling rate as compared to the other projects in this group.



(a)

(b)

Figure 3.10 Laboratory deicer scaling results for field concrete projects with (a) and without (b) joint associated distress

The scaling development is approximately linear with number of cycles (figure 3.10). This is consistent with findings from another study by Pinto and Hover (2001) based on a ponding test (ASTM C672). Therefore, the scaling rate ($\text{lb/ft}^2/\text{cycle}$) can be considered an inherent concrete property of resistance to deicer salt exposure during freeze-thaw cycle. For similar water-cement ratios and mix designs, which is typical for highway concrete, improved resistance to frost in general is achieved through air-entrainment. Typically, total air is used in specifications due to the ease of measurement of air in fresh concrete. Thus, scaling rate and air content, as a first measure, may provide insight into field resistance of hardened concrete. Results in figure 3.11 show a strong correlation between scaling rate and total air content. Closed symbols refer to pavements with joint associated distress while open symbols are for projects without distress. The results are for each specimen per test and thus shows for some test sections considerable variation in scaling resistance between two different core samples (M-14, M-46), which is attributed to paste in homogeneity. The concrete with premature joint associated distress have higher scaling rates due to lower total air content (entrained plus entrapped air), while the concretes without field distress have lower scaling rates and higher air content, consistent with expectations.

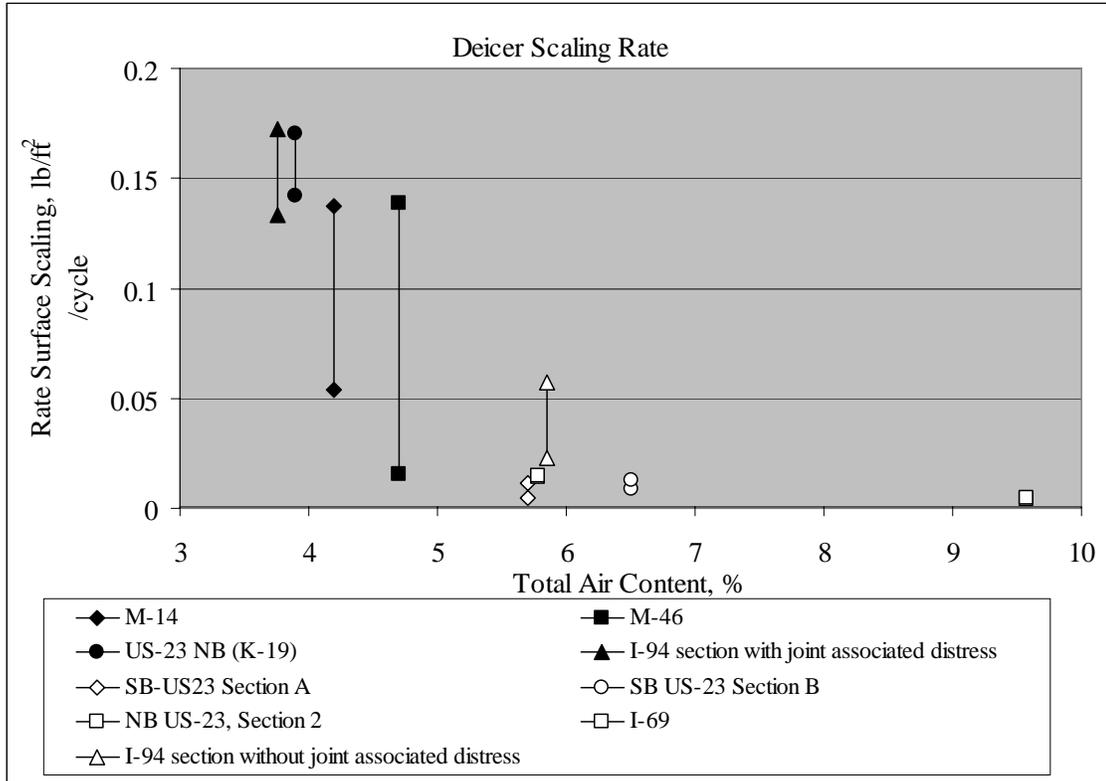


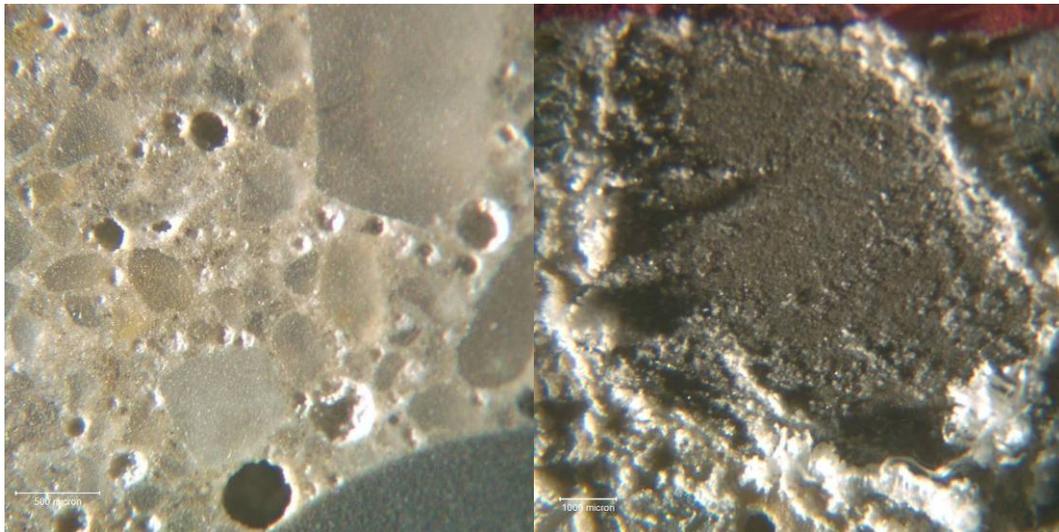
Figure 3.11 Deicer scaling rate for field concrete versus air content.

The results here suggest that total air exceeding about 5.8% can result in frost resistant concrete for a severe exposure condition (i.e. salt frost attack). From Table 3.1, an average value for infilling is 18.9% of total. This translates into a minimum recommended fresh air content of slightly over 7%, when taking into account that infilling of air-voids over time can be expected in the joint area.

Table 3.1 Summary air-void results based on point-count method

Route	PROJECT		Air Void Analysis by Point-Count Method			
	CS	PN	Infilling Percent	Estimated original total air content Percent	Present total Air Content Percent	
M-14 EB	81105	34962	1.5	5.8	4.3	
M-46	74062	47172	1.2	6.3	5.1	
US-23 SB Section A	58034	32750A	1.0	6.7	5.7	
US-23 SB Section B	58034	32750A	1.4	7.7	6.3	
I-69	19042& 76024	01978A	-	-	-	
I-94 WB (section without distress)	80023	45859	1.6	7.5	5.9	
I-94 WB (section with joint distress)	80023	45859	1.0	4.8	3.8	
US-23 NB (K-19)	58034	32750A	2.0	5.8	3.8	
US-23 NB (Section 2)	58034	32750A	1.0	6.8	5.8	

An example of infilling is shown in Figure 3.12. The white powder seen inside the air-voids is most likely salt since water-sorption tests on dried field-samples showed presence of salt. During water absorption test of freeze-thaw specimens, salt crystallization in the porous interface between coarse aggregate and the paste was common for the I-94 concrete (figure 3.12b). The I-94 section had received substantial amounts of road-salt during winter periods.



(a)

(b)

Figure 3.12 Air void infilling (a) and crystallization of salt on the surface during water sorption test for WB I-94 concrete obtained from joint area in the section with joint associated distress.

Powers spacing factor is typically used as a fundamental indicator of concrete frost resistance when exposed to water during a freeze-thaw test. The results in this study suggest that field concrete for Michigan environmental conditions and mix proportion the critical spacing factor is about 59 mils (0.150 mm) for deicer salt exposure (figure 3.13). The critical spacing factor for water exposure is typically 98 mils (0.250 mm). A lower spacing factor requires more air entrainment and thus greater total air content. Fagerlund (2004) has suggested a spacing factor in the range of 63 mils (0.160 mm) to 77 mils (0.200 mm) for salt-frost resistant concrete. Spacing factor values are listed in table 3.2. Excellent agreement was obtained for total air content based on the manual point-count method (Table 3.1) and the automated linear traverse (Table 3.2) method. Linear traverse measurements further show that entrapped air ranges from 0.5% to 2.1%, which is also consistent with expected values (PCA, 2003).

Table 3.2 Air-void results based on ASTM C457

Projects	Chords < 0.0394inch	Chords > 0.0394inch	Total air by linear traverse (ASTM C457)	Infilling Air by point count	Total air including infilling air	Spacing Factor (in))
M-14	3.21	1.04	4.25	1.51	5.76	0.0085
M-46	4.08	1.00	5.08	1.2	6.28	0.0065
US23SB Sec A	3.93	1.79	5.72	1	6.72	0.0056
US23SB Sec B	5.39	0.94	6.33	1.39	7.72	0.0047
US23 Sec 2	4.8	0.98	5.78	1.02	6.8	0.0039
US23NB K-19	2.33	1.53	3.86	1.97	5.83	0.0116
I-94 Sec1 MP	5.01	1.29	6.3	0.94	7.24	0.0054
WB I-94 w/o Joint distress	3.78	2.07	5.85	1.57	7.42	0.0051
WB I-94 with Joint distress	3.32	0.44	3.76	1.01	4.77	0.0086
I-69	9.12	0.45	9.57	-	-	0.0032
US 131 (New Construction)	7.35	0.79	8.14	-	-	0.0027

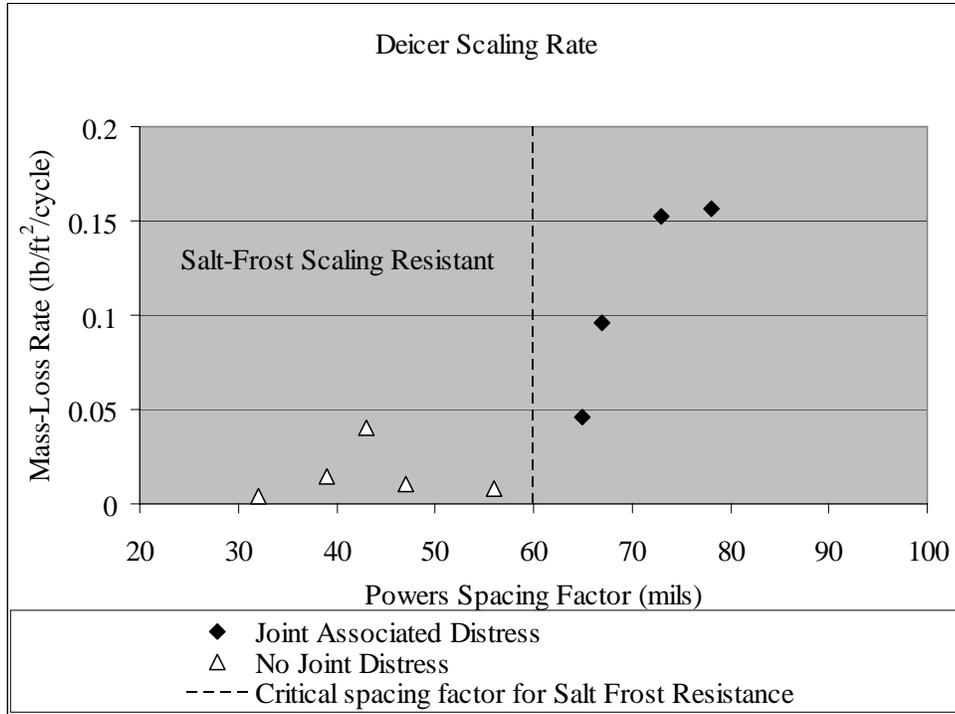


Figure 3.13 Deicer scaling rate versus Powers Spacing Factor

A closer examination of the deteriorated surfaces of the I-94 concrete by optical microscopy revealed that freeze-thaw deterioration was the result of cracking within the portland cement paste consistent with a poor air-void system (figure 3.14). Cracking is the result of excessive pore-pressure associated with freezing and associated expansion. A unique feature of freezing with a salt solution on the surface is that part of the salt solution remains liquid after freezing starts in the pores within vicinity of the surface. This condition creates a cryogenic suction pump and rapid pore-filling during the entire freezing cycle. Once a surface layer consisting of mortar has peeled off the process continues. Therefore, scaling increases linearly with number of freeze-thaw cycles, as long as the paste below the surface has similar properties. Microscopic evaluation of the scaled concrete surface showed no deterioration within the coarse aggregate for any of the pavements investigated in this study.

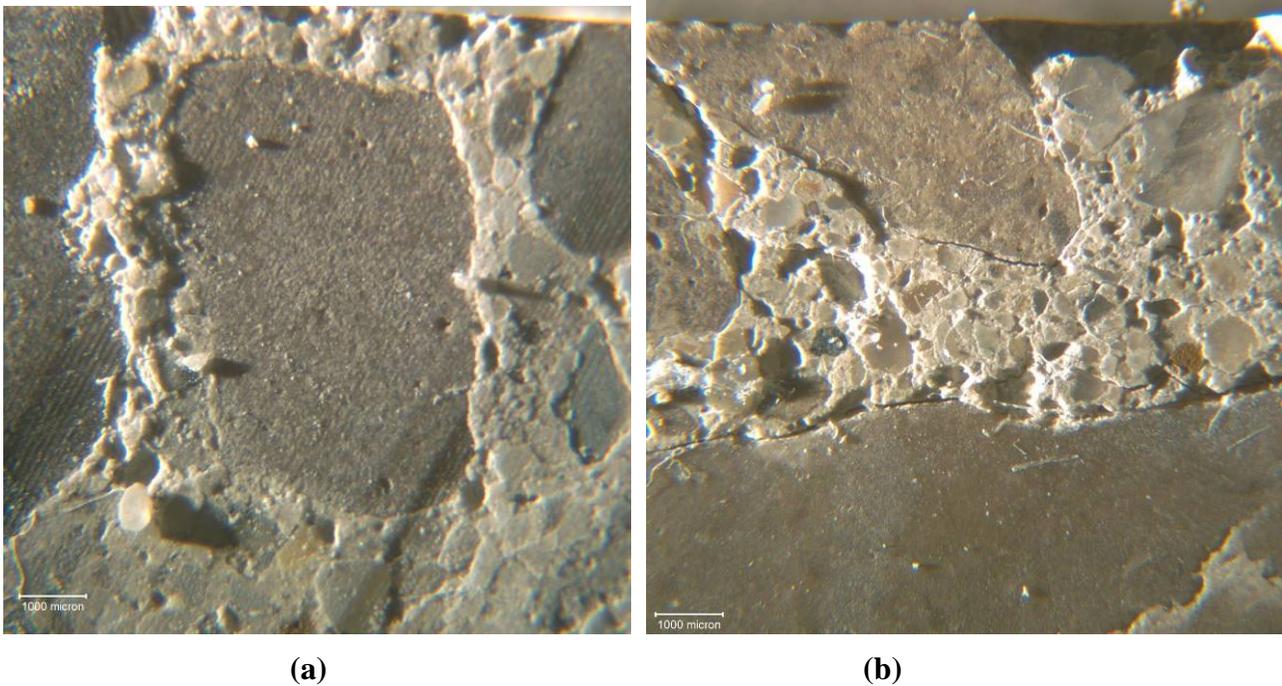


Figure 3.14 (a and b) I-94 section 2 joint concrete surface following 3 freeze-thaw cycles in 3%NaCl solution.

3.3 Improved Scaling Resistance of MDOT P-1 MOD Mix Containing Slag Cement

Three slag cement concretes of increasing air contents, based on the P-1 MOD mix and materials used for an ongoing overlay project (US-131), were tested for deicer scaling resistance. The slag cement concretes are lab mixes using field materials. One lab control mix (i.e. without slag cement) containing target air content of 6.5% was tested for comparison. Duplicate specimens were used and results are plotted for each specimen in figure 3.15. These concretes were water cured for 28 days, then dried for two weeks and re-saturated prior to freeze-thaw testing. Average scaling rates are plotted in figure 3.16 for the lab concretes along with the field concrete. The slag cement systems have markedly improved scaling resistance for same air content. Scaling in control concrete is more pronounced around coarse aggregate (figure 3.17 a) while paste scaling in slag cement concrete is uniform (Figure 3.17 b). This is attributed to an improved interface zone without tendency for agglomeration of air-voids (figure 3.18) embedded within a more porous paste (i.e. higher local water-cement ratio), typical for the control concrete system (figure 3.19). Consequently, a better air-void distribution is achieved in the slag cement concrete, which in turn improves salt frost scaling resistance for same total air content as a control concrete.

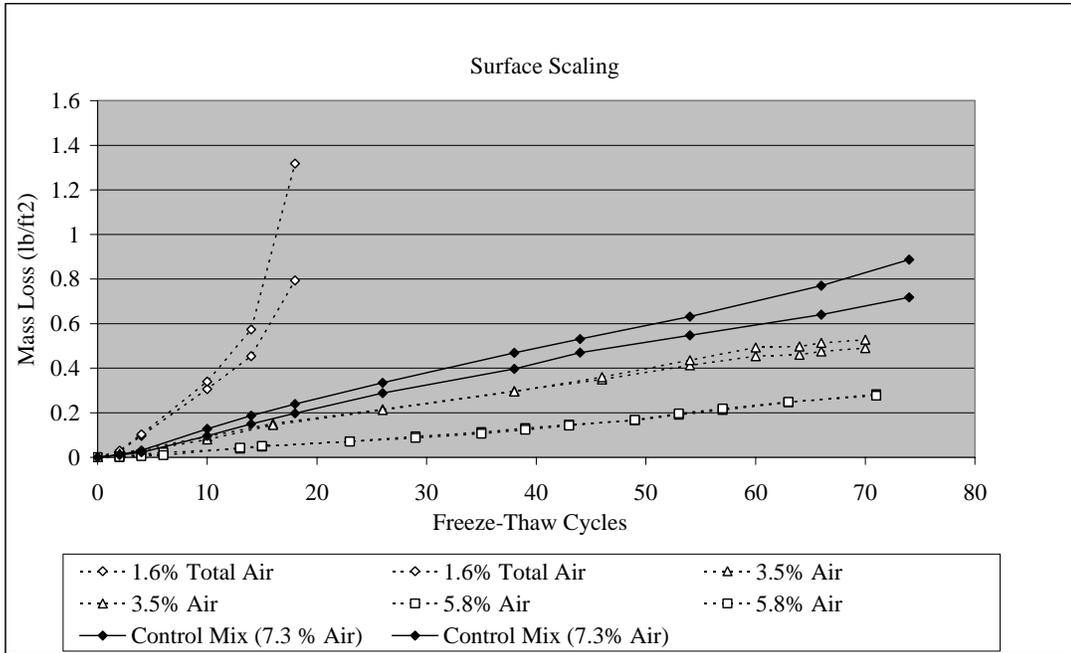


Figure 3.15 Mass loss of various air content concrete in de-icing solution

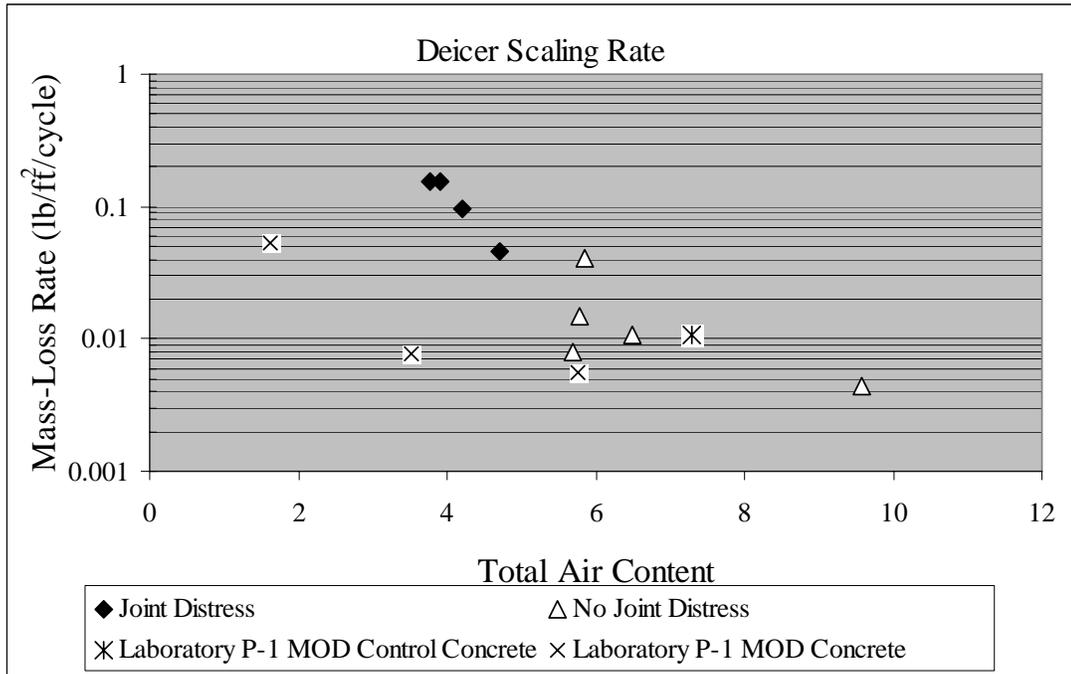


Figure 3.16 Scaling rate for P-1 MOD lab concrete and field concrete

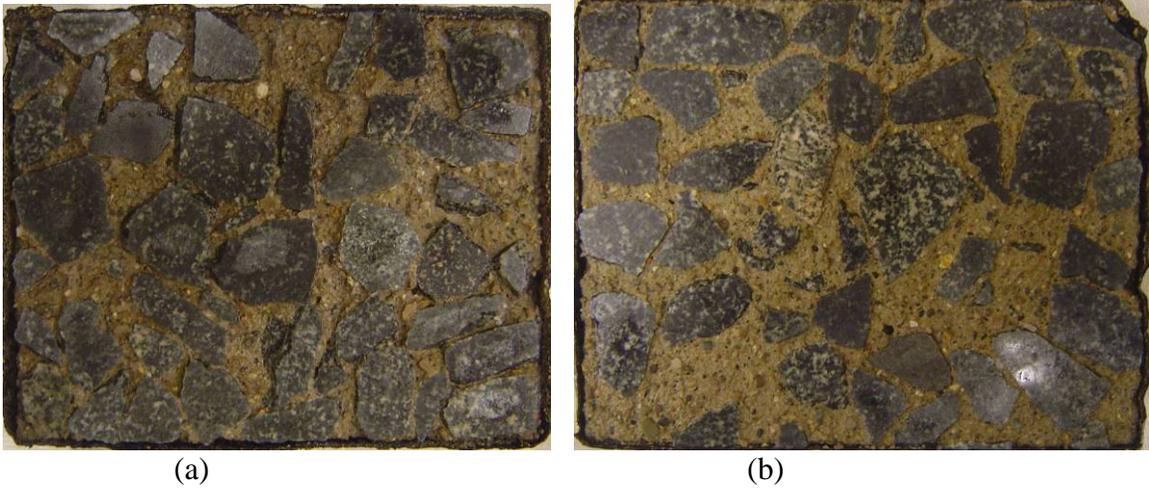


Figure 3.17 Control concrete with 7.3 % air (a), and slag-cement concrete with 5.8 % air after 42 freeze-thaw cycles in salt solution

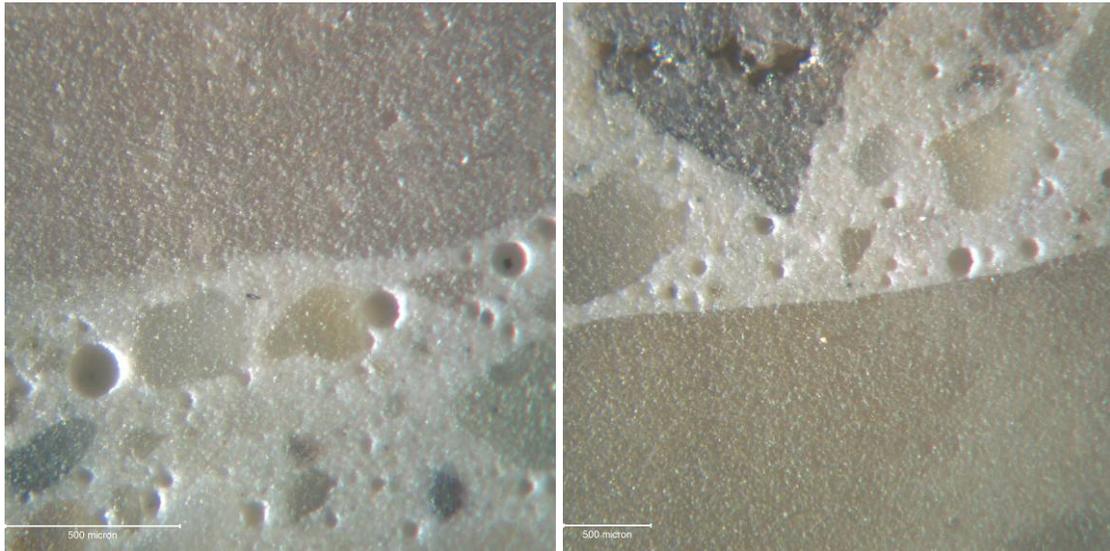


Figure 3.1 Typical interface zone in slag cement concrete

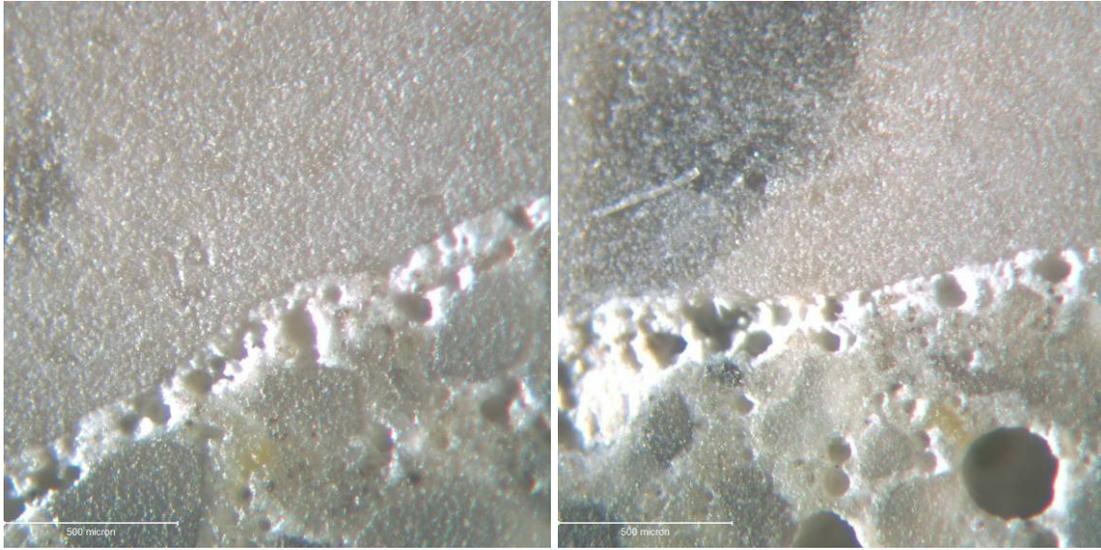


Figure 3.19 Highly porous interface zone (agglomeration of air-voids) around the coarse aggregate in the control concrete.

4. Conclusions and Recommendations

Materials related distress (MRD) characterized by “starburst” type corner spalling at the longitudinal centerline joint, and occasional transverse joint spalling have developed at a rapid rate in a number of JPCP projects constructed since 1999. The main objective for this project was to isolate the major cause(s) for suspected freeze-thaw deterioration, and to provide recommendations for improved materials specifications in order to ensure long-term freeze-thaw resistance to severe surface exposure conditions (i.e. surface contact with either water or 3% NaCl) during repeated freezing and thawing. Four younger (<10 years) field projects with this type of MRD and four older field projects without MRD were selected for laboratory freeze-thaw testing for two different exposure conditions (water and 3% NaCl) during cyclic freeze-thaw.

The major findings of this study are:

- Laboratory freeze-thaw test results and air-void analysis clearly demonstrated the cause for the joint associated distress which has developed in a number of JPCP's since 1999. The four selected projects with this type of distress suffer from inadequate air-entrainment, which lowers freeze-thaw resistance to deicer salt solution.
- The air-void system was found to be inadequate for a severe exposure condition which exists at poorly draining joints when a concrete surface is exposed to deicer salt solution during freeze-thaw.
- Threshold values for total air content and maximum spacing factor were developed, which can form the basis for improved material specifications for obtaining frost resistance in the field for Michigan environmental conditions.
- MDOT's P-1 MOD concrete containing slag cement had improved deicer frost resistance as slag cement improves the paste-aggregate interface zone, which reduces water sorptivity rate and amount of water uptake as compared to a control concrete. Air-void agglomeration around the coarse aggregate was common in the field concrete and absent in the slag cement concrete. These factors have a major impact on frost resistance.

The major recommendations are:

- Increase minimum target air content in fresh concrete to about 7%, up from the current minimum of 5%. Supplementary cementitious materials such as slag cement can improve paste quality and deicer scaling resistance. The results here suggest that a reduction in the minimum air content is feasible using a P-1 MOD slag cement concrete. However, further testing is needed.
- Ensure that the base and subsurface is sufficiently drained so that water and deicer solutions are not permitted to accumulate at or beneath joints or other discontinuities in the concrete pavement surface. Ensuring adequate drainage will reduce the likelihood that the surrounding concrete at joints will become critically saturated, thus, reducing the risk for MRD and premature deicer-related freeze-thaw deterioration.

5. Implementation of Study Findings.

The findings from this study has provided the understanding and necessary evidence to modify specifications and construction practices to prevent future occurrences of similar premature deterioration caused by the durability factors discovered during this study.

The steps involved to implement the study's findings, after review and acceptance by the department, are similar to other past efforts to modify a specification, or when new requirements for construction are adopted. These steps are generally:

Education –A combination of test methods including a German based freeze-thaw method, air-void analysis according to ASTM C457, microscopic evaluation of deterioration, and water sorptivity tests have been proven effective in understanding the causes for the rapid deterioration of the field concrete in several Michigan pavements constructed since 1999. A better understanding of these causes can provide better solutions to improving concrete pavement performance.

Communication - The department will need to explain the need for the additional acceptance criteria to the construction industry through their in-place committee contacts.

Preparation/Development - The department will need to revise current requirements for air content in fresh concrete and need to incorporate SCM (supplementary cementitious materials) in concrete mixtures for pavement applications.

Surface Treatment Method to improve Deicer Scaling Resistance of Existing JPCP's-

There is evidence that surface sealers could be effective in reducing surface scaling rate. This should be evaluated for projects which have poor deicer scaling resistance such as the I-94 JPCP near Lawrence or M-14, Ann Arbor, K-19 on NB US-23, and M-46. Especially, joint areas are expected to benefit from surface treatment.

Summary: Education and communication between the Department and Industry are essential in improving service life of JPCP. The following points should be emphasized:

- Agreement on the causes and solutions to prevent starburst F-T deterioration in JPCP.
- How to improve existing construction practices and quality control procedures to eliminate this problem.
- Identify new QC/QA procedures that may be needed.

6. References

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Appendix A-Test Results

Nomenclature: (2) refers to average value based on two specimens

1. Water Saturation Results:

Pre Saturation (M%): Water

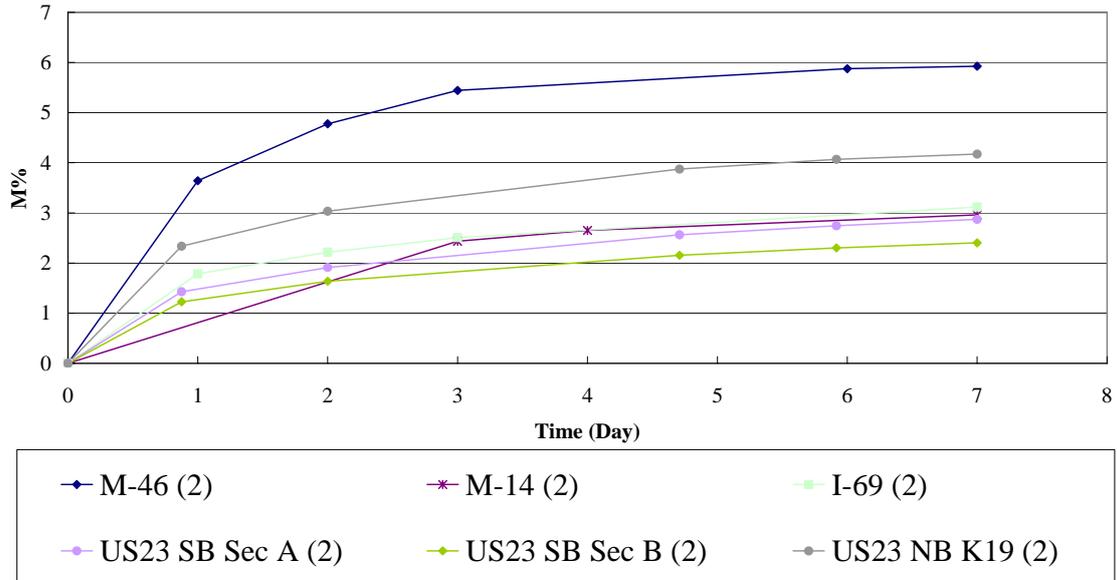


Figure A-1 Moisture uptake due to pre-saturation in water

Pre Saturation (M%): De-icer

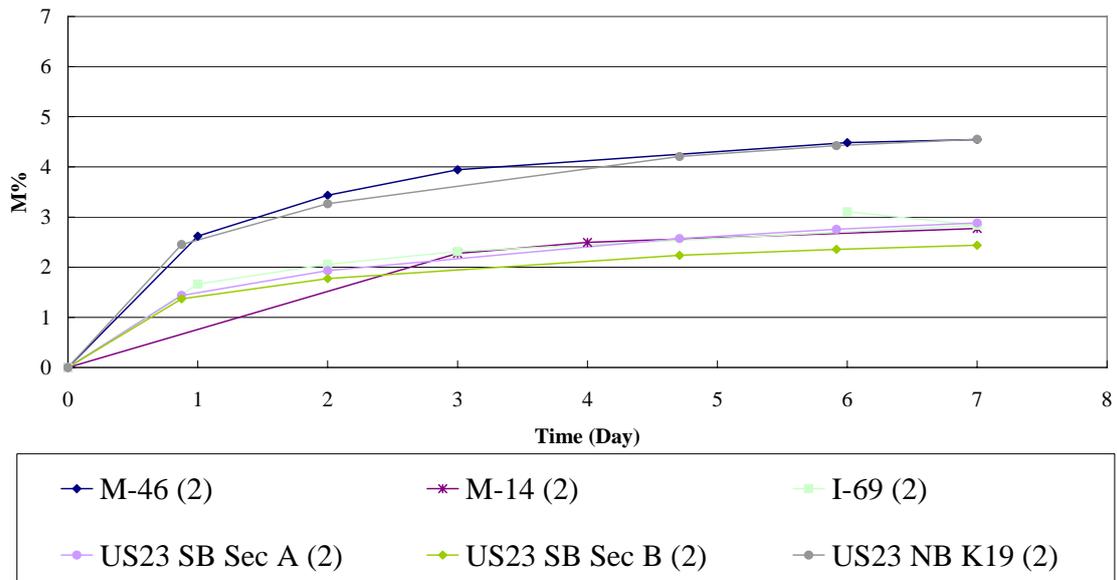


Figure A-2 Moisture uptake due to pre-saturation in 3% NaCl solution

2. Internal Damage

Evaluation of the internal damage: Water

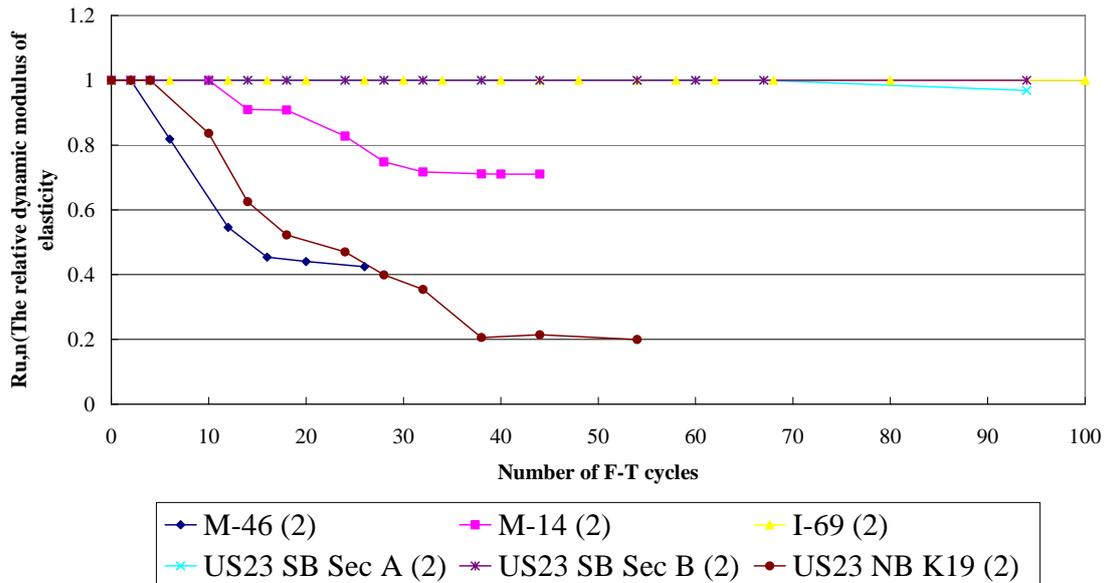


Figure A-3 Relative damage due to combined freeze-thaw and water exposure

Evaluation of the internal damage: De-icer

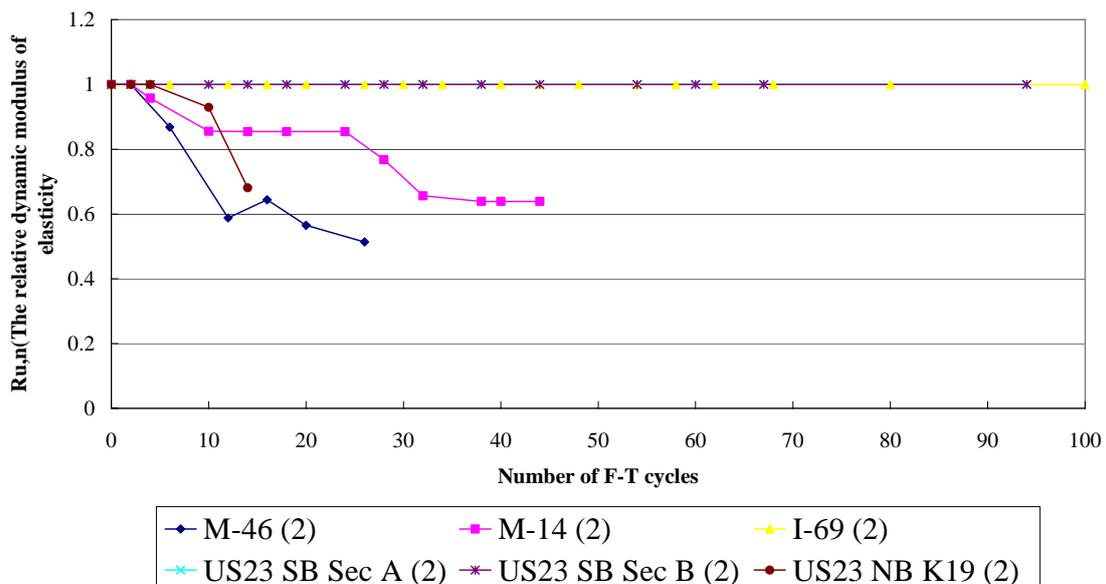


Figure A-4 Relative damage due to combined freeze-thaw and deicer salt exposure

3. Scaling Resistance in water and 3% NaCl solution.

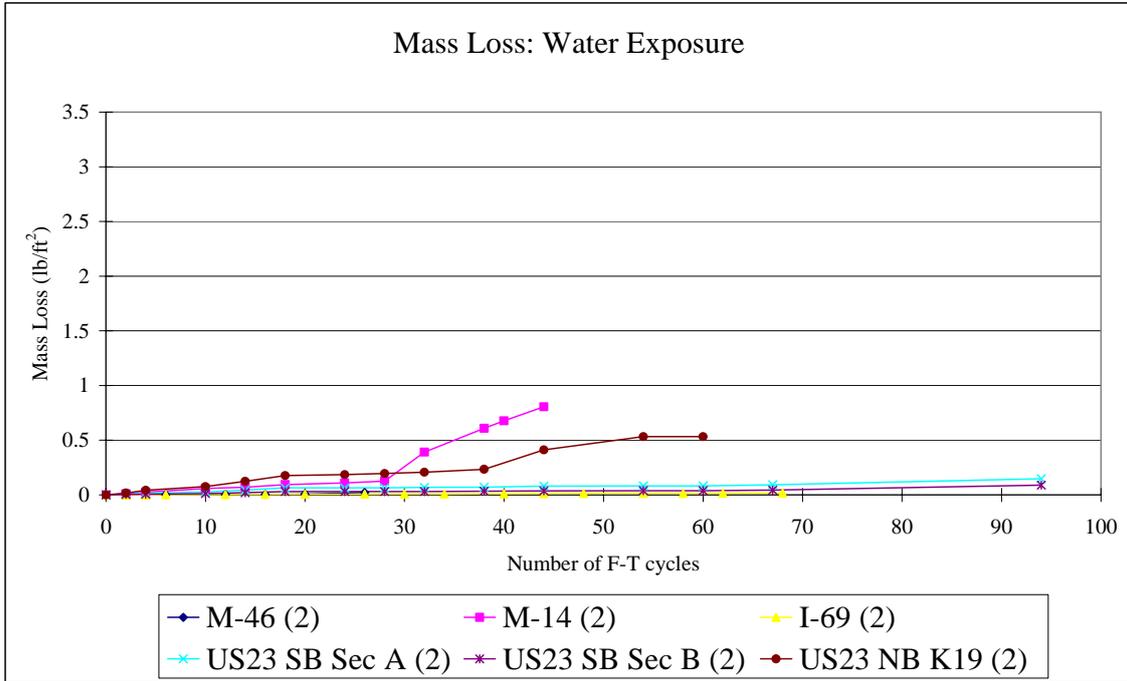


Figure A-5 Mass-loss due to freeze-thaw and water exposure

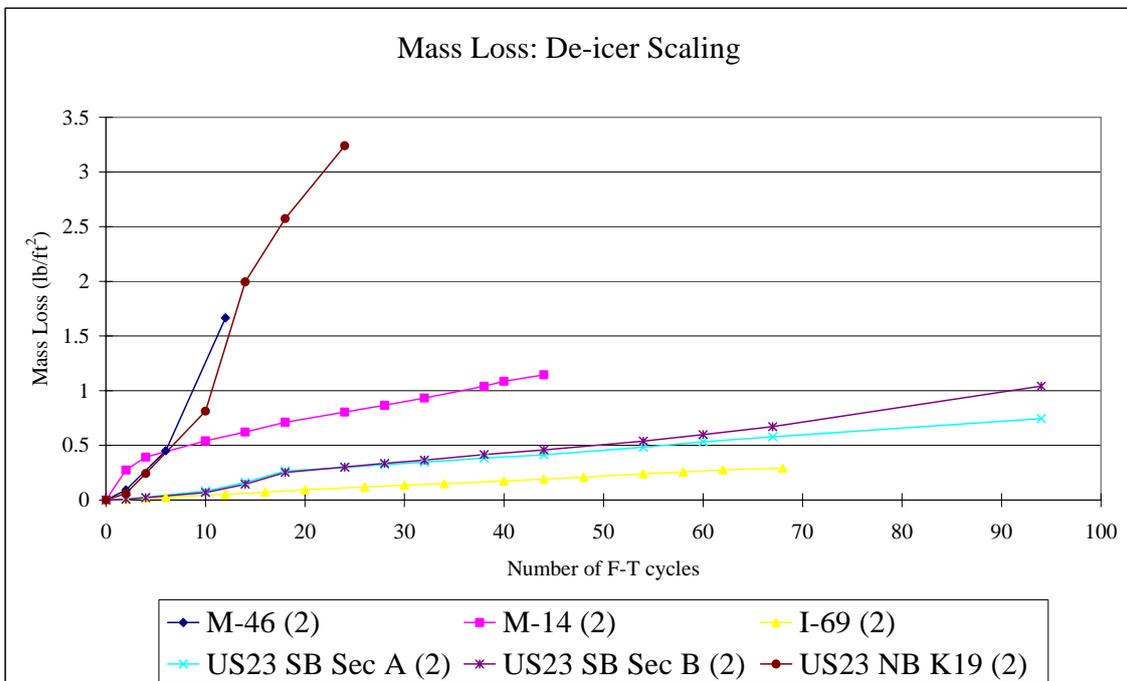


Figure A-6 Mass-loss due to freeze-thaw and deicer salt exposure

4. Moisture Uptake During Freeze-Thaw Testing in water and 3% NaCl solution

Moisture Uptakes: Water

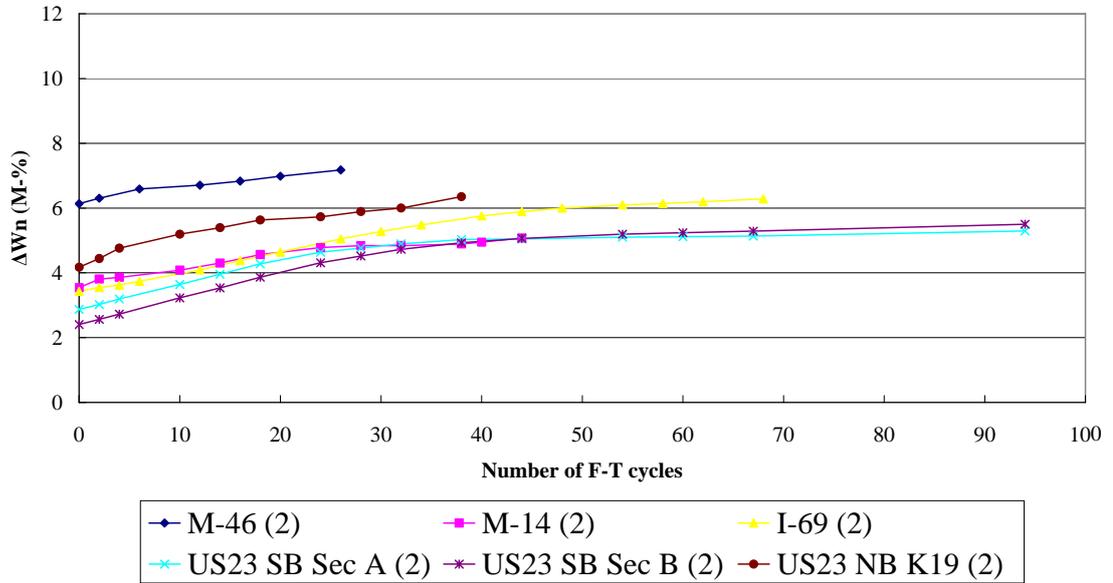


Figure A-7 Water uptake due to freeze-thaw and water exposure

Moisture Uptakes: De-icer

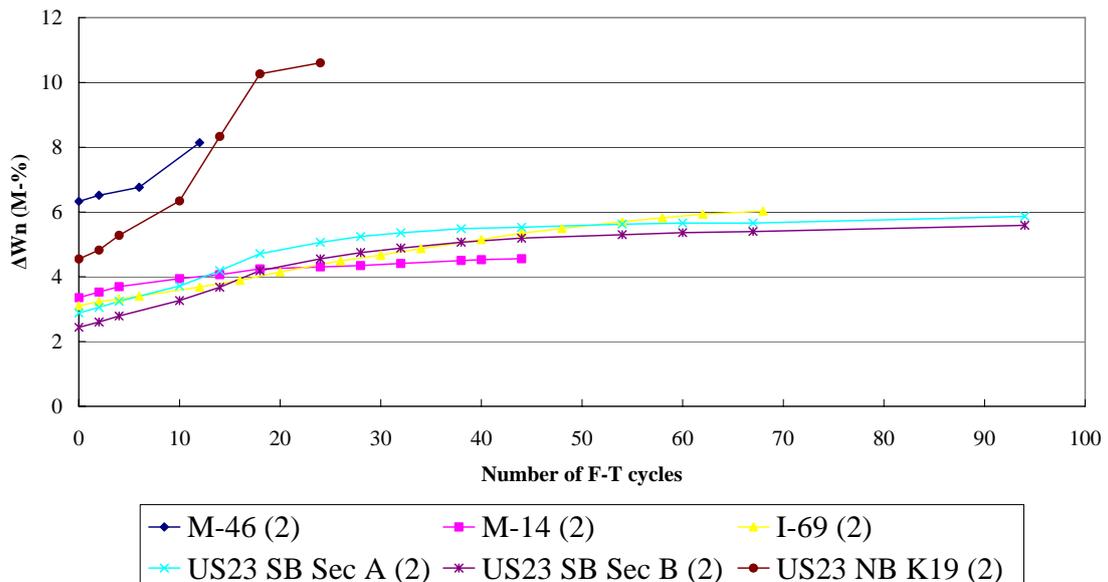


Figure A-8 Water uptake due to freeze-thaw and deicer salt exposure

5. WB I-94 Section 1(no distress) and section 2 (joint associated distress)

I-94 : Pre Saturation (M%): Water

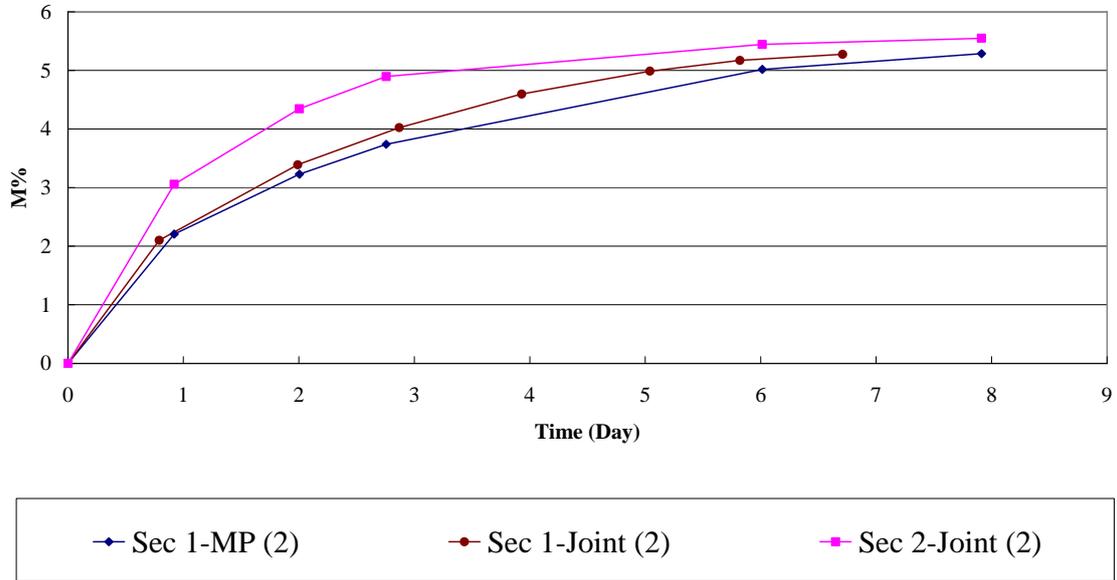


Figure A-9 Water uptake during pre-saturation test

I-94 : Pre Saturation (M%): De-icer

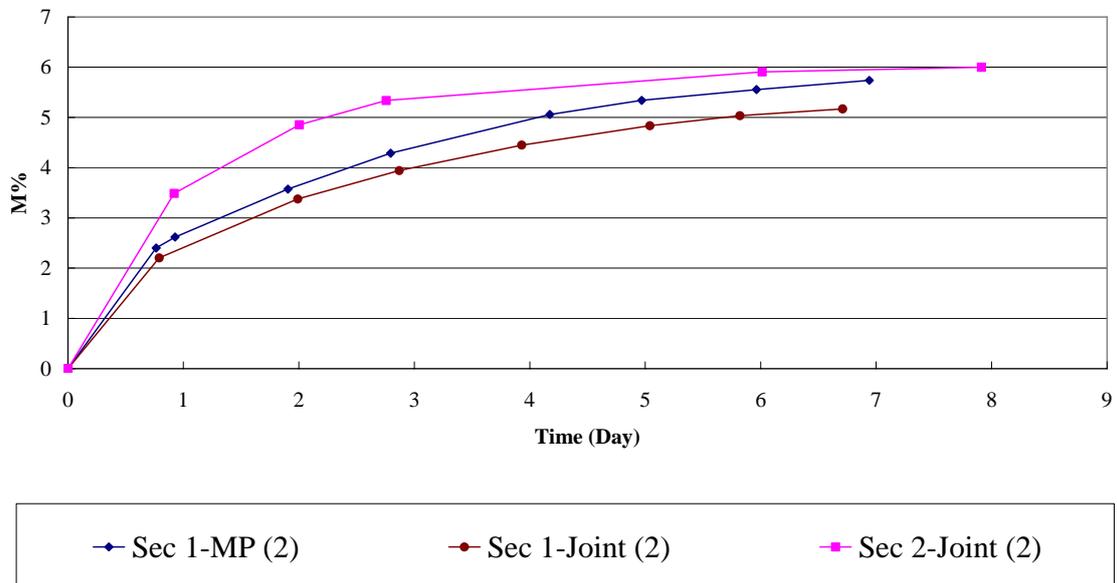


Figure A-10 Deicer salt solution uptake during pre-saturation test

I-94 : Evaluation of the internal damage: Water

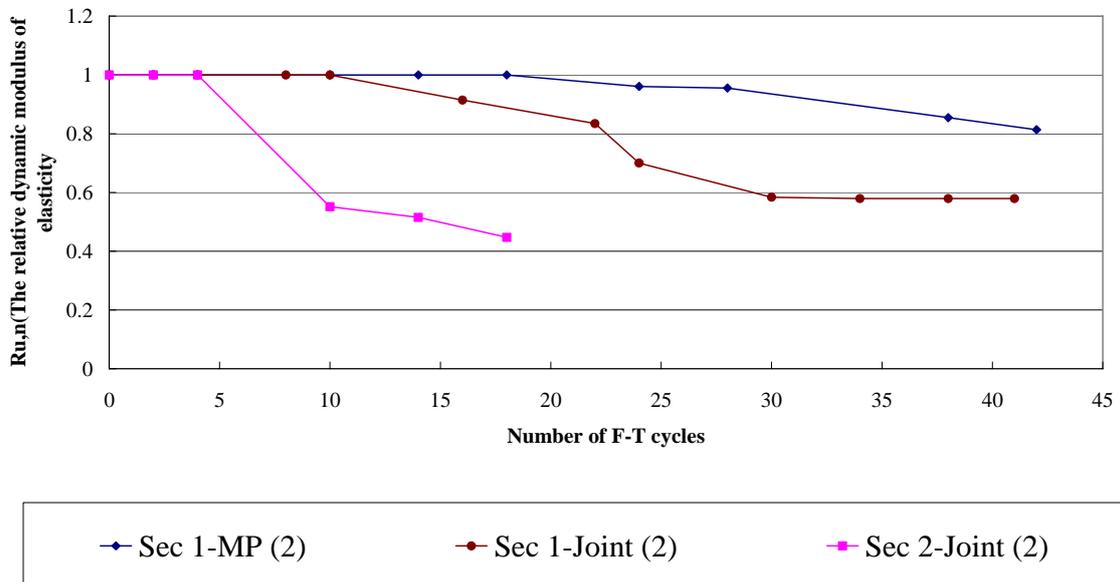


Figure A-11 Relative damage due to combined freeze-thaw and water exposure.

I-94 : Evaluation of the internal damage: De-icer

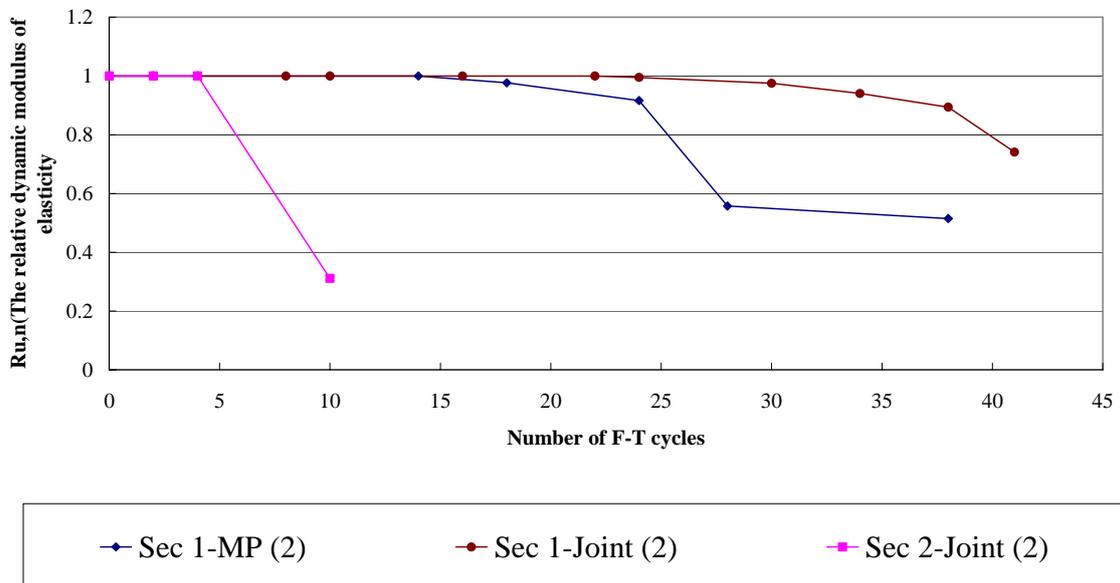


Figure A-12 Relative damage due to combined freeze-thaw and deicer salt exposure.

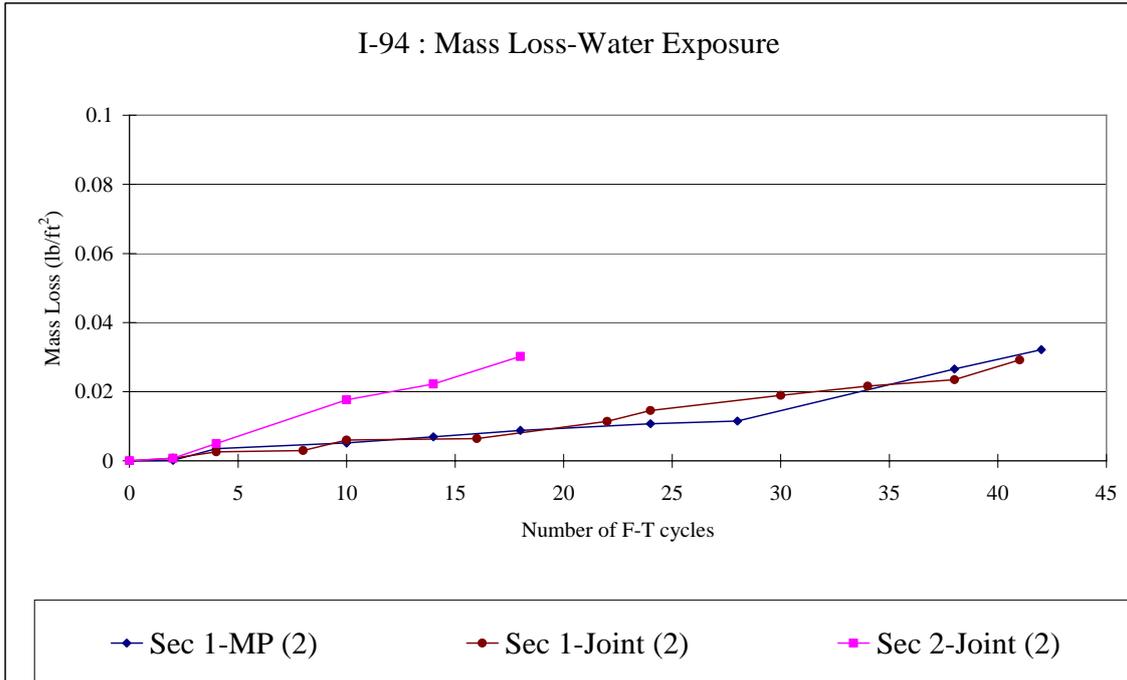


Figure A-13 Mass-loss due to combined freeze-thaw and water exposure

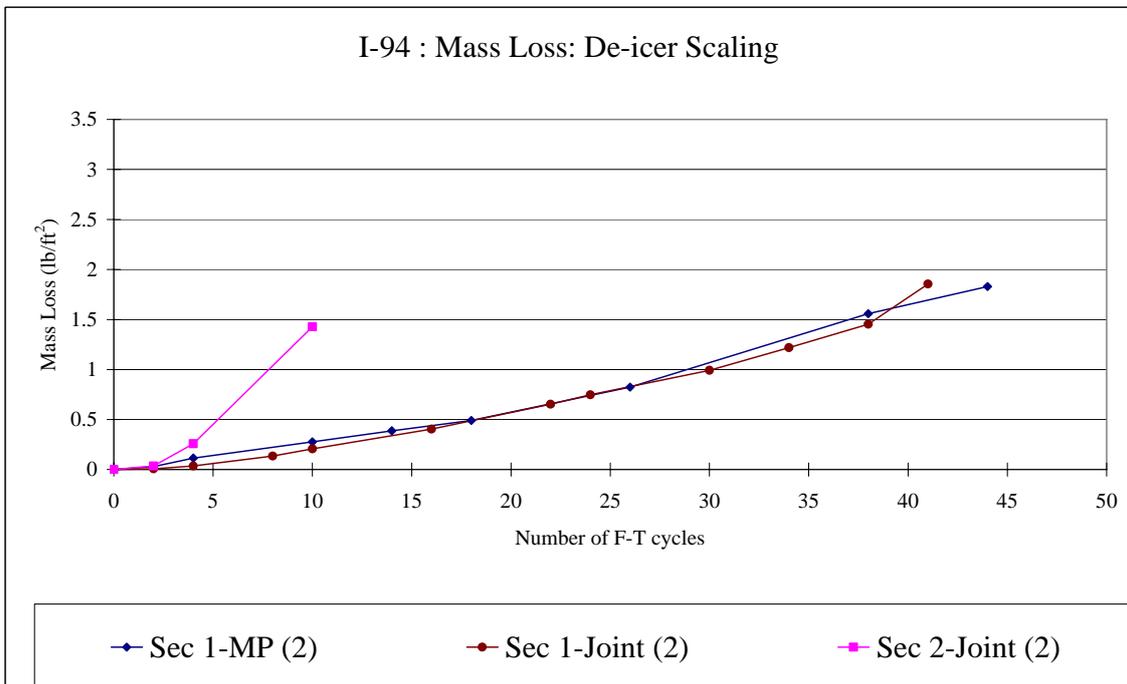


Figure A-14 Mass-loss due to combined freeze-thaw and deicer salt exposure

I-94 : Moisture Uptakes : Water

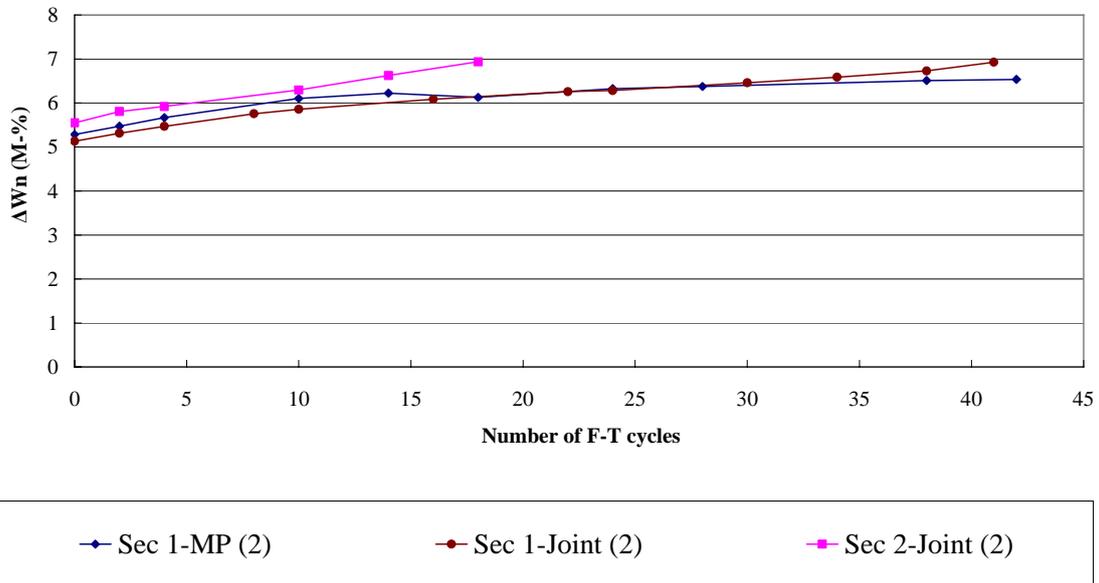


Figure A-15 Net moisture uptake from combined freeze-thaw and water exposure

I-94 : Moisture Uptakes : De-icer

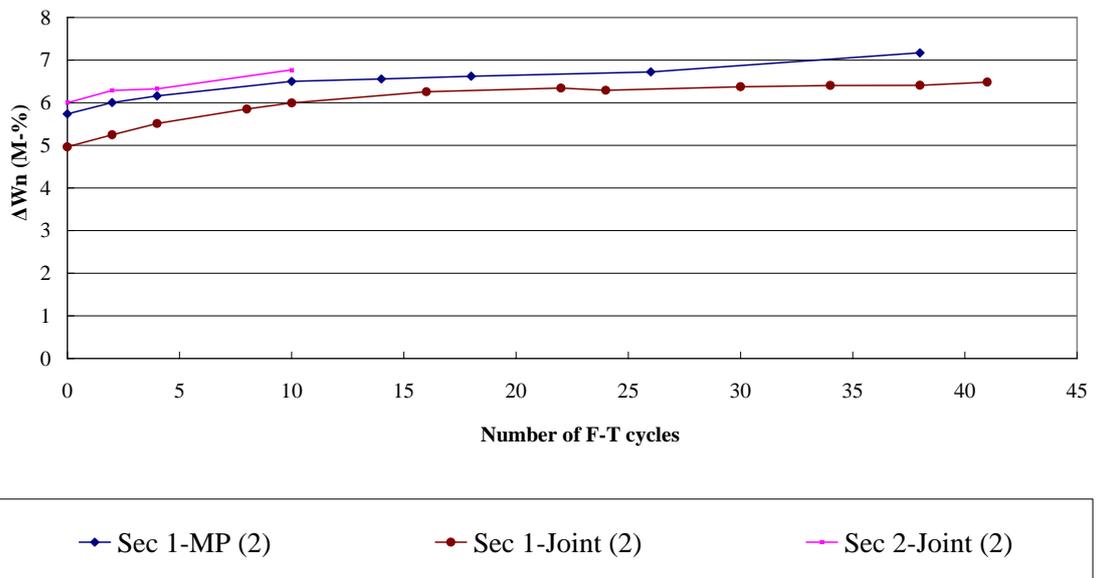


Figure A-16 Net moisture uptake from combined freeze-thaw and deicer salt exposure

Appendix B- MDOT P-1 MOD Concrete Mix Proportioning

Concrete Mix Design Report

Project ID: US 131 Rockford	SME Proj. No.: 'PP 52226
Location: Kent County MI	Date: 4/24/2007
Contractor: Ajax Paving Industries	Architect/Engineer: MDOT
Proposed Use: Pavement	Project Number: NH 41132
Mix Number: 4322-1	Job Number: 50758A

(U.S. Customary Units)

Class of Concrete: P-1 MOD	
Brand and Type of Cement: St. Mary's Char. Type I	
GGBS: St. Mary's Grade 100	
Source of Sand: Ottawa Aggregate 2NS MDOT P# 41-152 SpGr=2.641, Abs.= 1.8%	
Source and Type of Course Aggregate 1: Port Inland MDOT 6AAAAM P# 75-5 SpGr=2.678, Abs.=0.6%	
Course Aggregate 2: Port Inland MDOT 25AM P# 75-5 SpGr=2.653, Abs.=0.7%	
Course Aggregate Dry Loose Unit Weight 1: _____ pcf	
% Course Aggregate: _____	
Brand of A.E.A.: ProAir	
Type and Brand of Admixture 1: PlastMix 500	
Admixture 2: _____	
Admixture 3: _____	
Max. Aggregate Size, in.: 2	
Spec. 28 Day Strength: 3500	
Min. # Sacks per yd ³ : 5	
Min Slump, in.: 1	
Max Slump, in.: 3	
Air Content, %: 6.5 % +/- 1.50%	

Design Quantities Per Cubic Yard Trial Batch Factor: 0.11

Material	Spec. Gravity SSD	Factor	Weight, Lbs. SSD	Volume Cubic ft. per yd ³	Total Batch Weights
Cement	3.15	156.590	326	1.66	35.9 lb
GGBS	2.85	177.540	164	0.92	18.0 lb
Sand	2.641	164.798	1387	7.93	143.3 lb
Coarse Agg. 1	2.678	167.107	1260	7.54	128.6 lb
Coarse Agg. 2	2.653	166.171	621	3.74	68.4 lb
Water	1	62.450	218	3.49	34.0 lb
A.E.A. *			1.25	1.75	0.63 fl oz
Admix. 1 *			0.00		2.15 fl oz
Admix. 2 *			0.00		0.00 fl oz
Admix. 3 *			0.00		0.00 fl oz
Total			3896	27.04	
			Concrete Unit Weight: 144.1	pcf	

* weight reported as fluid ounces per 100 lb cement

Figure B-1 US-131 Overlay mix design report for P-1 MOD Concrete