Forensic study of premature failures with unbonded concrete overlay on interstate 70 in Ohio

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Abstract: This paper presents the results and findings from a forensic investigation initiated in 2014 to identify the causes of premature failures on an unbonded concrete overlay (UBCO) on Interstate 70 in Madison County, Ohio. This project was constructed in 1999 and 2000. Premature distress, including transverse cracking, corner breaks and slab settlement began to appear in 2008. Falling weight deflectometer (FWD) and distress survey data were collected from the field during the investigation. MIT Scan was used to evaluate dowel alignment. Concrete samples were taken from the field and tested in the laboratory. HIPERPAV was used to evaluate early behaviour of the Portland cement concrete (PCC). Results of finite element analysis was used to help understand the mechanisms responsible for the premature distresses.

Key findings include: sections with thicker bondbreaker delayed distress formation; and lack of drainage led to the presence of water in the joints, which contributed to distress.

Keywords: UBCO; unbonded concrete overlay; forensic investigation; pavement performance; pavement distress; finite element; FWD; falling weight deflectometer; HIPERPAV; rigid pavement.

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Biographical notes: Junqing Zhu received the MS degree from Ohio University in Civil Engineering. Since May 2015, he has been a PhD candidate in Civil Engineering at Ohio University and worked as a Research Assistant at Ohio Research Institute for Transportation and the Environment (ORITE) on the project of development of JPCP design catalog for New York State. He was also devoted on the project of forensic investigations on unbonded concrete overlays in Ohio. His current research includes three-dimensional finite element analysis of rigid pavement response, forensic investigations of highway pavements, resilient modulus and permanent deformation of unbound granular base materials, field data acquisition and analysis, and development of MEPDG calibration factors.

Shad Sargand earned his PhD in Civil Engineering from Virginia Tech in 1981. Since then he has been on the Faculty of the Civil Engineering Department of Ohio University's Russ College of Engineering and Technology, and was named Russ Professor in 1990. He has authored over 270 journal articles, conference papers, and technical reports. Since its inception in 1995, he has been the lead researcher of the Ohio Strategic Highway Research Program (SHRP) National Test Road on US Route 23 in Delaware County, Ohio. He is the Associate Director of the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University, which operates the Asphalt Laboratory and Accelerated Pavement Load Facility in Lancaster, Ohio.

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1 Introduction

The installation of an unbonded concrete overlay (UBCO) is one of the techniques employed by the Ohio Department of Transportation (ODOT) to rehabilitate deteriorated concrete pavements. Most of the UBCOs constructed in Ohio have significantly extended pavement life (Williams and Chou, 1994). However, a UBCO section on Interstate 70 in Madison County, Ohio failed prematurely. This UBCO project was constructed in eastbound direction in 1999 and in the westbound direction in 2000. The buildup design of the UBCO pavement was a 9 in (230 mm) jointed, plain, dowelled concrete was overlaid on top of an existing 9 in (230 mm) jointed, reinforced, dowelled concrete pavement with a 1 in (254 mm) asphalt bondbreaker. Joint spacing of the concrete overlay is 15 ft (4.57 m) and slab width is 12 ft (3.66 m). By 2008, transverse cracking, corner breaks, and slab settlement began to appear in the eastbound direction. An initial forensic investigation conducted by ODOT in 2009 showed 15% of slabs in the eastbound direction and 5% of slabs in the westbound direction had transverse cracks. Figure 1(a) shows faulting distress and Figure 1(b) shows transverse cracking found on MAD-70 eastbound direction. Figure 2 shows the location maps of the MAD-70 project and investigation locations within the project.

Figure 1 (a) MAD-70 EB faulting (June 25, 2008) and (b) MAD-70 EB transverse cracking (March 30, 2015) (see online version for colours)

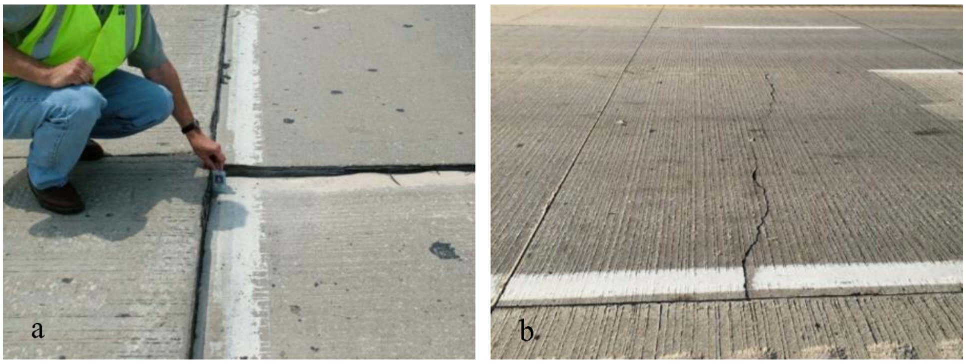


Figure 2 Location map of MAD-70 (see online version for colours)

When a pavement experiences premature distress, it may be a result of poor design, poor construction technique, poor drainage, substandard construction material, higher than anticipated truck volumes, heavier than anticipated traffic loads, environmental factors such as the climate during pavement placing or curing, warping and curling stresses, or a combination of these. The objective of this research was to identify the underlying causes of the premature failures found on MAD-70 and recommend changes to design procedures, plan details and/or materials and construction specifications to eliminate or delay the formation of these distresses on future projects of this type. This paper presents the results and findings of the forensic investigation conducted between 2014 and 2016 on Interstate 70. Standard forensic investigation procedures suggested by NCHRP report 747 were generally followed (Rada et al., 2013). HIPERPAV and finite element method analyses were conducted to help understand failure mechanisms.

The literature regarding studies of UBCO was reviewed. An Illinois Department of Transportation study monitored the performance of UBCO built in 1995 on I-74 in Knox County, IL. The UBCO performance was excellent and no maintenance or patching had been necessary (Heckel, 2002). Hansen and Liu (2013) from the University of Michigan investigated UBCOs experiencing premature distresses in Michigan. The distresses included corner breaks and longitudinal cracks originating at the joints. The evaluation consisted of nondestructive testing at the site and laboratory testing of core samples. The researchers confirmed the major cause of distress was pumping, which was a direct result of poor drainage. The poor drainage was either because of construction related factors that blocked water from reaching the drainage trench or because no drainage system was built.

New York State DOT sponsored an Ohio University evaluation of the performance of UBCOs placed in 2006 on I-86 near Hinsdale, NY over an existing pavement subjected to three different treatments. The existing pavement on Section 1 was left untreated; Section 2 was broken and seated (B&S); and Section 3 was rubblised. LVDTs, strain gauges and thermocouples were installed during construction in each section to monitor the performance. FWD data were also collected annually. It was found that rubblisation and B&S treatment to the existing concrete pavement produced less strains and stresses in the overlay caused by environmental effects. Load transfer efficiency (LTE) of transverse joints was also found to be higher with these two techniques used. In comparison, sections with no treatment to the existing concrete pavement produced highest level of strains and stresses caused by environmental effects. By 2009, mid-panel top-down cracks were observed in 90% of the pavement slabs in the untreated section compared to about 5% of the pavement slabs in the rubblised and B&S sections. The researchers recommended pretreating the existing concrete pavement before placing an UBCO (Sargand et al., 2012).

Kivi et al. (2013) monitored and reported 10-year performance of a UBCO in Toronto, Ontario. The concrete overlay was constructed and instrumented in 2003 during a rehabilitation of Bloor Street, which was subjected to high volumes of heavy transit bus traffic. Overall, the overlay section has shown excellent performance in its first 10 years of service. The author concluded that concrete overlays and inlays are excellent rehabilitation options for urban pavements subjected to high volumes of traffic. Also, the author suggested that compressive strain at the bottom might be the result of a bond between the two concrete layers, which could add additional structural capacity, but was generally undesirable because reflective cracking was more likely to occur.

Chen et al. (2006) reported studies on reflective cracking of overlays on top of jointed concrete pavement. Several strategies were evaluated and it was found that crack-retarding grid was not a satisfactory method. The author also found break-and-seat was performing badly on weak subgrade and suggested this method should not be applied on subgrade with DCP penetration rate exceeding 25 mm/blow. Petromat fabric underseal and crack-retarding asphalt material had been performing satisfactorily to retard reflective cracking.

2 Distress survey

A Road Tester 3000 profiler was used to collect digital images and measurements of pavement condition and ride quality on May 22, 2015. The overall average international roughness index (IRI) of each lane is presented in Figure 3. Table 1 shows the correlation of IRI to pavement condition ratings (PCR). As can be seen from the graphs, overall IRI for most of the tested lanes was 'Good'. The only exception was the driving lane for MAD-70 which showed 'Acceptable' condition. The westbound lanes of MAD-70 are relatively smoother than the eastbound lanes.

Figure 3 Average IRI on MAD-70, all lanes (1 in/mi = 1.58 × 10^{-2} m/km)

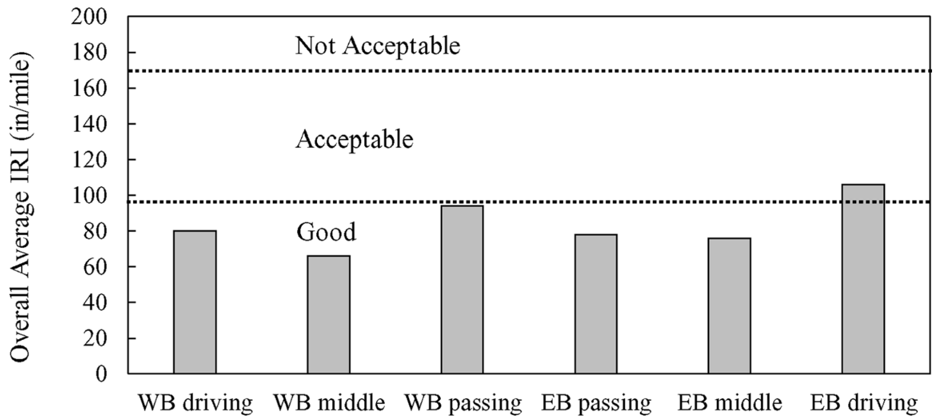


Table 1 Correlation of IRI to pavement condition rating (PCR)

Condition level	*IRI* (in/mile)	*IRI* (m/km)	*PCR*
Good	IRI < 95	IRI < 1.5	Good
Acceptable	95 ≤ IRI ≤170	1.5 ≤ IRI ≤ 2.7	Acceptable
Not acceptable	170 < IRI	2.7 < IRI	Not acceptable

The number of transverse cracks along the whole length of the UBCO section was counted from images collected with the profiler. The cracks per station were counted and plotted over the length of the project in Figure 4 (eastbound) and Figure 5 (westbound). Crack surveys conducted by ODOT in 2008 and 2009 were added to the plot. In the plots, the shaded areas are locations of full-depth concrete reconstruction (Portland cement concrete (PCC) thickness = 13 in or 330 mm). From the graph, it can be seen the number of cracks per station increased from 2008 to 2009. In 2015, number of cracks decreased, because some of the slabs were repaired during the interim. Comparing the two directions, the eastbound direction experienced much more cracking than the westbound direction. Comparing the UBCO with the full-depth repairs the UBCO portions have many more cracks.

Figure 4 Eastbound cracking plot (100 ft = 30.5 m)

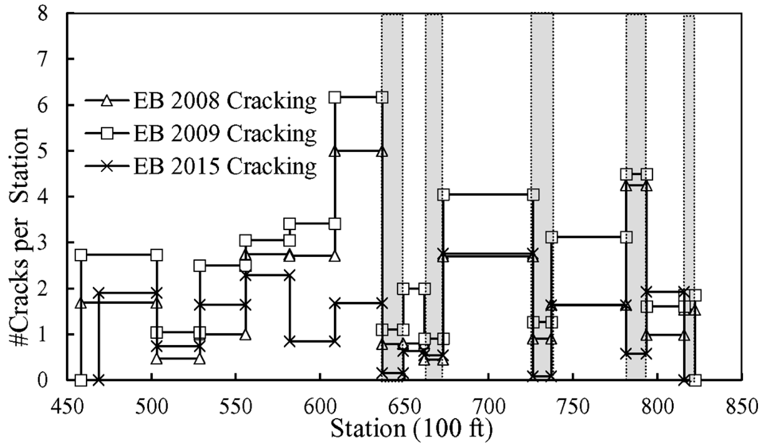


Figure 5 Westbound cracking plot (100 ft = 30.5 m)

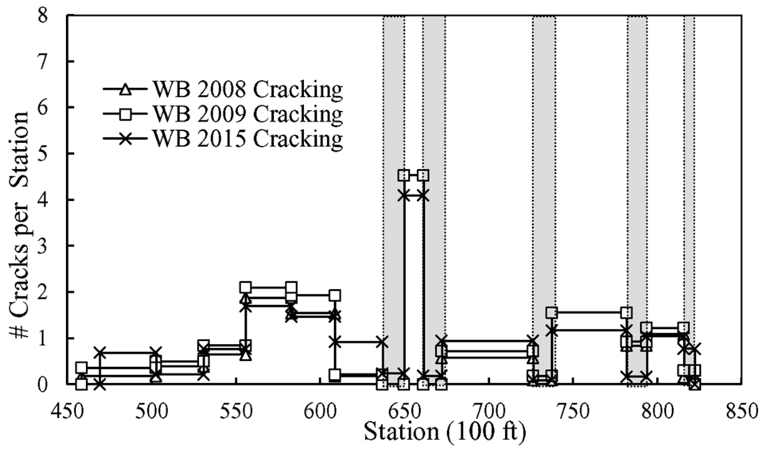


Table 2 presents major distresses identified on MAD-70 based on distress survey and visual assessment. A PCR history table provided by ODOT was also used to confirm the distresses. Primary and contributing factors were listed below based on the distress types and causes table in NCHRP Report 747 (Rada et al., 2013). The possible causes were listed based on NCHRP tables as well as the research team's judgement.

3 Falling weight deflectometer (FWD) test

The FWD measurements were conducted to evaluate pavement conditions. Deflections and LTE were obtained from testing. LTE is defined as the degree to which adjacent slabs move together (Alavi et al., 2008). It indicates the pavement's ability to transfer loads across the joints and is calculated by LTE = $D_{\text{unloaded}}/D_{\text{loaded}} \times 100\%$, where D_{unloaded} represents the deflection of the unloaded PCC slab, and D_{loaded} represents the deflection of the loaded PCC slab (Pierce et al., 2003). Factors affecting the LTE include support material, pavement temperature, aggregate interlock and presence of dowel bars (Sargand et al., 2002).

Table 2 Major distresses identified on MAD-70 and possible causes

Major distress	*Primary factors*	*Contributing factors*	*Possible causes*
Transverse cracking	Design; Load; Construction	Temperature; Materials	Loss of support; fatigue; curling and warping; dowel misalignment; poor construction practices; freeze-thaw and moisture-related settlement; materials related problem; high volumes of heavy traffic; poor drainage
Corner break	Load	Design; Water; Temperature	
Slab settlement	N/A	Design; Load; Water; Construction	
Faulting	Design; Load; Water	Temperature; Materials	

3.1 Pre-investigation FWD results

The FWD measurements were conducted along the entire length of the MAD-70 project in 2009 and 2014. The FWD loads were applied every 200 ft (61 m) to 500 ft (152 m) at these locations on the slab: joint approach, joint leave, and mid-slab. This way, a representative sample of pavement response along the whole section was measured. The results gave a general idea of the response of the tested section and were used to identify areas with the worst performance for further investigation. Figures 6–9 present normalised joint deflections (NDf1) and LTE results for eastbound and westbound directions. Shaded areas are full-depth concrete pavement sections. Findings from these graphs are summarised below:

- Full-depth sections (shaded in the graphs) have higher joint deflections than UBCO sections. This can be explained by the fact that UBCO has old concrete pavement as a base, which is much stiffer than aggregate base in the full-depth repairs.
- Comparing eastbound direction with westbound direction, eastbound direction has higher and more variable joint deflections. LTE of eastbound direction is lower and more variable than westbound direction. Comparing data of 2014 with those of 2009, joint deflections increased by a small percentage while LTE dropped significantly from 2009. Note the joints tested in 2014 were not necessarily the same ones tested in 2009, however.

3.2 Results of FWD testing on selected sections

On the basis of the results of earlier FWD, IRI, and distress survey, the worst performing section of the overlay was selected for more testing. A control section, the best performing in terms of deflection, IRI, and distress, was selected for comparison. The selected distressed section consisted of 26 slabs of total length 390 ft (119 m) ranging from eastbound Station 765+86 to Station 769+76, or interstate mile markers 84.97–85.05. This section included several distress types representative of the deteriorated eastbound direction. The selected control section is in the westbound direction. It included 14 slabs of total length 210 ft (64 m) from Station 610+50 to Station 608+40, or interstate mile markers 82.03–81.99. The locations of both selected sections are shown in Figure 2. The distress map of the selected sections are shown in Figure 12. FWD testing was conducted on the selected sections on August 19, 2015.

Figure 10 shows the LTE results of selected test sections. LTE is generally poor on the distressed section. Most joints have LTE less than 70% and greater variation joint to joint; in some joints the LTE less than 20%. This indicates the dowels are ineffective. The control joints showed satisfactory LTE; only one joint had LTE at 70% or less. The temperatures during testing are 77°F (25°C) in distressed section (EB) and 88°F (31°C) in control section (WB), which are relatively high and slab expansion would have tended to lead to joint interlock, which would improve LTE, thus the joints with low LTE would be expected to have even lower LTE at lower temperatures.

Figure 6 MAD-70 eastbound normalised joint deflections (1 mil/kip = 5.71 mm/MN, 100 ft = 30.5 m)

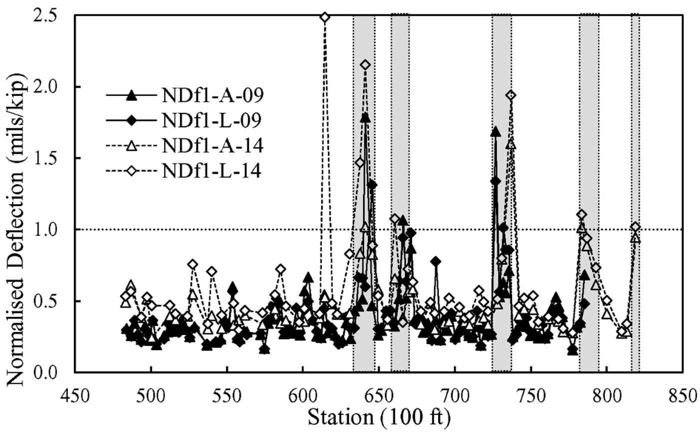


Figure 11 shows the normalised deflection results of the selected sections. The distressed section showed high normalised joint deflections, as great as 3.7 mil/kip (21 mm/MN), with high variation from joint to joint. Deflections on the joint leave position are relatively higher than the joint approach position. The control section showed small and uniform normalised joint deflections, most below 0.25 mil/kip (1.43 mm/MN).

Figure 7 MAD-70 westbound normalised joint deflections (1 mil/kip = 5.71 mm/MN, 100 ft = 30.5 m)

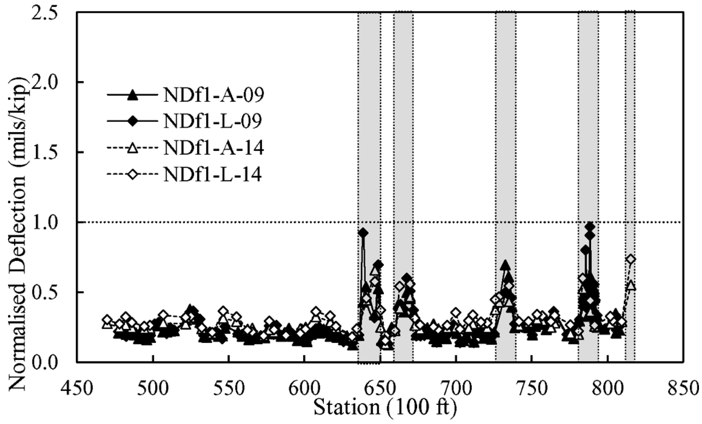


Figure 8 MAD-70 eastbound LTE (100 ft = 30.5 m)

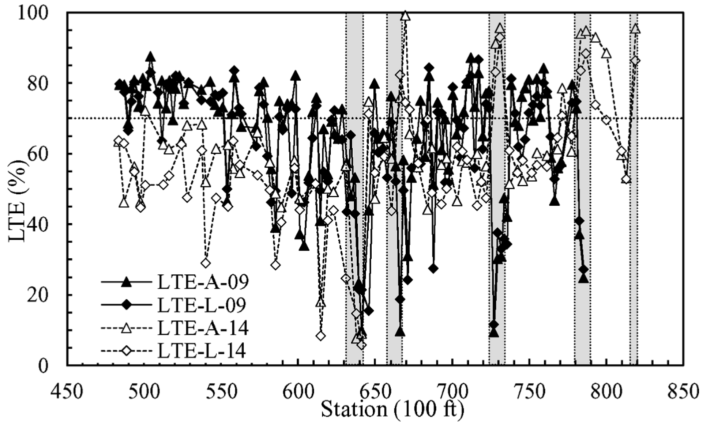


Figure 9 MAD-70 westbound LTE (100 ft = 30.5 m)

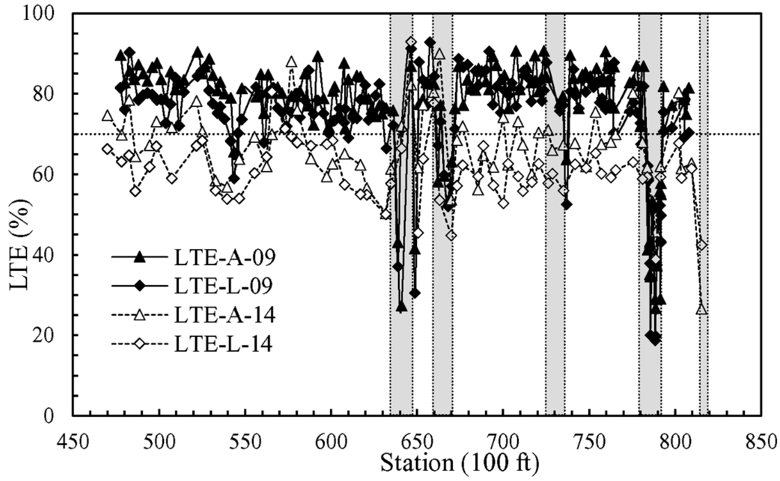
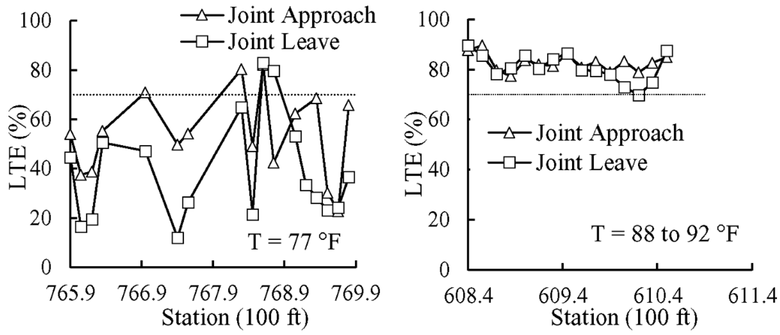
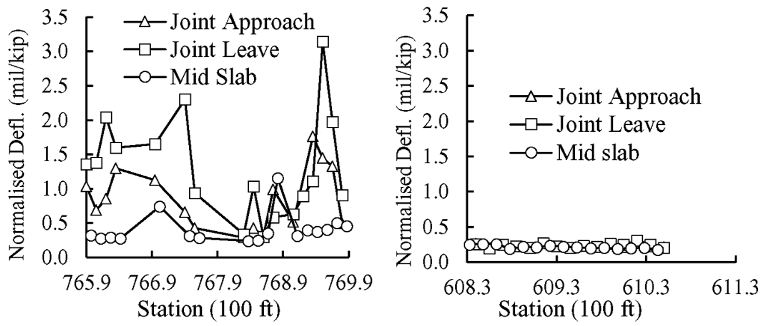


Figure 10 (a) Distressed section (EB) LTE and (b) control section (WB) LTE (100 ft = 30.5 m) (T = pavement surface temperature)



(a) (b)

Figure 11 (a) Distressed section (EB) normalised deflections and (b) control section (WB) normalised deflections (1 mil/kip = 5.71 mm/MN, 100 ft = 30.5 m)



(a) (b)

4 PCC coring and laboratory testing

In total 36 cores were collected from the MAD-70 selected sections on August 19, 2015 at locations marked in the coring plan and distress map in Figure 12. Cores were generally collected near cracks or corner breaks on the distressed section. On the control section, cores were generally taken from mid-slab or near joints. On each test section, an intact slab was identified and five cores were collected transversely across the middle of the slab.

During coring, water drained very slowly from the core holes on both sections, indicating a lack of drainage for water entering the pavement through the joints. It is possible this water saturated the asphalt bondbreaker near joints and cracks.

In the distressed section (EB), bondbreaker was soft or missing in areas with angled cracks and corner breaks. Seven of the 19 core holes on the distressed section have no bondbreaker material or only deteriorated pieces. Five of these core holes are located next to or near the joints. Tenting was found in a failed joint and was beginning in a joint that looked good from the surface. A core hole adjacent to a corner break revealed a small gap between the bondbreaker and the overlay slab.

In the control section (WB), bondbreaker was found in all core holes, including those at joints, and at an average thickness of 1.9 in (48 mm), 46% thicker than in the eastbound direction, which averaged 1.3 in (33 mm). Only one joint had bondbreaker that was damaged but in the hole the bondbreaker felt solid. Only two joints out of 15 showed any signs of distress. The worst one was cored. The core collected in the wheel path fell apart. A core on the transverse joint broke and showed signs of tenting. A core was collected at a small crack which verified the presence of top down cracking.

Figure 12 Distress map and coring plan on MAD-70 (numbered joints were scanned by MIT Scanner)

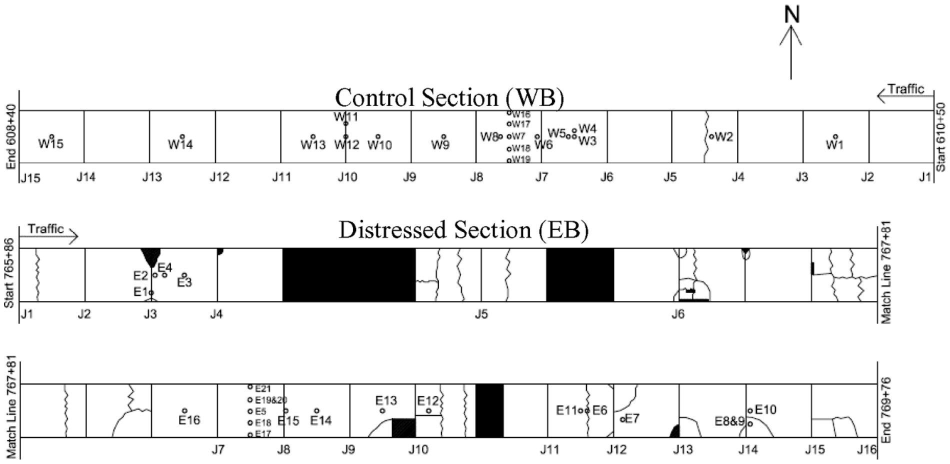


Table 3 summarises the thickness measurements on the collected cores. Only intact cores were measured and recorded. The average thickness of PCC overlay is 9.3 in (236 mm) on distressed section (EB) and 9.0 in (229 mm) on control section (WB). The average thickness of AC bondbreaker is 1.3 in (33 mm) on distressed section (EB), which is thinner than the 1.9 in (48 mm) on the control section (WB). This reduced thickness potentially made the eastbound bondbreaker more susceptible to pumping damage, which led to decreased structural support under the slabs and led to transverse cracking, faulting, and corner breaks. Tables 4 and 5 present the summary of lab testing results of collected PCC cores. Tests included compressive strength, splitting tensile test, elastic modulus, Poisson's ratio and coefficient of thermal expansion (CTE). With the exception of elastic modulus, test values met or exceeded ODOT specifications or design values. The design value of elastic modulus is 5.0 million psi (34 GPa). Tested core E12 has an elastic modulus of 2.8 million psi (19 GPa), which is 44% below design value. Tested core W14 has an elastic modulus of 4.4 million psi (30 GPa), which is about 12% below design value. However, testing error could not be excluded since there is only one sample tested on each direction.

Ten cores were sent off for a petrographic analysis. A summary of findings and remarks from petrographic analysis team are presented below:

- Concrete from both directions was found to be well cured. Air void content and spacing factor were generally acceptable. Infilling of the air voids with Ettringite and Friedel's salt deposits were frequently found in almost all tested cores. Top-down cracking was observed.

Table 3 Thickness of PCC and AC bondbreaker

		PCC overlay thickness			*No.*	*Bondbreaker thickness*			*No.*
Direction	*Units*	*Max.*	*Min.*	*Avg.*	*cores*	*Max.*	*Min.*	*Avg.*	*cores*
EB	(in)	10.1	8.7	9.3	19	2	0.8	1.3	14
	(mm)	257	221	236		51	20	33	
WB	(in)	9.2	8.8	9.0	17	2.2	1.5	1.9	18
	(mm)	234	224	229		56	38	48	

Table 4 Lab testing summary of distressed section (EB) cores

	Compressive strength (f'c)		*Tensile strength*		*Elastic modulus (E)*		*Poisson's ratio υ*	*CTE (α)*	
Core	psi	MPa	psi	MPa	10^6 psi	GPa	–	10^{-6}/°F	10^{-6}/°C
E7	8710	60.05							
E8	8950	61.71							
E12	7360	50.75			2.8	19.31	0.22		
E10			701	4.83					
E13			635	4.38					
E14			625	4.31					
E16								4.11	7.40
Avg.	8340	57.50	655	4.52	2.8	19.31	0.22	4.11	7.40

Table 5 Lab testing summary of control section (WB) cores

	Compressive strength (f'c)		*Tensile strength*		*Elastic modulus (E)*		*Poisson's ratio υ*	*CTE (α)*	
Core	psi	MPa	psi	MPa	10^6 psi	GPa	–	10^{-6}/°F	10^{-6}/°C
W1	10,920	75.29							
W2	10,580	72.95							
W14	9450	65.16			4.41	30.41	0.15		
W5			565	3.90					
W9			745	5.14					
W13			845	5.83					
W15								4.31	7.76
Avg.	10,310	71.08	720	4.96	4.41	30.41	0.15	4.31	7.76

5 MIT Scan and slab removal

MIT Scan-2 is a state-of-the-art nondestructive testing device for measuring and recording the position and alignment of dowel bars (Yu and Khazanovich, 2005). The MIT Scan was performed on selected sections on August 19, 2015. Figure 13 shows the locations of scanned joints (labelled e.g., 'J1', 'J2', etc.). In total, 16 joints were scanned in the eastbound direction of MAD-70; 15 joints in the westbound direction. Many states have adopted the Federal Highway Administration (FHWA) recommended limits for horizontal and vertical alignment (rotation) of ¼ in (6.4 mm) over 12 in (305 mm) or 2% (FHWA, 1990). Table 6 presents the dowel bar tolerances adopted by ODOT. The distribution of dowel misalignment is presented in Table 7. It can be seen from the table that alignment in the control section (WB) is generally better than in the distressed section (EB). For example, dowel bar misalignment by vertical rotation in the distressed section was 20.2% over 0.7 in (18 mm) compared to 4.1% for the control section. However, misalignment in depth translation and in horizontal translation were both highly prevalent. For horizontal translation, only 10.8% of dowels met the acceptance criterion in the control section, while in the distressed section the acceptance rate was a mere 1.9%, and 85.7% met or exceeded the rejection criterion.

Some deteriorated joints and slabs on MAD-70 were repaired on April and September 2015. During the repair work on September 15, 2015, the Ohio University research team was on site to document the condition underneath the overlay slabs. Observations made during slab removal include:

- Excessive water was found trapped in the asphalt bondbreaker layer at multiple locations. Some bondbreaker material was soft and deteriorated. Tenting distress was found at some joints.
- There was no evidence the joints or cracks in the underlying concrete pavement were reflecting into the unbonded overlay. The underlying concrete pavement base appeared to be complete and smooth.

Figure 13 Plan view of FE model (1 in = 25.4 mm, 1 ft = 0.305 m)

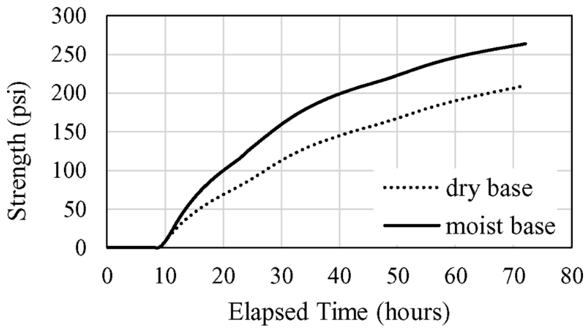


Table 6 Dowel bar tolerances in ODOT specifications

Alignment parameter	*Acceptance tolerance D1* (in.)	*Rejection criteria D2* (in.)
Horizontal translation	±0.50	±2
Longitudinal translation	±2.0	±2.30
Depth translation	±0.50	±0.66
Horizontal rotation	±0.50	±0.70
Vertical rotation	±0.50	±0.70

Source: Ohio Department of Transportation (2013)

Table 7 Distribution of dowel misalignment in selected I-70 sections

Section	*Type of misalignment*	$\lvert d \rvert < D1$ (%)	$D1 < \lvert d \rvert \leq D2$ (%)	$\lvert d \rvert > D2$ (%)	*# Bars*
Control (WB)	Horizontal rotation	98.6	1.4	0.0	148
	Vertical rotation	89.2	6.8	4.1	148
	Depth translation	60.1	23.0	16.9	148
	Longitudinal translation	93.2	6.1	0.7	148
	Horizontal translation	10.8	36.5	52.7	148
Distressed (EB)	Horizontal rotation	91.3	1.9	6.8	161
	Vertical rotation	57.1	13.7	29.2	161
	Depth translation	57.1	8.7	34.2	161
	Longitudinal translation	89.4	3.7	6.8	161
	Horizontal translation	1.9	12.4	85.7	161

6 HIPERPAV analysis

HIPERPAV is a simulation tool for the analysis of early-age (first 72 hours after construction) PCC pavement behaviour (Xu et al., 2009). It was first developed for the FHWA in 1996. The latest version is HIPERPAV III and was used to evaluate the early age performance of the PCC in MAD-70 UBCO sections. Table 8 presents the MAD-70 overlay PCC mix, which is Class C Option 3 concrete from ODOT specifications with Type D admixture. The aggregate type is limestone. The water to cementitious material ratio is 0.5. A single coat curing method was applied. Defaults were used for initial PCC mix temperature and initial support layer temperature. Weather data were estimated from three nearby weather stations in Columbus, Dayton, and Mansfield. High and low temperatures of each day of construction day were extracted from the construction diary and were used in the analysis. The construction dates as well as temperatures are presented in Table 9. The analysis results (pass/fail) are also presented in the table. An examination of pictures taken during construction indicated the bondbreaker was dry before placing the concrete overlay, contrary to ODOT specifications. All construction days passed the HIPERPAV analysis when constructed with moist base (wetting the asphalt bondbreaker before placing concrete), but 6 out of 17 days concrete failed prematurely when the concrete was placed on a dry base. Figure 14 shows predicted concrete strength development for the overlay placed on Aug-31-1999. It can be easily seen the concrete on moist base cured much faster than concrete on dry base. The tensile strength at 72 h is 263.4 psi (1.816 MPa) for concrete on moist base and 209.4 psi (1.444 MPa) for concrete on dry base, the latter being 20.5% lower. Based on the HIPERPAV analysis, it is obvious concrete on moist base cures much faster in the first 72 h and is less likely to crack.

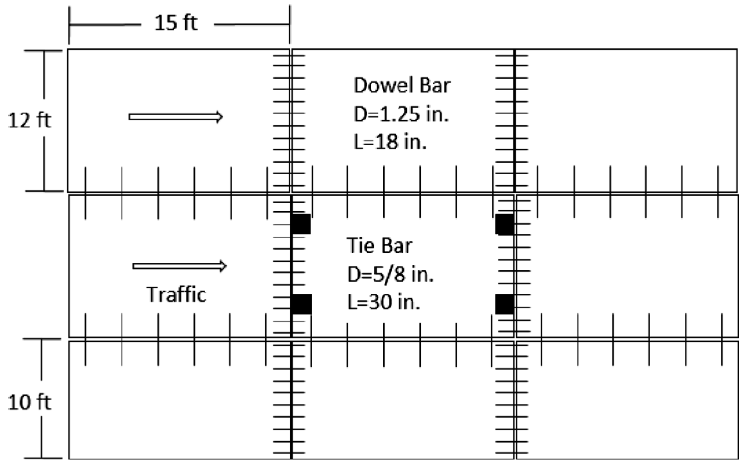
Table 8 ODOT class C, option 3 PCC mix design

Density unit	*Coarse aggregate*	*Fine aggregate*	*Cement (Type I)*	*Water*	*GGBF slag*	*Total*
(lb/yd^3)	1670	1310	385	275	165	3805
(kg/m^3)	991	777	228	163	98	2257

Table 9 HIPERPAV results of all construction days of MAD-70

			air temperature (°F)		*Pass the analysis* (*pass/fail*)	
Direction	*#*	*Date*	*Low*	*High*	*Moist base*	*Dry base*
EB	1	8/17/1999	70	92	pass	pass
	2	8/18/1999	68	87	pass	pass
	3	8/20/1999	64	84	pass	pass
	4	8/23/1999	63	86	pass	pass
	5	8/27/1999	67	87	pass	pass
	6	8/30/1999	58	76	pass	pass
	7	8/31/1999	56	81	pass	fail
	8	9/2/1999	61	84	pass	pass
WB	9	5/12/2000	60	87	pass	fail
	10	5/15/2000	55	72	pass	pass
	11	5/16/2000	49	65	pass	fail
	12	5/17/2000	52	72	pass	fail
	13	5/18/2000	44	64	pass	fail
	14	5/19/2000	47	63	pass	fail
	15	5/24/2000	58	72	pass	pass
	16	5/30/2000	59	79	pass	pass
	17	6/1/2000	63	85	pass	pass

Figure 14 Early stage strength development of PCC placed in Aug-31-1999



7 Finite element analysis

The general purpose three-dimensional finite element program ABAQUS was used to analyse the MAD-70 UBCO. Figure 13 shows the plan view of the model used in the analysis. The build-up of the model is the same as MAD-70 UBCO. 9 in jointed plain concrete pavement (JPCP) was overlaid on top of 9 in existing concrete pavement with 1 in asphalt bondbreaker. The original 304 base is 6 in. Table 10 presents the material properties used in this model. A nonlinear negative temperature gradient and a wheel load were applied to simulate the environmental and live loads on the pavement. Stress and deflection on the top surface of the middle slab was obtained and plotted along wheel path line and transverse mid-slab line.

A parametric analysis was conducted to evaluate the effect of loss of support under the joint as observed in the field. Loss of support was achieved by removing part of the asphalt bondbreaker under the transverse joint and truck load was applied on top of the joint to simulate the worst case scenario. It was found that the level of tension on the slab surface was significantly higher above the point of loss of support as well as in the middle of slab. The level of tension was even higher when the environmental and truck loads occurred in concert. Potential of transverse cracking is largely increased in this case and it matches the findings of the transverse cracks observed in the field. The effect of bondbreaker thickness was also evaluated and it was found that a thicker bondbreaker layer reduces stresses in the overlay slab under truck load. Readers are referred to the final report for the detailed analysis (Sargand et al., 2017).

Table 10 Material properties (English units were used in the FEA)

		E			*γ*		*α*	
Part	*Material*	(psi)	(MPa)	*ν*	(lb/in^3)	(kg/m^3)	(1/°F)	(1/°C)
Overlay/existing concrete	Concrete	4,000,000	27,579	0.15	0.087	2408	5.5E-6	9.9E-6
Bondbreaker	Asphalt	400,000	2758	0.3	0.085	2353	–	–
Base	Crushed stone	35,000	241	0.35	0.081	2242	–	–
Subgrade	Medium clay	5000	34	0.45	0.06	1661	–	–
Dowel and tie bars	Steel	29,000,000	199,948	0.3	–	–	–	–

8 Summary of findings

Key findings from forensic investigation of the overlay on MAD-70 are summarised below:

- Overall, westbound direction performed better than eastbound direction based on the distress survey and FWD results.
- The selected control section (WB) showed more consistency in measured properties, thickness, and dowel bar alignment than the distressed section (EB). This indicates better construction and material quality control in the westbound direction.

- During coring, water drained very slowly from the core holes in both sections, indicating a lack of drainage.
- Loss of support under the joints was observed in the field; bondbreaker was deteriorated or missing at the damaged joints.
- During slab removal, there was no indication the underlying cracks and joints in the original pavement had an effect on the location of cracking or deterioration in the UBCO.
- Laboratory tests results showed good material properties of concrete, except for elastic modulus of one eastbound core (E12) was fairly low.
- Thickness of bondbreaker in the control section (WB) is significantly greater than in the distressed section (EB).
- Tenting was observed in the concrete near the joints. It is likely a result of the formation of ettringite that moved into and filled the air voids in the concrete. The reduced air voids in the concrete resulted in cracking and reduced durability of the concrete. In addition, water would dissolve salt applied to the road surface for deicing and then accumulate underneath the slab because of the poor drainage. The dissolved salt penetrated into the concrete, further reducing air voids and causing concrete deterioration.
- The petrographic analysis showed the following:
  - concrete from both sections were found to be well cured
  - slag cement is good practice
  - freeze-thaw is potentially a cause of damage indicated by the low air voids due to infilling
  - top-down cracking was observed.
- Based on review of a photograph taken during construction, the asphalt bondbreaker was dry before the concrete overlay was placed. HIPERPAV analysis shows that mix design used in this project passed the analysis on all actual construction days when base is moist. But when base is dry, the curing is slowed and is more likely to fail in the first 72 hours.
- From the finite element analysis, it was found that:
  - when a loss of bondbreaker occurs under the joints, the slab is under great tension on the top surface when truck load and negative temperature gradient were applied together
  - a thicker bondbreaker layer reduces stresses in the overlay slab under truck load.

9 Conclusions and recommendations

The major contributions to distress came from the presence of water at the joints. This excess water was not able to drain, leading to negative impacts on both asphalt and concrete. The excess water was trapped in the thin layer of the bondbreaker. Traffic loads caused high pore water pressure, damaging the asphalt and causing loss of support under the overlay slab. This led to corner breaks, faulting, and in some places to mid-panel breaks, all of which were observed in the field.

It appears there were some mineral constituents in the concrete which migrated into the air voids. In the majority of petrographic specimens, the air voids are filled. There are two consequences: chemical deterioration that weakens the concrete, and the filled air voids will allow freeze-thaw process to crack the concrete. Tenting was observed in the concrete near the joints as a consequence. Also road salt applied during winter dissolved and migrated into the joints. Because of the lack of drainage, the salt is retained in the water and migrates into the concrete. Moreover, the petrographic analysis verified the concrete was well cured and the slag cement content was not an issue.

The westbound direction performed better than eastbound. The bondbreaker was thicker in the westbound side. A thinner bondbreaker is more susceptible to water damage when subjected to heavy truck traffic. A thicker bondbreaker could absorb a larger volume of water and provide volume for the water to migrate into when pressure is applied by a load, thus reducing the potential for early deterioration. Also, a thicker bondbreaker layer reduced the stress transmitted below more than a thin layer. The westbound direction also showed more consistency in measured properties, thickness, and dowel bar alignment, indicating better construction and material quality control.

The finite element analysis found the level of stress was significantly higher in zones where cracks were observed, particularly when the environmental and traffic loads occurred in concert. The finite element analysis also verified a thicker bondbreaker layer reduces stresses in the overlay slab under truck load.

Based on a review of photographs taken during construction, the asphalt bondbreaker was dry before the concrete overlay was placed. This probably had an impact on its strength. HIPERPAV results verified curing is slowed and more likely to fail when base is dry rather than wet as specified. However the PCC still had good strength in laboratory tests.

During slab removal, there was no indication the underlying cracks and joints in the original pavement had an effect on the location of cracking or the deterioration in the overlay.

Recommendations were made to ODOT. The lack of drainage resulted in the trapped water in the joints and under the UBCO, creating optimal conditions for premature distresses. This could be solved by draining the water using fabrics or permeable asphalt bondbreaker of sufficient thickness, 2 in (51 mm) or greater. In future UBCO projects ODOT should ensure specifications are adhered to and the bondbreaker layer is wetted before placing the concrete overlay. Lastly, Ohio is using slag cement and not sealing joints. There practices may continue, as both improve the performance of the concrete. Another recommendation based on the literature review is ODOT could consider pretreating the old concrete pavement before placing concrete overlay, using break-and-seat or rubblisation.

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