Bonded Whitetopping Overlay Design Considerations with Regard to the Prevention of Reflection Cracking, Joint Sealing and the use of Dowel Bars

A Paper Accepted by the Transportation Research Board for Publication

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Word count: 8253
Submission date: March 2010

Key Words: thin whitetopping, reflection cracking, concrete overlay, joint sealing, dowel bars.

ABSTRACT

Hundreds of bonded Portland cement concrete (PCC) overlays of hot mix asphalt (HMA) pavements are being constructed all over the United States and around the world. Increasing interest in this rehabilitation method has lead to a need to further define the most common forms of distresses, quantify the extent of influence of design parameters on performance and to develop rational design guidelines. The main focus of this study is to evaluate the performance of in-service pavements to establish criteria on when reflection cracks might develop. It is revealed that reflection cracking is dictated by the thickness of PCC overlay and HMA layer, panel size, climatic conditions, and by the accumulated vehicle loads. It has been found that when the stiffness of the PCC overlay relative and HMA layer (defined during the coldest month of the year) falls below the critical value 1, then reflection cracking develops. The rate of development is a function of the load-related stress in the overlay. The performance analysis of the in-service pavements also verified the benefits of joint sealing and the use of small diameter dowel bars for high volume roadway applications.

Word Count: 187

INTRODUCTION

Whitetopping refers to placing a thin concrete overlay directly on top of an existing distressed hot mix asphalt (HMA) pavement. The discussion here will focus on thinner Portland cement concrete (PCC) overlays, which require bonding to insure good performance. A bonded whitetopping is commonly referred to as a bonded concrete overlay over an HMA pavements but it will be referred to here as bonded whitetopping for brevity. For long-term performance, the thin concrete must bond to the underlying HMA so that the two layers respond in a monolithic manner, thereby reducing load-related stress. A short joint spacing is also used to help reduce curling/warping and bending stresses. Typical applications would include low to medium volume pavements where rutting, washboarding or shoving is present; such as intersections, bus stops, airport aprons, taxiways or parking lots *(1)*.

To gain more experience in both the design and performance of thin whitetopping, the Minnesota Department of Transportation (Mn/DOT) constructed a whitetopping project consisting of nine test sections on I-94 at the Minnesota Road Research facility (Mn/ROAD) *(2, 3)*. The objective here will be to use the performance data from these test sections to better understand when reflection cracking will develop. The effects of joint sealing and usage of dowel bars on the performance of bonded whitetopping will also be evaluated.

PROJECT DESCRIPTIONS

I-94 is a heavily trafficked roadway with over 1 million equivalent single-axle load (ESALs) per year (Average Daily Traffic [ADT] of approximately 25,000 with over 12 percent truck traffic). Low severity transverse cracks had developed every 4.8 m (15 ft) and approximately 6 mm (0.25 in) of rutting had developed in the right wheelpath of the driving lane. Although interstate roadways are not a typical application, it provided the opportunity to monitor the performance of the overlay under accelerated loading conditions and to evaluate bonded whitetopping as an overlay alternative for high volume roads. The first bonded whitetopping sections were constructed in October of 1997. This included test Cells 92 through 97. A description of each test cell is provided in Table 1. Of these, Cells 93, 94 and 95 began to deteriorate and were reconstructed in October 2004. The thin overlay was milled, the surface was swept and new bonded whitetopping sections were placed. The new cells were numbered 60 through 63 and the design details for these cells are also provided in Table 1.

PERFORMANCE ANALYSIS

A summary of the performance of these test sections is provided in Table 2. It can be seen that corner breaks, and to a lesser extent transverse cracks, were the predominate distress observed in these bonded whitetoppings. As the thickness and the panel size of the overlay is increased, corner breaks and transverse cracks no longer develop but longitudinal cracking is observed. More information in regards to the mechanisms behind the development of these distresses can be found elsewhere (*1-11*). The focus here will be on predicting the occurrence of reflection cracking in the bonded overlay and looking at the effects of joint sealing and the installment of dowel bars on the performance of the overlay.

Reflection Cracking

Reflection cracking is one of the distresses observed in bonded whitetoppings constructed in the northern regions of the United States as well as at Mn/ROAD. Pre-existing transverse cracks in the HMA were surveyed prior to the construction of the whitetopping test cells at Mn/ROAD.

This survey was used along with the distress data collected for each whitetopping section to identify the pre-existing cracks that reflected through the overlay. A reflection crack is shown in Figure 1. The crack in the asphalt shoulder in Figure 1 marks the location of a temperature crack that extended across both lanes in the existing HMA layer prior to the construction of the inlay. This crack propagated up through the concrete inlay in the driving lane during the first winter following construction and in the passing lane during the second winter following construction. Reflection cracking is a function of both uniform temperature- and load-related stress. The thermal contraction of the HMA in the winter creates a stress concentration at the bottom of the concrete in the region near the tip of the crack in the HMA. The magnitude of the tensile stress at the bottom of the concrete is then increased as a result of vehicle loads, thereby causing the crack in the underlying HMA to propagate up through the concrete overlay. The fact that these cracks develop during the winter and early spring and that they develop at a faster rate in the driving lane than the passing lane support the statement that reflection cracking is a function of both uniform temperature- and load-related stress.

Influence of Traffic, Overlay Thickness and Joint Spacing

A summary of the reflection cracking observed for the Mn/ROAD test sections constructed in 1997 is provided in Table 3. As of the spring of 2009, the 152-mm (6-in) overlays did not experience any reflection cracking. The last detailed distress survey for Cells 93 through 95 was performed in 2001 when the sections were about 4 years old and had carried approximately 3.7 million ESALs. The 76-mm (3-in), 102-mm (4-in) and 127-mm (5-in) thick overlays did exhibit reflection cracking. Reflection cracking typically occurred earlier in the driving lane than in the passing lane indicating the development of reflection cracks is influenced by the number of accumulated vehicle loads. Approximately 80 percent of the traffic travels in the driving lane at Mn/ROAD.

The combined effects of both the panel size and overlay thickness affect the development of reflection cracking. After 4 years of service, the section with the shortest joint spacing and the thinnest overlay (76-mm [3-in] overlay with 1.2-m x 1.2-m [4-ft x 4-ft] panel spacing) experienced the highest percentage of cracks reflecting through the overlay, while no cracking occurred in the thickest [152-mm (6-in)] overlay. The 102-mm (4-in) overlay with the same panel size (1.2-m x 1.2-m [4-ft x 4-ft]) had a slightly lower percentage, but this difference might not be statistically significant.

The 76-mm (3-in) section with larger panels (1.5-m x 1.8-m [5-ft x 6-ft]) had the lowest percentage of thermal cracks propagating through the overlay among the three designs that developed reflection cracking. Although decreasing the joint spacing decreases the bending and curling stresses, the performance of these test sections have shown the thicker [102-mm (4-in) vs. 76-mm (3-in)] slabs with shorter joint spacings [1.2-m x 1.2-m (4-ft x 4-ft) vs. 1.5-m x 1.8-m (5-ft x 6-ft)] exhibit more cracking. See Table 3. This is because the load-related stress is higher in thin overlays with 1.2-m x 1.2-m (4-ft x 4-ft) panels because the longitudinal joint lies in the wheelpath. It can be seen in Table 3 for Cells 93 through 95, that increasing the panel size to 1.5-m x 1.8-m (5-ft x 6-ft) from 1.2-m x 1.2-m (4-ft x 4-ft) provides an increase in performance equivalent to increasing the overlay thickness by 25 mm (1in). Some of this increase in performance might also be attributed to the polyolefin fibers used in the 76-mm (3-in) overlay with larger panels (1.5-m x 1.8-m [5-ft x 6-ft]) since polypropylene fibers were used in the cells with the shorter 1.2-m x 1.2-m (4-ft x 4-ft) panels. The increase in stress produced by the shorter joint spacing also resulted in higher reflection cracking. The load-related stress coupled with thermal stress generated during the colder months of the year work together to promote the reflection of cracks from the HMA into the overlay. This emphasizes the importance of keeping the longitudinal joints out of the wheelpath to help reduce the potential for reflection cracking as well as other types of cracking.

The effect of increasing both the overlay thickness and the panel size can be observed in the performance of Cells 60 through 63. The reflection cracking observed for Cells 60 through 63 after 4.5 years and 3.8 million ESALs is summarized in Table 4. This is about the same age and number of traffic loads accumulated as Cells 93 through 95 in 2001 when the detailed distress survey was performed so direct comparisons can be made. The distress surveys for Cells 60 through 63 show reflection cracks also developed for both 102-mm (4-in) and 127-mm (5-in) overlays with 1.5-m x 1.8-m (5-ft x 6-ft) panels. Cell 61 [(127-mm (5-in) overlays with 1.5-m x 1.8-m (5-ft x 6-ft) panels] had two transverse cracks that developed off from two separate existing crack in the HMA. Two transverse cracks developed off from the same existing transverse crack in the HMA in Cell 62 [(102-mm (4-in) overlays with 1.5-m x 1.8-m (5-ft x 6-ft) panels]. In Cell 63 [(102-mm (4-in) overlays with 1.5-m x 1.8-m (5-ft x 6-ft) panels], three transverse cracks developed off from two different transverse cracks in the HMA.

When comparing the performance of the 102-mm (4-in) overlays with the 1.2-m x 1.2-m (4-ft x 4-ft) panels and the 1.5-m x 1.8-m (5-ft x 6-ft) panels, increasing the panel size helped substantially in decreasing the reflection cracking. Less stress is generated by the passing truck traffic when the wheelpath can be moved further away from the longitudinal joint. Again, it can be seen that by reducing the load-related stress, the reflection cracking is decreased. It is interesting that the amount of reflection cracking in the 76-mm (3-in) overlay with 1.5-m x 1.8-m (5-ft x 6-ft) panels is comparable to that found in the 102-mm (4-in) overlay with 1.5-m x 1.8-m (5-ft x 6-ft) panels. Even though the panel size is the same, the slab thickness is 25-mm (1-in) less than the 102-mm (4-in) overlay. This equivalent performance might be attributed to a combination of the joints not being sealed in the 102-mm (4-in) overlay and the use of polyolefin fibers in the 76-mm (3-in) overlay since fibers have been shown to help increase the resistance to cracking *(7)*. Increasing the slab thickness in 102-mm (4-in) thick overlay with 1.5-m x 1.8-m (5-ft x 6-ft) panels by 25 mm (1 in) did help to decrease the reflection cracking, or at least the rate of its development.

Design Criteria

The stiffness of the HMA and the quality of the bond between the concrete overlay and the HMA has a significant effect on the performance of the overlay. Based on the performance of these sections at Mn/ROAD, it appears that reflection cracks are a function of the relative stiffness of the concrete and the underlying HMA layer as well as the accumulation of heavy traffic loads. The relative stiffness of the PCC and HMA layers can be determined using the equation given below.

$$D_{PCC/HMA} = \frac{E_{PCC} \times h_{PCC}^3}{E_{HMA} \times h_{HMA}^3}\left(\frac{1-\mu_{HMA}^2}{1-\mu_{PCC}^2}\right) \qquad \text{(i)}$$

where $D_{PCC/HMA}$ is the relative stiffness of the PCC and HMA layer; E_{PCC} and E_{HMA} are the elastic modulus of the concrete and resilient modulus of the HMA layer, respectively; h_{PCC} and h_{HMA} are the thickness of the PCC and HMA layer, respectively; μ_{PCC} and μ_{HMA} are the

Poisson's ratio of the PCC and HMA layer, respectively. Reflection cracks are anticipated to develop if the value of $D_{PCC/HMA}$ falls below 1 at a temperature measured on-site.

The performance data from the test sections at Mn/ROAD were used to further evaluate the relationship between this ratio and the potential for the development of reflection cracking. Temperatures ranging between 38 ^{o}C (100 ^{o}F) and -16 ^{o}C (4 °F) have been measured using thermocouples embedded in the middle of the HMA layer during the construction of the Mn/ROAD sections (6). This is based on temperature measurements made every 15 minutes throughout the life of the overlay. Cores taken from the Mn/ROAD sections were used to characterize the resilient modulus of the HMA layer as well as the temperature sensitivity. The relationship between the resilient modulus of the HMA layer and temperature can be found in Figure 2. The poison's ratio for the HMA layer is assumed to be 0.35. The elastic modulus and poison's ratio of the PCC was also measured for each cell and is summarized in Table 5.

Using equation 1, $D_{PCC/HMA}$ was calculated for each test section at Mn/ROAD for the range of temperatures measured in the middle of the HMA layer and is presented in Figure 3 and 4. All overlays less than 152 mm (6 in) exhibited a $D_{PCC/HMA}$ less than 1 at the lower HMA temperatures. The overlays with a $D_{PCC/HMA}$ less than 1 developed reflection cracks, with the exception of Cell 60. This helps to show that if the thickness of the HMA layer and/or the stiffness of the HMA during cold temperatures is sufficiently high then reflection cracks can and will develop. The critical value for this ratio appears to be 1, with reflection cracks developing when the flexural stiffness ratio falls below this value. The exception to this was Cell 60, which was just constructed in 2004. It is possible that Cell 60 still might exhibit reflection cracking at some point further into its service life.

This concept can be further evaluated using the distress data from another bonded whitetopping section constructed in Elk River, Minnesota. The advantage to this test section is that thin overlays were constructed on top of a thin layer of HMA that was of poor quality. This is contrary to the Mn/ROAD test sections that were constructed on a full-depth HMA pavement that was of good quality when the overlay was placed. The three different test sections were constructed along the approach to three consecutive intersections on US-169. The designs for these test sections are provided in Table 6. Comparing the pre-overlay distress survey to the distress surveys performed after the overlay had been in-service revealed none of the transverse joints or cracks in the HMA reflected into the overlay for any of the US-169 test sections. The same overlay thicknesses and joint patterns used on US-169 were also constructed on I-94. The difference in the performance can be attributed to the fact that the bonded whitetopping on US-169 was placed on 76 mm (3 in) of HMA exhibiting signs of raveling and the bonded whitetopping on I-94 was constructed on 178 mm (7 in) or more of quality HMA. This resulted in a higher bond strength and structural rigidity in the HMA layer producing higher tensile stresses at the bottom of the bonded whitetopping in the regions of the cracks in the HMA.

To further evaluate the previously established critical flexural stiffness ratio of 1, the relative stiffness of the PCC and HMA layer, $D_{PCC/HMA}$ for the US-169 test sections was determined. The stiffness of the HMA was conservatively assumed to be the same as that measured at Mn/ROAD even though it was of poorer quality and hence would have a lower stiffness. The flexural stiffness ratio was found to be greater than 1 for the range of possible HMA temperatures that could develop at the project site (Figure 5). This supports the fact that no reflection cracks should have developed. A summary of the $D_{PCC/HMA}$ determined for each of the sections is provided in Table 7. It can clearly be seen that when the $D_{PCC/HMA}$ is less than 1, reflection cracks will develop. Again, the only cell that did not exhibit reflection cracking while having a $D_{PCC/HMA}$ less than 1 was Cell 60 and this cell was just constructed in 2004. Therefore, it still might exhibit reflection cracking at some point further into its service life.

It should be noted that the cracks in the existing HMA layer for I-94 and US-169 were of lower severity without significant deterioration. The design criteria established above is only intended for HMA pavements with transverse cracks that are not severely deteriorated. As the crack deteriorates to the point that it is no longer a defined plane but a deteriorated area with a reduction in the HMA stiffness in the regions adjacent to the crack within this area, the relative stiffness design criteria no longer applies.

The presence of reflection cracks emphasizes the need to take extra precautions during construction to match up the transverse joints in the overlay with the exiting temperature cracks in the HMA when the potential for reflection cracking exists. Other preventions methods, such as placing a bond breaking material over the crack, have also proved to be successful in preventing reflection cracking at Mn/ROAD (*6*).

Joint Sealing

These thin bonded overlays rely on the underlying HMA to carry a portion of the load. The strain measurements made at these test sections just discussed emphasize the importance of the support provided by the HMA layer *(6).* A reduction in this support can occur when the temperature of the HMA is increased or when the HMA begins to ravel. The results from the strain measurements and the cores pulled from the test sections indicate the HMA ravels at a faster rate along the joints where there is greater access for water to enter the pavement structure. The lane shoulder joint is the most difficult to keep sealed and therefore the HMA along this joint was found to be more susceptible to stripping/raveling. Figure 6 shows raveling of the HMA layer supporting the bonded whitetopping. It is essential that water be kept out of the pavement structure to maintain the bond strength at the overlay/HMA interface and to prevent the loss of the structural support provided by the HMA due to stripping/raveling.

To further evaluate the effects of sealing on the performance of the bonded whitetopping, companion test sections were constructed for a 102-mm (4-in) overlay with 1.5-m x 1.8-m (5-ft x 6-ft) panels and a 127-mm (5-in) overlay with 1.5-m x 1.8-m (5-ft x 6-ft) panels with one section sealed and one section unsealed. Both transverse cracking and corner cracking can be the result of, or exacerbated by, water entering into the joints. This is because these distresses initiate at the edge of the panel where water can infiltrate due to unsealed or poorly sealed joints. Therefore, the transverse and corner cracking for these sections after just 4 years of service have been summarized in Table 2. The preliminary results indicate that even after just a short period of time, the benefits of joint sealing are starting to be revealed. The reason for this is evident by the photos taken shortly after it rained. See Figure 7. The photos clearly reveal the water on the pavement near the joints has drained into the joint while water puddles across the joints in the section that is sealed.

In other jointed concrete pavements, the effects of joint sealing might not be as evident. For bonded whitetopping, it is essential that water be kept from infiltrating the joints. This is critical in protecting the bond and the underlying HMA layer, both of which are essential to the long-term performance of the overlay. Based on these results, it is recommended that a 3-mm (1/8-in) to 7-mm (1/4-in) wide saw cut be made and that this saw cut be sealed with an asphalt sealant.

Dowel Bars

The benefit dowel bars provided in the performance of the bonded whitetopping sections at Mn/ROAD was also observed. In the Mn/ROAD whitetopping sections, only Cell 92 contained doweled joints. Cell 92 and Cell 97 are companion sections in that the designs are exactly the same but Cell 92 contains 25 mm (1-in) dowels. The faulting history for Cell 92 and 97, shown in Figure 8, indicates that the presence of dowel bars helps to reduce faulting in Cell 92. Whereas very little faulting is visible in Cell 92, Figure 9 clearly shows the presence of faulting in Cell 97. It should be noted that Cell 97 accumulated over 5 million ESALs before exhibiting faulting greater than 6 mm (0.25 in). For typical bonded whitetopping applications, this would meet or exceed a 20- or even 30-year design life. It does show the potential for using thin bonded whitetopping for high volume roadways to extend the performance of an HMA pavement 10 to 15 years and that only a small 25-mm (1-in) diameter dowel could drastically increase the performance of this overlay.

CONCLUSION

The distress data from the Mn/ROAD test sections on I-94 indicate that reflection cracking is a function of both temperature- and load-related stress. Typically, reflection cracks develop earlier in the driving lane than in the passing lane indicating that reflection cracking is influenced by the number of accumulated vehicle loads and that these cracks develop more quickly when the load-related stresses are higher or more frequent. The source of the increase in applied stress can also result from reducing the thickness of the concrete overlay or having longitudinal cracks in the wheelpath. The Mn/ROAD test sections have shown that increasing the panel size from 1.2-m x 1.2-m (4-ft x 4-ft) to 1.5-m x 1.8-m (5-ft x 6-ft) so that the wheelpath is moved away from the longitudinal joint had the same effectiveness in decreasing reflection cracking as increasing the thickness of the overlay by 25 mm (1 in). The interesting outcome of this analysis was to be able to verify that the occurrence of reflection cracking is a function of the stiffness of the concrete relative to that of the HMA layer. The performances of the I-94 Mn/ROAD and US-169 test cells indicated that reflection cracking will develop in bonded whitetopping if the relative stiffness of the layers falls below 1. The number of reflection cracks that will develop is a function of the factors affecting stress development due to external loads (such as, traffic, joint layout and slab thickness). Additional performance data from other locations should be used to help validate this concept as it becomes available.

The performance review of the I-94 project has verified that sealing the joints of thin bonded whitetopping will extend the life of the pavement. The sealant prevents the infiltration of water, which helps to insure a good bond is maintained between the PCC and the HMA and also helps to maintain the quality of the HMA. It is recommended that a 3-mm (1/8-in) to 7-mm (1/4-in) wide saw cut be made and that this saw cut be sealed with an asphalt sealant.

This study has also shown the positive effects of even small diameter dowels (25 mm [1in]) when expanding the thin bonded whitetopping application to higher volume roadways.

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LIST OF FIGURES

TABLE 1 Mn/ROAD Design Features

Cell	Age	Length (ft)	Thickness of PCC slab mm (in)	Slab size m x m (ft×ft)	Thickness of HMA layer mm (in)	Sealed joint (Y/N)	Dowel dia. mm (in)	Fiber type
92	Oct ‘97- Present	170	152 (6)	3x3.7 (10×12)	178 (7)	Y	25 (1)	Polypropylene
93	Oct ‘97- Oct 04	300	102 (4)	1.2 x1.2 (4×4)	229 (9)	Y	None	Polypropylene
94	Oct ‘97- Oct ‘04	300	76 (3)	1.2 x1.2 (4×4)	255 (10)	Y	None	Polypropylene
95	Oct ‘97- Oct ‘04	300	76 (3)	1.5x1.8 (5x6)	255 (10)	Y	None	Polyolefin
96	Oct ‘97- Present	180	152 (6)	1.5x1.8 (5x6)	178 (7)	Y	None	Polypropylene
97	Oct ‘97- Present	170	152 (6)	3x3.7 (10×12)	178 (7)	Y	None	Polypropylene
60	Oct ‘04- Present	220	127 (5)	1.5x1.8 (5x6)	178 (7)	Y	None	None
61	Oct ‘04- Present	220	127 (5)	1.5x1.8 (5x6)	178 (7)	N	None	None
62	Oct ‘04- Present	220	102 (4)	11.5x1.8 (5x6)	203 (8)	Y	None	None
63	Oct ‘04- Present	220	102 (4)	1.5x1.8 (5x6)	203 (8)	N	None	None

TABLE 2 Cracking Summary for Mn/ROAD Test Sections

Cell	Age (yrs)/ESALs	Corner		Transverse		Longitudinal		Panels cracked (%)		
		Driving lane	Passing lane	Driving lane	Passing lane	Driving lane	Passing lane	Driving lane	Passing lane	Total
93[2]	6.5/6.4 million	43	6	9	4	0	0	23[1]	4[1]	27
94[2]	6.5/6.4 million	391	84	8	8	0	0	94[1]	34[1]	64
95[2]	6.5/6.4 million	30	16	5	2	0	0	32[1]	16[1]	20
92	11.5/9.8 million	0	0	0	0	3	6	17	35	26
96	11.5/9.8 million	0	0	0	0	1	0	1	0	0
97	11.5/9.8 million	0	0	0	0	7	0	42	0	21
60	4.5/3.8 million	0	0	0	0	3	0	3	0	2
61	4.5/3.8 million	0	0	2	0	5	4	7	5	6
62	4.5/3.8 million	0	0	0	2[3]	0	0	1	1	1
63	4.5/3.8 million	7	1	3	0	8	5	15	8	11

[1]Panels repaired in 2001 are not included in the calculated percentage.
[2]Distress data provided by Burnham, 2005.
[3]Both cracks propagated off the same reflection crack.

TABLE 3 Summary of Transverse Reflection Cracking for Mn/ROAD Test Sections Constructed during 1997

Cell	Age (yrs)/ESALs	Thickness of PCC slab mm (in)	Slab size m x m (ft×ft)	Transverse cracks	Transverse cracks that are reflective (%)	HMA transverse cracks reflected (%)
93	4/3.7 million	102 (4)	1.2 x1.2 (4×4)	27	19	50
94	4/3.7 million	76 (3)	1.2 x1.2 (4×4)	19	47	56
95	4/3.7 million	76 (3)	1.5x1.8 (5x6)	4	100	32
92	11.5/9.8 million	152 (6)	3x3.7 (10×12)	0	0	0
96	11.5/9.8 million	152 (6)	1.5x1.8 (5x6)	0	0	0
97	11.5/9.8 million	152 (6)	3x3.7 (10×12)	0	0	0

TABLE 4 Summary of Transverse Reflection Cracking for Mn/ROAD Test Sections Constructed During 2004

Cell	Age (yrs)/ESALs	Thickness of PCC slab mm (in)	Slab size m x m (ft×ft)	Transverse cracks	Transverse cracks that are reflective (%)
60	4.5/3.8 million	127 (5)	1.5x1.8 (5x6)	0	0
61	4.5/3.8 million	127 (5)	1.5x1.8 (5x6)	2	100
62	4.5/3.8 million	102 (4)	1.5x1.8 (5x6)	2	100
63	4.5/3.8 million	102 (4)	1.5x1.8 (5x6)	3	100

TABLE 5 Hardened Concrete Properties for Mn/ROAD Test Sections Constructed during 1997 and 2004

Cell	92	93	94	95	96	97	60	61	62	63
Elastic Modulus, (MPa x10^4)	3.31	3.31	3.31	3.03	3.24	3.24	2.42	2.42	2.42	2.42
Poison's ratio	0.20	0.19	0.18	0.19	0.20	0.20	0.20	0.20	0.20	0.20

TABLE 6 Design Features and Hardened Concrete Properties for US-169 sections

Cell	Thickness of PCC slab mm (in)	Slab size m x m (ft×ft)	Thickness of HMA layer mm (in)	Sealed joint (Y/N)	Dowe-led (Y/N)	Fiber type	Elastic Modulus of PCC (MPa x 10^4)	Poison's Ratio of PCC
98	76 (3)	1.2x1.2 (4×4)	76 (3)	Y	N	Polypro-pylene	2.79	0.20
91	76 (3)	1.2x1.2 (4×4)	76 (3)	Y	N	Polyolefin	2.91	0.20
99	76 (3)	1.8x1.8 (6x6)	76 (3)	Y	N	Polypro-pylene	2.76	0.20

TABLE 7 $D_{PCC/HMA}$ for I-94 and US -169

Cell	Thickness of PCC slab mm (in)	Slab size m x m (ft×ft)	Thickness of HMA layer mm (in)	Sealed joint (Y/N)	Fiber type	Flexural stiffness ratio at -16° C ($D_{PCC/HMA}$)	Reflection cracking observed (Y/N)
92	152 (6)	3x3.7 (10×12)	178 (7)	Y	Polypropylene	1.76	N
93	102 (4)	1.2 x1.2 (4×4)	229 (9)	Y	Polypropylene	0.24	Y
94	76 (3)	1.2 x1.2 (4×4)	255 (10)	Y	Polypropylene	0.08	Y
95	76 (3)	1.5x1.8 (5x6)	255 (10)	Y	Polyolefin	0.07	Y
96	152 (6)	1.5x1.8 (5x6)	178 (7)	Y	Polypropylene	1.73	N
97	152 (6)	3x3.7 (10×12)	178 (7)	Y	Polypropylene	1.73	N
60	127 (5)	1.5x1.8 (5x6)	178 (7)	Y	None	0.75	N
61	127 (5)	1.5x1.8 (5x6)	178 (7)	N	None	0.75	Y
62	102 (4)	1.5x1.8 (5x6)	203 (8)	Y	None	0.26	Y
63	102 (4)	1.5x1.8 (5x6)	203 (8)	N	None	0.26	Y
98	76 (3)	1.2x1.2 (4×4)	76 (3)	Y	Polypropylene	2.36	N
91	76 (3)	1.2x1.2 (4×4)	76 (3)	Y	Polyolefin	2.47	N
99	76 (3)	1.8x1.8 (6x6)	76 (3)	Y	Polypropylene	2.34	N

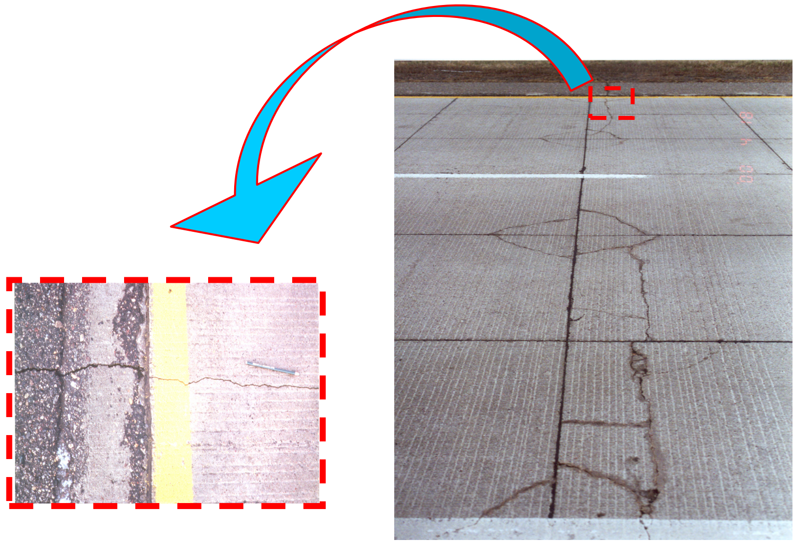

FIGURE 1 Reflection cracking thin bonded whitetopping.

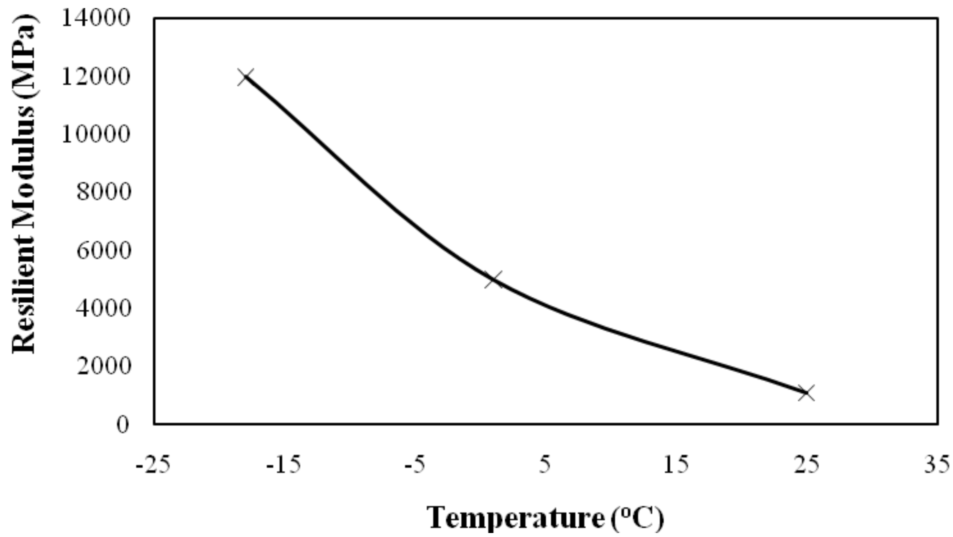

FIGURE 2 Resilient modulus of HMA layer at Mn/ROAD.

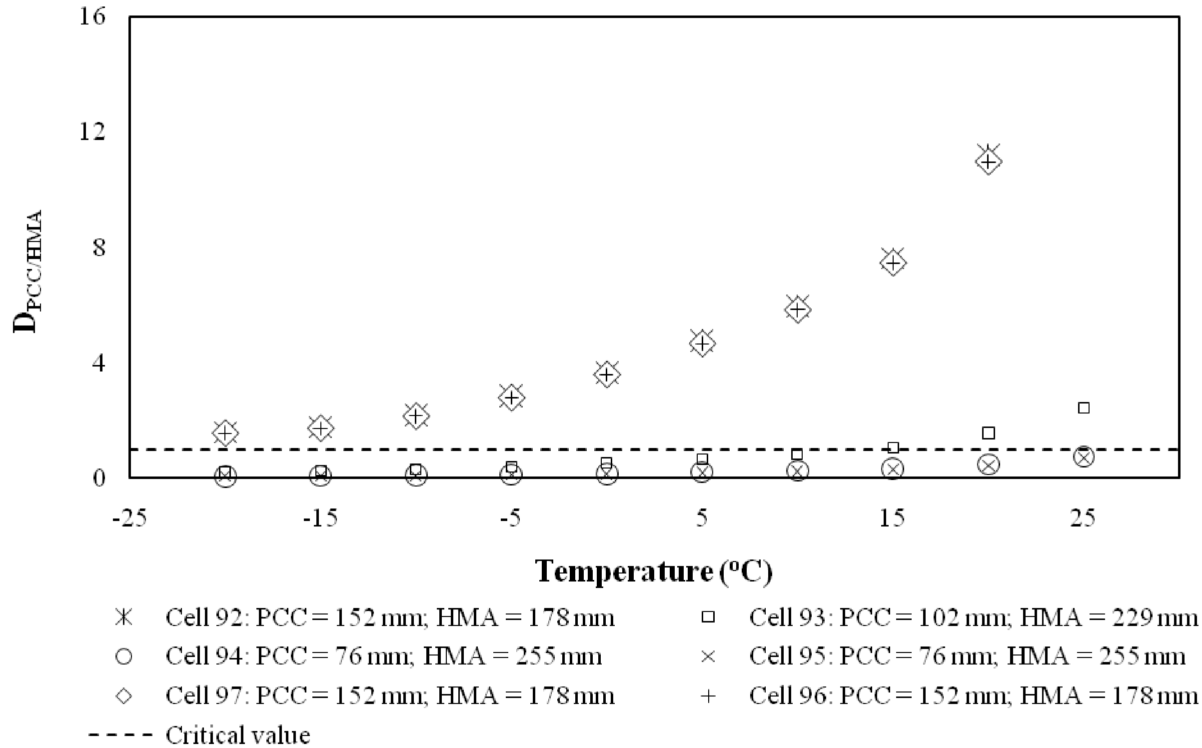

FIGURE 3 Relative stiffness of PCC and HMA layers for Cells 92 through 97.

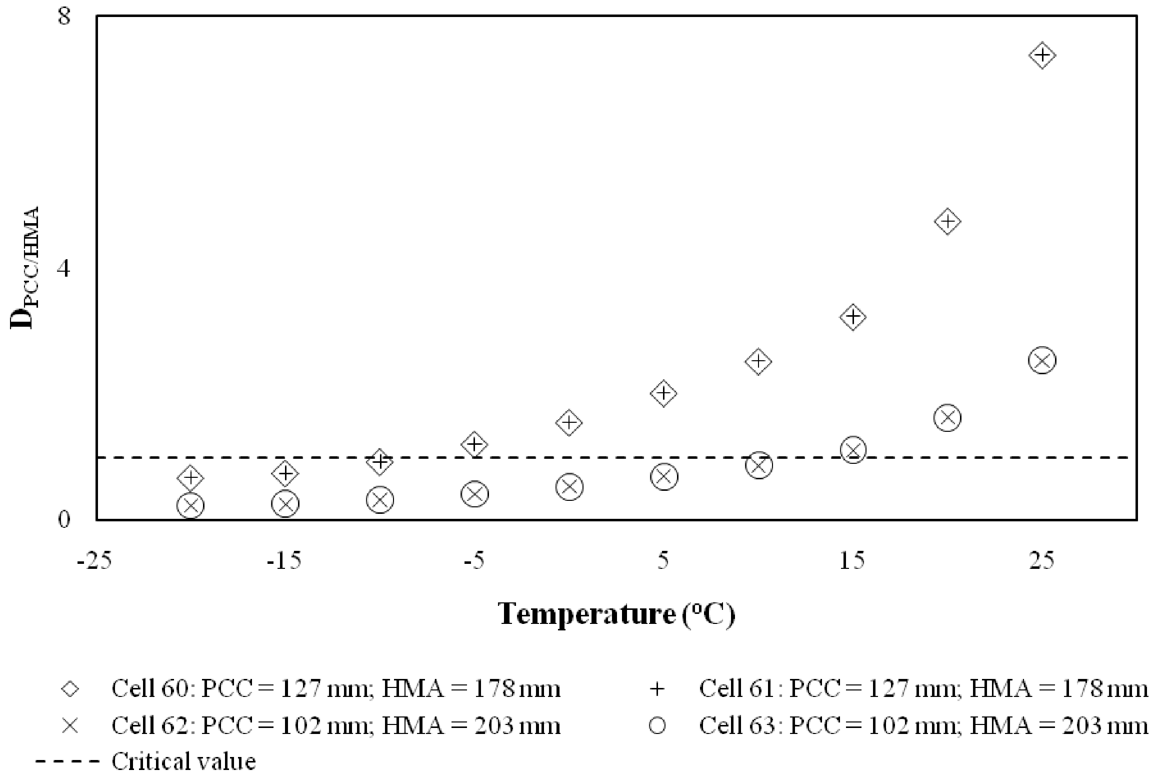

FIGURE 4 Relative stiffness of PCC and HMA layers for Cells 60 through 63.

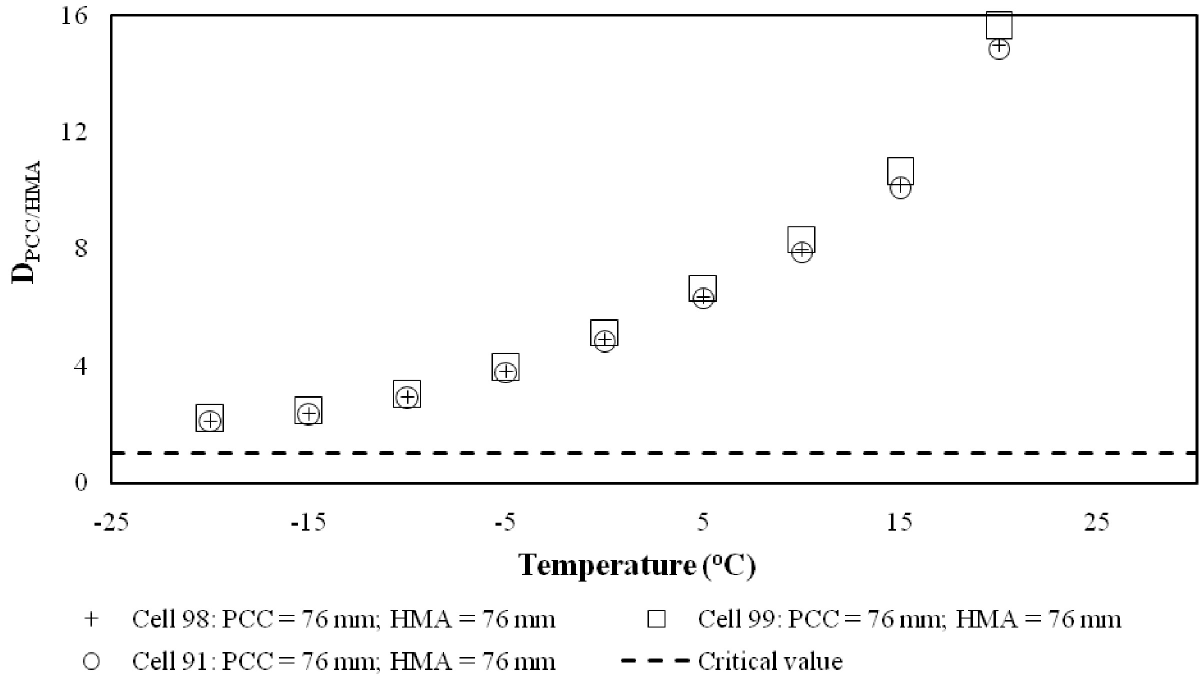

FIGURE 5 Relative stiffness of PCC and HMA layer for US-169 test sections.

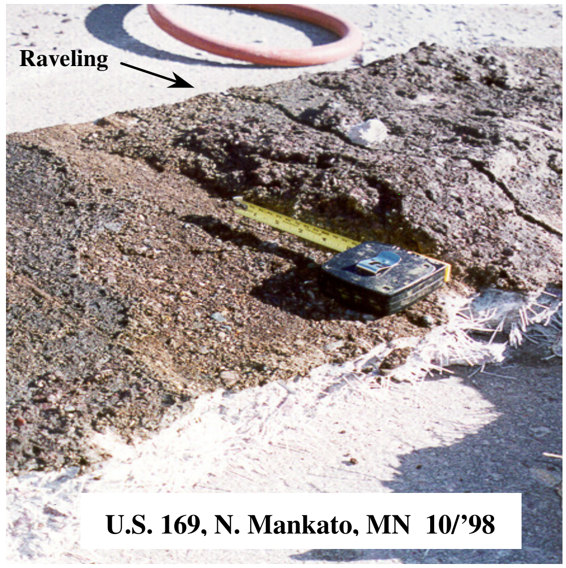

FIGURE 6 Three different modes of debonding between the HMA and concrete overlay.

FIGURE 7 Companion test sections with sealed and unsealed joints.

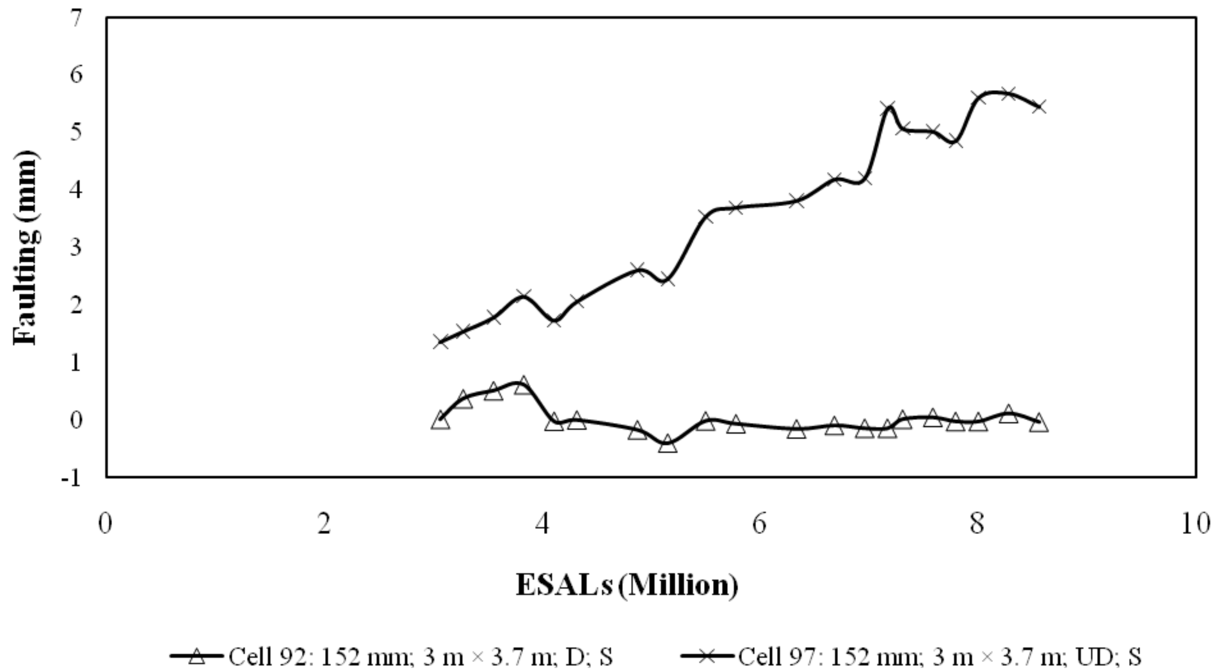

FIGURE 8 Faulting history for Cells 92 and 97.

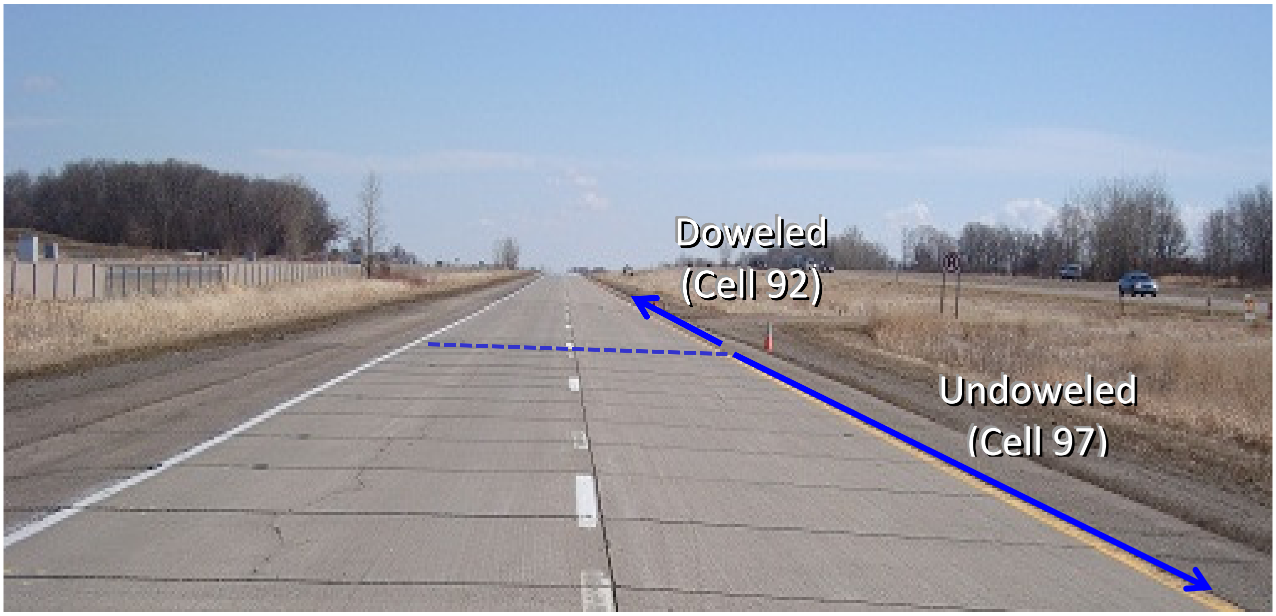

FIGURE 9 Visible faulting for the undoweled Cell 97.