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Predicting the Occurrence of Bumps in Overlays

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16. Abstract (Limit: 250 words)

This report presents the results of two field evaluations in rural Minnesota counties to investigate the development of bumps in asphalt overlays. The primary objective was to identify crack sealant types, reservoir geometries, and construction methods that provide a higher probability of avoiding the occurrence of bumps in an asphalt overlay. One field site evaluated various crack sealant methods and materials while holding construction methods constant, and the other site evaluated different construction practiced intended to prevent bumps while utilizing constant crack sealant methods and materials, as well as other overlay preparation methods.

The results of this research indicate that there are specific types of sealant materials and methods (type of sealant, reservoir geometry) as well as specific construction activities (rolling pattern, roller type, mat temperature at rolling) that can have great impact on the formation (and prevention) of bumps in asphalt overlays.

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Final Report

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John Brunkhorst, McLeod County engineer
Mike Flaagan, Pennington County engineer
Art Bolland, materials engineer, Mn/DOT District 8
Roger Olson, Mn/DOT Office of Materials
James McGraw, Mn/DOT Office of Materials

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EXECUTIVE SUMMARY

This report describes the work completed by a joint effort between Minnesota State University, Mankato, and the Office of Materials and Road Research of the Minnesota Department of Transportation on the occurrence of bumps in asphalt overlays. This project is a continuation of the original bumps-in-overlays project (LRRB INV-802) completed in 2005.

In many cases the occurrence of bumps in overlays can be directly related to sealant type and/or reservoir geometry. More often the cause is related to rolling techniques (type of rollers, vibratory or static, temperature at which various stages of compaction are conducted, etc.). A summary of the observations and recommended actions to reduce the likelihood of bumps includes the following.

- Lower air and pavement temperatures (below 80 and 125°F, respectively)
- Low-modulus and crumb rubber sealant type
- Narrow and shallow crack reservoirs
- Pneumatic rollers for breakdown compaction through 200°F followed by steel finishing rollers
- Non-vibratory breakdown rollers

It is important to note that each of the effects summarized above was in some way correlated with the formation or prevention of bumps in overlays, but that these findings are not absolute, and are included here as recommendations, or a "starting point" from which to determine the best course of action in a bump mitigation strategy. These and other recommendations in this report are added to the updated *Common Practices for Avoiding Bumps in Overlays* booklet prepared under the INV-802 project. It is also important to consider all aspects of overlay construction and performance such as density, ride, and others when determining the best method for eliminating or preventing bumps in overlays.

In developing these recommendations, the project established two test sites for observation of the performance of various crack sealant and construction methods. The first site consisted of 19 sections with varying crack preparation methods (reservoir geometry and sealant materials) and maintained constant construction methods. The second site consisted of several sections with varying construction methods (when overlay bumps began occurring) with a single sealant material and reservoir geometry. After establishing the test sites (sealant materials and methods in Jackson County, and construction methods in Lincoln County, Minnesota) the overlay construction was observed for the development of bumps in the new overlays, and the overlays were then monitored for a period of two years.

Chapter 1. INTRODUCTION

This report describes the continuation of development of a set of guidelines for preventing and mitigating the occurrence of bumps that are often observed immediately after construction of bituminous overlays. The research effort described in this report was funded by the Minnesota Local Road Research Board.

Background

This project was a continuation of the original "Bumps in Overlays" project (LRRB INV- 802). As in the initial project, a joint effort between Minnesota State University, Mankato, and the Office of Materials of the Minnesota Department of Transportation was conducted. The project INV-802 was intended to investigate the hypotheses suggested as the cause of bumps in overlays – specifically the thermal expansion of crack sealant material which was suspected to push the hot asphalt layer upward, forming a bump. The project team determined that the thermal expansion of the crack sealant is likely not the cause of bumping, but found many other theories that try to explain the bump phenomenon. During the course of the project, the team addressed several of these theories while continuing in the original objectives of the research.

This project included a more comprehensive plan to identify the major contributors in the bump development problem, and was intended to identify, more explicitly, methods for predicting them and mitigating their effects.

Investigation 802 included a survey of counties and cities for their experiences with the bumps issue, and received 22 responses. Four test sites were established for instrumentation of sealed cracks during HMA overlay. Laboratory testing was conducted on new and existing material to determine thermal expansion properties and softening points of over a dozen materials.

The research described in this report is a continuation of the previous study, with the addition of construction site observation and instrumentation for specific materials and construction methods that are suspected in the formation of bumps in overlays. One site installation (CSAH 5 in Jackson County, Minnesota) evaluated the effects of crack sealant type and reservoir geometry on bump formation. At this site, the construction methods were held constant. The second set of construction sites was at various locations in Lincoln County, Minnesota. At these sites there was only one set of crack sealant and reservoir geometry, but various construction methods were used to mitigate the formation of bumps in overlays.

Objectives

The primary objective of this project was to identify crack sealant types, reservoir geometries, and construction methods that provide a higher probability of avoiding the occurrence of bumps in an asphalt overlay. A secondary objective was to update the manual of practice for avoiding and mitigating bumps which was developed initially in the INV-802 project.

Technical Advisory Panel

The technical advisory panel consists of members representing county highway departments and the Minnesota Department of Transportation. The list of panel members includes:

- County representatives
  John Brunkhorst, McLeod County Engineer
  Mike Flaagan, Pennington County Engineer
- Mn/DOT representatives
  Art Bolland, Materials Engineer, Mn/DOT District 8
  Roger Olson, Mn/DOT Office of Materials
  James McGraw, Mn/DOT Office of Materials
- Project representatives
  James Wilde, Minnesota State University, Mankato
  Ed Johnson, Mn/DOT Office of Materials

Content of the Report

This report is organized into several chapters, addressing the following topics.

- Identification and establishment of test sites
- Construction and observations
- Site monitoring
- Conclusions and Recommendations

Literature Review

Much of the information used in this project is taken from the final report for the INV-802 project. The test sections defined in this chapter are based on the results of the common practices learned from pavement engineers and technical staff at the municipal, county, and state levels. In addition, a very few other states have conducted similar studies, and some equipment and product manufacturers have investigated the problem of bumps in overlays. The following paragraphs are synopses of research reports, product literature, and project reports with information that is valuable to the current study.

"Performance and Selection of Pavement Crack Sealant under Nevada Conditions and Before Overlays"

The state of Neveda conducted a research effort to evaluate several problems with crack sealing in the state. One objective of the research was to evaluate crack sealant regarding their probability in causing the overlay bumps that have been observed in Minnesota. The research also attempted to determine to what extent the thermal expansion of crack sealants affects the formation of bumps, and to evaluate the long-term effects of those crack sealants that do not cause the bumps.

"Bump Formation and Prevention in Asphalt Concrete Overlays," Vern Thompson, Central Region Sales Manager presented at the Colorado Asphalt Pavement Association's Asphalt Industry Forum Technical Meeting, 9 December 2005.

Mr. Vern Thompson presented additional "best practices" that have been used successfully in the prevention of bumps in overlays. Some of the practices included in his presentation that were not included in the LRRB INV-802 final report include modification of rolling patterns and slowing rollers when bumps form.

"Occurrence of Bumps in Overlays," Minnesota Local Road Research Board, Wilde, W. James and W. Zerfas, LRRB Report No. 2005-28, Minnesota Department of Transportation, St. Paul, Minnesota, July 2005.
As part of LRRB project 802, a survey of common practices was made of city, county, and state engineers involved in bituminous pavements. From this survey and the entire 802 project, many practices for compiled that have been used successfully by those engineers surveyed. The information was compiled and presented in booklet form to be used by field engineers, paving contractors, and other involved in the bituminous overlay process where a potential for overlay bumps is present.

"Overlay Bump Investigation," North Carolina Department of Transportation Memorandum, Thomas M. Hearne, 2004.
In 2004, Mr. Tom Hearne investigated overlay bumps related to crack sealants in several projects in North Carolina. This memorandum describes a small investigation into the physical properties of crack sealants used in the particular construction projects. The investigation addressed the temperature effects on these properties, and addressed several of the same theories as the INV-802 project, but to a lesser extent. It is interesting to note, however, that the small investigation conducted in North Carolina confirms some of the conclusions made in that report. The memo listed several factors "thought to enhance the formation of bumps". These include wide transverse cracks, deep sealant reservoir, incompressible material directly under sealant, fine-graded low-stability asphalt mix rich in asphalt cement, and rolling too soon after placement. Many of these factors are addressed in the common practices guidelines in Appendix A.

"Crack Seal Application," Pavement Preservation Checklist Series, Publication No. FHWA-IF-02-005, Federal Highway Administration, Washington, DC, 2001.
This small pocket guide mentions bumps in overlays as a problem and provides potential solutions. Such solutions include sealing at least one year prior to overlay placement, using a stiffer tack coat, proper selection of rollers, and minimizing the amount of crack sealant material at the surface.

Johnson, A.M., "Best Practices Handbook on Asphalt Pavement Maintenance," Report No. MN/RC-2000-04, Minnesota Department of Transportation, St. Paul, 2000.
This report presents background information on pavement maintenance techniques and the importance of preventive maintenance in a pavement preservation program. It highlights the distinction between preventive maintenance and rehabilitation, and stays within the realm of maintenance. In the section on crack treatments, it describes the difference between crack sealing and filling, and discusses the materials and methods appropriate for each. In a table entitled "Effective Crack Sealing Tips" the report makes mention of the potential problem with bumps in overlays, the report states: "Crack sealing is recommended 6-12 months prior to an overlay. To eliminate bumps in overlays caused by too much sealant or roller slippage, use proper sealant application procedures and roller techniques."

"Bumps In Overlays Don't Have To Happen," Crafco Incorporated, Chandler, AZ, 1995.
This article is an informational paper on Crafco's recommended policy on preventing bumps during an overlay. It mentions two potential causes – too much sealant expands as it warms, and compaction equipment slips over the sealant material. It provides some precautionary steps to

avoid the problem, including: minimize overbanding, rout cracks when sealing them, place crack sealant slightly below the surface of the pavement, avoid vibratory rollers on the first pass, and place clean, dry concrete sand over any squeegeed sealant. The article also suggests conducting crack sealing 6 – 12 months prior to an overlay.

Belangie, M.C., and D.I. Anderson, "Evaluation of Flexible Pavement Crack Sealing Methods Used in Utah," UDOT-MR-81-1, Utah Department of Transportation, Salt Lake City, 1981.
This report details an evaluation of various crack sealants used in Utah. The evaluation found that routing and sealing cracks and presawing (sawing and sealing) were the most promising methods for the conditions present in their evaluation at that time.

Tons, E., and V.J. Roggeveen, "Laboratory Testing of Materials for Sealing Cracks in Bituminous Concrete Pavements," Highway Research Abstracts, Vol. 25, No. 8, Highway Research Board, Washington, DC, 1955.
While it is recognized that much technological advance has been made since this paper was published in 1955, most of the results of this research are applicable today, including that crack sealants should not change their properties in hot weather, and that the sealant should not extrude from the crack or become tacky on its exposed surface during periods of high temperature. This paper mentions the possibility for thermal expansion of the crack sealant, and states that this is an undesirable property of the material.

"Use of Crack Sealing Prior to Placement of Hot Mix Asphalt, Flexible Pavements of Ohio," Technical Bulletin, Columbus, OH, undated.
This article, published by the asphalt industry as an aid in preventing overlay bumps, addresses many of the common theories considered to be the cause of the bumps. It mentions HMA sliding on the crack sealant, the difference in the melting point of the materials, and friction between the two materials. It suggests the following as potential contributory factors: amount of overbanding, amount of sealant, age of sealant, thermal expansion of the sealant, thickness of the overlay (also a preventive factor), and direction of travel of the compaction equipment. The article mentions thicker overlays, polymer-modified asphalt, fabrics and interlayers, and saw and seal operations as treatments for preventing the bumps. If crack sealing is done, the article recommends that it be done at least one year prior to the overlay, and that excessive crack sealing should be avoided. The article also gives recommendations specific to Ohio specifications and sealant types, regarding when different types should be used.

"Bump Formation and Prevention in Asphalt Concrete Overlays which have been Crack Sealed," Crafco, Inc., Chandler, AZ, 2003.
This article is the most direct treatment of the bump problem of all the literature found in this review. It describes the method of bump formation, describes factors in the formation of the bumps, and proposes methods to avoid the formation of bumps. As factors in the development of the bumps, the article mentions mixtures with high frictional properties, higher mix temperatures, roller speed and pattern, number of roller passes, type of roller, and stiffness of tack coat.

Chapter 2. Test Site Identification and Establishment

This chapter describes the identification of potential test sites, and the establishment of those sites (test location layout and other efforts). This chapter is divided into several sections, describing activities including

- Objectives for each test site
- Selection and location of test sites
- Test matrix development
- Site establishment and pre-overlay activities
- Other observations

Since the project started later in the construction season than anticipated, observation sites were not selected in time to prepare the materials prior to the end of the construction season in 2006. The project team decided that the sites could be selected and prepared at the beginning of the construction season in the summer of 2007. Thus, for the sealant materials and methods test site, the sealant materials were installed at the site early in the season, and the construction activities occurred late in the season.

Test Sections – Objectives

Two test sites were established, observed and monitored during this research project. The first site evaluated various crack sealant materials and methods (the "sealant site"), while holding construction methods constant. The second site used a single type of sealant and sealing method, while varying construction methods (the "methods site"). The following sections describe the basic objectives of each section that was observed.

Sealant Materials and Methods

The sealant site consisted of 19 sections that are each approximately 250 feet long, for a total of about 4,750 feet in length. The sealants were installed early in the construction season in 2007, on a project that was subsequently overlaid late in the same construction season. The primary objective of this site was to evaluate the effect that various crack sealant materials (hot-poured, crumb rubber, elastic, extra-low modulus, etc.) and various sealant reservoirs (routed, not routed, wide and shallow, narrow and deep, etc.) have on the probability of the development of bumps curing overlay construction.

Construction Methods

The methods site was less rigidly established, since the construction methods that were performed could only be done once bumps had begun to occur. The project team utilized GPS and more traditional location methods of paint and rolling wheels to indicate the beginning and ending points of the various construction methods.

Selection and Location of Test Sites

This section describes the selection and the location of the test sites that were established for this project. Table 1 is a summary of the basic attributes of the sealant site at Jackson County CSAH 5 and the three methods sites in Lincoln County which will be discussed in this section. Each of these sections received a single-lift bituminous overlay on bituminous pavement. The section number in the far right column will be used throughout this report to identify the test sections.

Table 1. Selected Test Site Locations.

County	Highway	Road Description	Section / Contractor
Jackson	CSAH 5	1 mile, 2-lane, low volume, North-South	Many subsections / one contractor
Lincoln	CSAH 5	2-mile, 2-lane, low volume, North-South	2 / A
	CSAH 15	2-mile, 2-lane, low volume, East-West	1 / A
		1-mile, 2-lane, low volume, East-West	3 (part 1) / B
		1-mile, 2-lane, low volume, East-West	3 (part 2) / B
		1000-ft, 2-lane low volume, East-West	4 / B

Sealant Materials and Methods

The sealant test site was located on CSAH 5 in Jackson County, Minnesota, shown in Figure 1 and Figure 2. The north end of the test section is at about 0.5 mile south of its intersection with CSAH 34 and extends to the south for about 5,500 feet. The project site was longer than the anticipated 4,750 feet due to the exclusion of some sections within the project limits for excessive pavement distresses, or pavement distresses that were significantly different than the other segments. The project team contacted Mr. Tim Stahl, Jackson County Engineer regarding the site. Mr. Stahl was fully supportive of the project and the test site. The sealants were installed early in June 2007 and the section was overlaid at the end of September 2007.

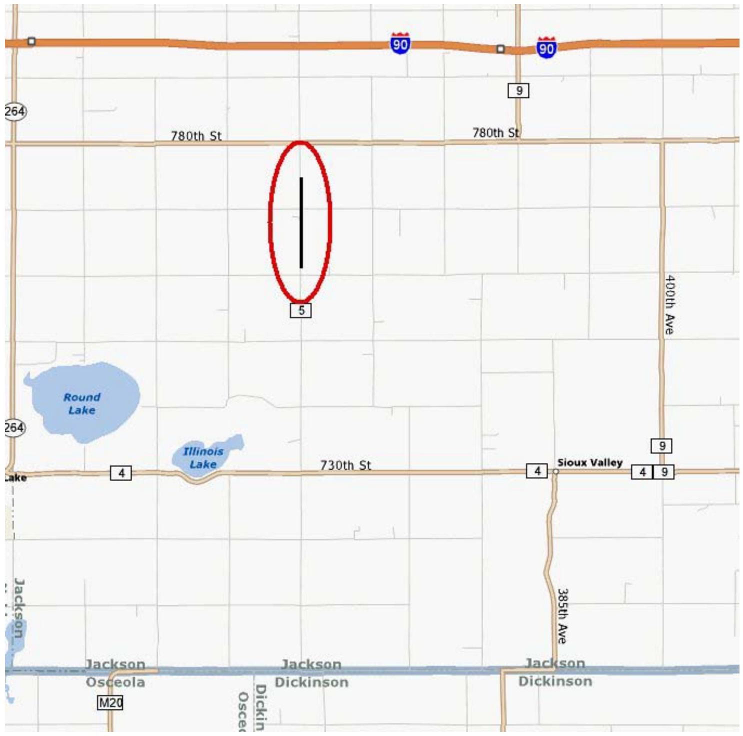


Figure 1. Map of Sealant Site Area – Jackson County.

Figure 2. Aerial View of Sealant Site Area – Jackson County.

Construction Methods

The methods site was divided into three overlay projects near each other in Lincoln County, Minnesota. These projects were located on CSAH 5 and CSAH 15. Figure 3 and Figure 4 show a map and aerial view of the general areas where the project team has established sites. It was determined that it would be advantageous to conduct observations of several overlay projects to increase the probability of observing bumps and to increase the effectiveness of the preventive methods discussed in this report.

Lincoln CSAH 15 runs east to west and is located five miles south of Ivanhoe, Minnesota, at the intersection with US 75. The 2007 construction included seven miles between CSAH 1 and US 75, and 4 miles between CSAH 7 and the Lyon County line. Lincoln CSAH 5 runs north to south and is located one mile east of Ivanhoe, Minnesota, at the intersection with MN 19. The 2007 construction included five miles between MN 19 and CSAH 15. The following test sections were established for the methods site.

Lincoln County CSAH 5

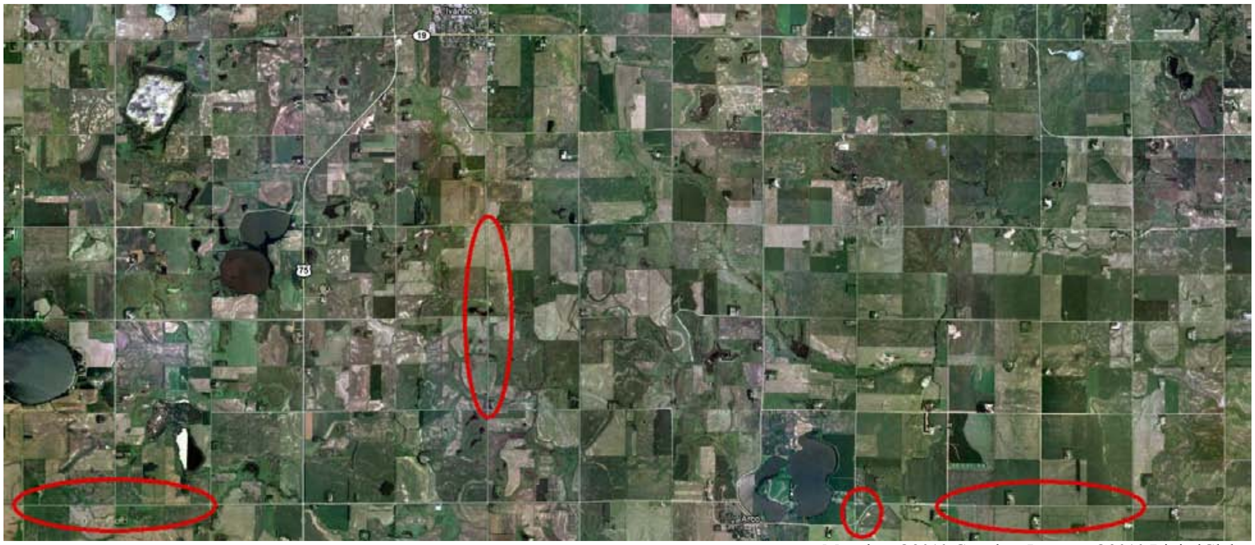
- Section 2, bounded by 240th Street and 260th Street (two miles long)

Lincoln County CSAH 15

- Section 1, bounded by 160th and 180th Avenues (two miles long)
- Section 3, bounded by 260th Avenue and 280th Avenue (two miles long, with profile data collected in one-mile segments)
- Section 4, east of CSAH 7 along the curve in the northwest quarter section (1,030 feet long)

Map data ©2010 Google

Figure 3. Map of Methods Site Area – Lincoln County.



Map data ©2010 Google – Imagery ©2010 DigitalGlobe

Figure 4. Aerial View of Methods Site Area – Lincoln County.

During the overlay construction at each of these sites, the project team was only able to observe the construction and watch for the bumps to occur. Once several significant bumps had formed, the various construction methods were implemented at various intervals. The use of two projects and two different contractors enabled the researchers to observe different construction methods in these segments. For the tight-blade portion of the test site, observations were made at other construction sites where the tight-blade operation had already been performed.

Test Matrix Development

With the test locations selected, a matrix of testing parameters was developed for each site. The sealant site included three sealant materials (and one control type – no sealant at all). This site also included six types of crack geometry and preparation (routing, saw and seal, overband, and the control – no routing at all). The methods site included a pre-overlay leveling treatment for deteriorated transverse cracks.

Sealant Materials and Methods

The materials and methods that were implemented in this site are described below. Each segment was assigned a sealant material and a reservoir geometry. All sealant materials conformed to Mn/DOT specification 3719, 3723, or 3725, for hot-poured crumb rubber, hot-poured elastic, and hot-poured extra-low modulus elastic materials, respectively.

Four sealant types

a. Mn/DOT 3719 (hot-poured, crumb rubber)
b. Mn/DOT 3723 (hot-poured, elastic)
c. Mn/DOT 3725 (hot-poured, extra-low modulus, elastic)
d. No sealant

The following crack preparation methods, or reservoir geometries were used. In addition, one section was established at which no treatment at all was established prior to the overlay.

Six preparation methods

a. Not routed, normal overband (up to 3 inches)
b. Routed ¾"x ¾", with normal overband
c. Routed ¾"x ¾", with no overband
d. Routed 1"x ¾", with sealant up to ¼" below the surface
e. Routed 1-½ " wide x ½" deep, with normal overband
f. Saw and seal

Other sections

1 control section with no treatment

Table 2 shows the combinations of sealant types and methods with approximately 250-ft segments.

Table 2. Sealant Type and Reservoir Geometry Combinations for Sealant Test Site.

Combination Number	Beginning station	Ending Station	Combination	Length, ft
1	0+00	2+70	3719, Not routed	270
2	2+70	5+00	3719, 3/4 x 3/4 inch	230
3	5+00	7+50	3719, 3/4 x 3/4 inch - no overband	250
4	7+50	10+00	3719, 1" wide x 3/4" deep	250
5	10+00	13+25	3719, 1-1/2" wide x 1/2" deep	325
6	13+25	15+75	3719, Saw and Seal	250
7	15+75	18+25	3723, Not routed	250
8	18+25	20+75	3723, 3/4 x 3/4 inch	250
9	20+75	24+00	3723, 3/4 x 3/4 inch - no overband	325
10	24+00	27+50	3723, 1" wide x 3/4" deep	350
11	27+50	30+50	3723, 1-1/2" wide x 1/2" deep	300
12	30+50	33+50	3723, Saw and Seal	300
13	33+50	36+10	3725, Not routed	260
14	36+10	37+50	Not used - major patching	140
15	37+50	40+00	3725, 3/4 x 3/4 inch	250
16	40+00	43+50	3725, 3/4 x 3/4 inch - no overband	350
17	43+50	46+00	3725, 1" wide x 3/4" deep	250
18	46+00	48+50	3725, 1-1/2" wide x 1/2" deep	250
19	48+50	51+00	3725, Saw and Seal	250
20	51+00	52+50	Not Used	150
21	52+50	55+00	No treatment	250

Construction Methods

The construction methods planned at the site included the following.

- Let the surface cool to about 225°F
- Change roller operation so that the lead drum is static and in drive mode.
- Slower roller speed
- Stiff tack coat
- Tight-blade leveling

As mentioned, the methods planned at the methods site were dependent upon the formation of bumps in the overlays, and as such, their use was not as consistent as in the sealant site.

Chapter 3. CONSTRUCTION AND OBSERVATIONS

This chapter includes discussion of the initial observations of the test sites and the activities during and immediately after construction of the overlays. The primary objectives of this effort were to install the sealant materials and to map the existing cracks at both test sites prior to overlay construction. This chapter also presents the observations of the project staff during construction of the overlays at each test site.

This chapter also includes identification of and quantification of bumps occurring immediately after construction. The monitoring conducted and reported in Chapter 4 also includes tracking the performance of both the construction related bumps and the overlay above any cracks that did not form bumps for a period of up to one year after construction.

Pre-Construction Observations

This section discusses the pre-overlay preparation and observations of the test sites, and a description of the pre-construction activity performed at each site. Pre-overlay condition surveys and existing pavement profiles were conducted at both sites, and the matrix of sealant types and reservoir geometries was established at the sealant site.

Sealant Materials and Methods

Early in the 2007 construction season, the existing cracks on Jackson County CSAH 5 were surveyed to provide a detailed map of the cracks prior to the overlay construction. In addition, the sections determined in the previous chapter were marked in preparation for the pre-overlay sealants that would be applied.

As described previously, a total of 19 test segments were established on this roadway. Each of the reservoir geometries was combined with each of the sealant materials. The segments were established with at least 10 cracks each. The initial layout was conducted using a measuring wheel, and by marking the extents of each segment with paint on the road surface and marked stakes in the fore slope of the ditch. The beginning of each section was marked with the type of sealant, the reservoir geometry, and the segment number. Figure 5 and Figure 6 show samples of the layout marking methods. The stakes in the ditch included the most information, since it would not be covered during the overlay construction. The markings in the roadway included only enough information to guide the crack sealant crew during the preparation phase of the project.

Figure 5. Stake Marking Segment Beginning.

Figure 6. Segment Markings on Roadway.

The location of individual cracks within each of the 19 segments was measured in two ways – a rough location by rolling measuring wheel and a precise location by high-resolution GPS. The precise crack survey, including the path of meandering cracks, was performed by the Jackson County Highway Department's GPS crew. A sample of the results of the precise crack location survey is shown in Figure 7.

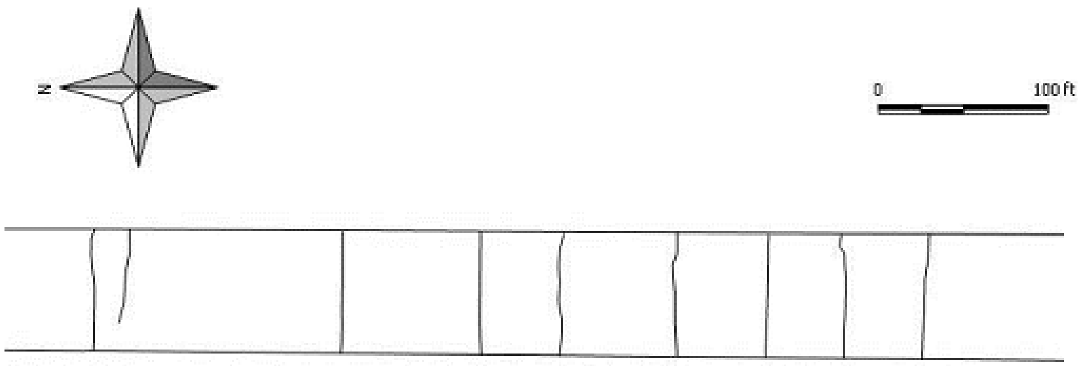


Figure 7. Sample of GPS-Based Crack Survey on Jackson County CSAH 5.

After the initial preparation of the sealant site, including the location of the segments, the sealants were installed by a crack sealing contractor. The cracks, which had been previously located by GPS, were sealed on 5 June 2007, according to the plan presented in Table 2. In July 2007, the project staff conducted a pre-construction assessment of the sealed cracks in the test site area of Jackson County CSAH 5. This assessment included visual observations of the crack sealants themselves, as well as pavement profile measurements at various locations throughout the project site.

Table 3. Jackson CSAH 5 Lightweight Profiler Surveys.

Direction	Lane, run	Average IRI (in/mi)	Length, feet	Length, miles
Northbound	Left, 1	80.6	5,836	1.105
	Left, 2	78.8	5,837	1.105
	Left, 3	78.4	5,837	1.105
	Average, NB left wheel path	***79.3***	***5,836.7***	***1.105***
	Right, 1	110.0	5,840	1.106
	Right, 2	140.2	5,838	1.106
	Right, 3	147.0	5,836	1.105
	Average, NB right wheel path	***132.4***	***5,838.0***	***1.106***
Southbound	Left, 1	81.0	5,838	1.106
	Left, 2	83.6	5,837	1.105
	Left, 3	82.7	5,837	1.105
	Average, SB left wheel path	***82.4***	***5,837.3***	***1.106***
	Right, 1	112.2	5,842	1.106
	Right, 2	138.5	5,841	1.106
	Right, 3	139.0	5,840	1.106
	Average, SB right wheel path	***129.9***	***5,841.0***	***1.106***

Note: The average variability in test section length as measured by the lightweight profiler was 0.03% and 0.02% for northbound and southbound lanes.

The project staff measured the pavement profile using a lightweight profiler. Profile data were collected in left and right wheel paths in both the northbound and southbound lanes. Multiple runs were made in each of the wheel paths, to obtain a measure of accuracy and repeatability. The sections were originally laid out using a measuring wheel referencing the southbound fog line, for a total length of 5,850 feet. The average length from the lightweight profiler measurement was 5,839.17 feet in the northbound lane and 5,837.33 in the southbound lane (respectively -0.19% and -0.22% error compared to the rolling wheel). A summary of the profile data taken after the cracks were sealed but before the overlay was placed is given in Table 3. Later, the segments were modified and the final length of 5,500 feet was established, as indicated in Table 2.

Construction Methods

Crack surveys were also conducted at the methods site along short segments at the time of construction, enabling the monitoring phase to proceed accurately based on the locations of cracks in the existing bituminous layer. In July 2007, the project staff met with the Lincoln County Highway Department for an inspection of potential test section sites. The sites were typically older HMA construction having sealed transverse cracks and chip-sealed surfaces. Prior to the inspection, the county maintenance staff had treated severe transverse cracks by patching and leveling using a fine HMA mixture. It is estimated that 80 to 90 percent of the transverse cracks in the three CSAH 15 segments were treated in this manner. The approximate distress level of remaining sealed cracks varied from low to medium. County maintenance forces spread and compacted the material at “cupped” transverse cracks.

Construction monitoring sections were established at the four locations discussed previously, and profile measurements were taken in the right wheel path using a lightweight profiler. Similar to the observations presented in the sealant site, pavement profiles were measured at the Lincoln County sites to establish their initial condition, prior to overlay construction. Table 4 provides a summary of the profile data and average IRI values for each segment in these sections. This table shows the IRI values after the cracks had been sealed (which occurred prior to the beginning of this project, about one year before overlay construction).

Table 4. Lincoln CSAH Lightweight Profiler Surveys.

Roadway	Section	Lane, run	Average IRI (in/mi)	Length, feet
CSAH 15	1 EB	Right, 1	96.9	10,835
	1 WB	Right, 1	121.4	10,817
CSAH 5	2 NB	Right, 1	108.2	10,599
	2 SB	Right, 1	113.1	10,601
CSAH 15	3 EB (Part 1)	Right, 1	110.0	5,312
	3 WB (Part 1)	Right, 1	100.4	5,306
CSAH 15	3 EB (Part 2)	Right, 1	91.1	5,212
	3 WB (Part 2)	Right, 1	113.2	5,212

Besides the initial crack survey and pavement profiles, no additional preparation activities were conducted on these sites. During construction and for two years thereafter, the overlays were observed and the condition of the existing cracks was noted.

Overlay Construction at Test Sites

This section includes construction monitoring of the sites established and installed, as discussed in the previous chapter. Construction at the sites consisted of placing a single-lift overlay on an unmilled bituminous surface. The sites established at the various locations described previously were each part of a larger, standard overlay project of much longer distance than the extent of the test sites. The project staff members coordinated with the paving contractors to ensure their presence while the overlays were placed at the sites. During construction at Lincoln County, the Mn/DOT thermal imaging camera was utilized to view heat patterns behind the paving machine and during the rolling operations. These will be discussed in later sections.

Sealant Materials and Methods

The Jackson County test site was established to monitor the formation of bumps with respect to crack sealant material and reservoir geometry. The construction methods were held constant. The contractor was instructed that if any bumps began to form within the limits of the study, the paving crew should not take any action to stop them, but to continue with constant construction methods.

General Observations

Since the presence of moisture has often been cited as a potential cause of bumps in overlays, the precipitation in the area of the test sites was obtained from the National Weather Service, for a period of 30 days prior to the construction. In just the seven days prior to paving, there was an accumulation of 1.6 inch of precipitation. This information is summarized in Figure 8.

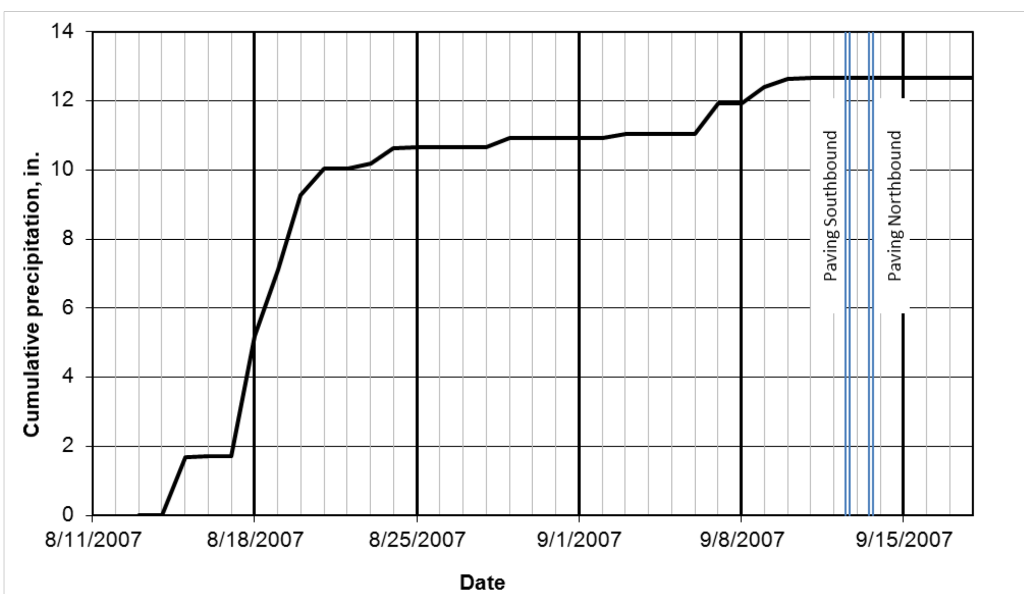


Figure 8. Sealant Site, 30-Day Cumulative Precipitation.

On the first day of paving (12 September 2007) weather was overcast with air temperature near 60° F. The southbound direction was paved on the first day. On the second day, the weather was sunny, with an air temperature of about 80° F. As will be discussed later, the weather conditions on the two days provided for a cool day with no solar radiation to further heat the pavement, and a warm day with much greater solar radiation to heat the pavement surface.

The breakdown roller was about 500 feet behind the paver. A pneumatic roller continued working the mat at temperatures near 140° F. On the "NO OVERBAND" sections the paving crew shoveled asphalt into the crack-sealed depressions ahead of the paver.

Construction

The overlay construction on Jackson County CSAH 5 occurred on 12 and 13 September 2007. The contractor was SMC from Mankato, MN. During the morning of 12 September 2007 the paving machine progressed from north to south in the southbound lane. The team followed the paver to observe and collected infrared temperature data and observe bump formation. Since the test section is located on the northern end of the project, paving was completed on all sealant test sections in the southbound lane by 11:20 AM.

Paving continued on 13 September 2007 in the northbound direction on the northbound lane. The project team arrived in the morning to collect ride data in the southbound lane. By 3:30 PM paving commenced on the sealant test sections and the team collected observations and infrared temperature data.

Bump Formation Observations

As had been done prior to construction, Jackson County personnel collected GPS data for mapping cracks and bumps on Jackson CSAH 5. Data had been collected before paving to locate each existing crack. After paving, any visible crack location and all bumps were located using the same GPS equipment. Jackson County developed crack maps for the project as shown by the example in Figure 9. The maps show patterns and locations of cracks before the overlay, and locations of cracks after overlay, arranged by sealant and installation types. In the sample below, the meandering lines are the original crack locations, and the straight lines that often only extend from the edge to the center of the roadway indicate the bumps that formed during overlay construction. In order to avoid repeating the intense labor effort donated by Jackson County, GPS location of the bumps was determined by a point at the edge of the pavement and by extending a line to the centerline of the roadway. In this way, each bump can be associated with an original crack, without attempting to locate the meandering characteristics of the original crack. It is sufficient to know that a bump developed at that crack location.

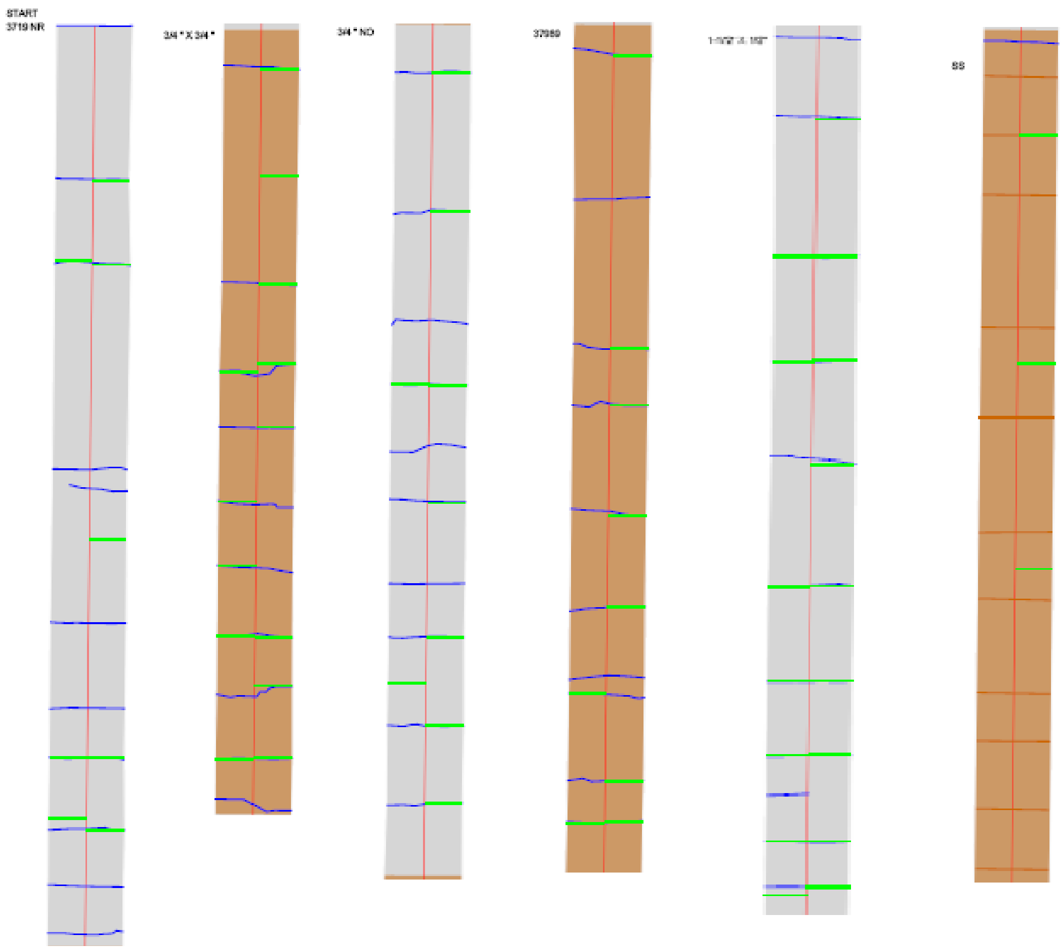


Figure 9. Sample of Crack and Bump Maps at the Sealant Site.

The information presented in Table 5 shows the segment treatments and general observations during construction on the CSAH 5 site in Jackson County, as described previously. The column labeled "Treatment" indicates the Mn/DOT sealant specification type:

- 3719 – hot-poured, crumb rubber,
- 3723 – hot-poured, elastic, and
- 3725 – hot-poured, extra-low modulus, elastic.

For the purposes of the analysis in this section, letters are assigned, in this and the tables that follow, indicating the reservoir treatment, as follows.

- A: Not routed, normal overband,
- B: Routed ¾" x ¾", normal overband,
- C: Routed ¾" x ¾", no overband,
- D: Routed 1" wide x ¾" deep, normal overband,
- E: Routed 1½" wide x ½" deep, normal overband, and
- F: Saw and seal.

Table 5. Observations on the Sealants and Methods Test Sections.

Section	Start	End	Treatment	Southbound	Northbound
1	0+00	2+70	3719-A	9AM – no bumps	
2	2+70	5+00	3719-B	Small bumps	
3	5+00	7+50	3719-C	Small bumps/dips	
4	7+50	10+00	3719-D	Slight movement of 2-ft level over cracks, 3 bumps	Bumps
5	10+00	13+25	3719-E	Small bump/dip	Bumps after breakdown roller
6	13+25	15+75	3719-F	Bump at 2nd crack	
7	15+75	18+25	3723-A		
8	18+25	20+75	3723-B		
9	20+75	24+00	3723-C		
10	24+00	27+50	3723-D		Appr. 8 bumps
11	27+50	30+50	3723-E		Appr. 6 bumps
12	30+50	33+50	3723-F		32+42: Bumps at edge of pavement
13	33+50	36+10	3725-A		33+88: 1/8-in bump cracked open (hairline) between wheel path 34+06: 1/4-in bump cracked open between wheel path
14	36+10	37+50	Not Used		
15	37+50	40+00	3725-B	Three slight bumps	
16	40+00	43+50	3725-C	Three small dips, one slight bump	
17	43+50	46+00	3725-D		
18	46+00	48+50	3725-E		Several closely spaced prominent bumps after breakdown roller
19	48+50	51+00	3725-F		
20	51+00	52+50	Not Used		
21	52+50	55+00	No treatment		

Construction Methods

The Lincoln County test site was established for observation of bump formation with respect to construction methods. The crack sealant material and methods were limited to a single type.

General Observations

As with the sealant site, a graph of cumulative precipitation occurring during the 30 days leading up to paving on the methods site was developed. Dry conditions prevailed in the weeks leading up to paving of the Sections 1 and 2. In the seven days prior to paving Section 3 there was an accumulation of 0.9 inch of precipitation with one day of drying weather. This information is summarized in Figure 10.

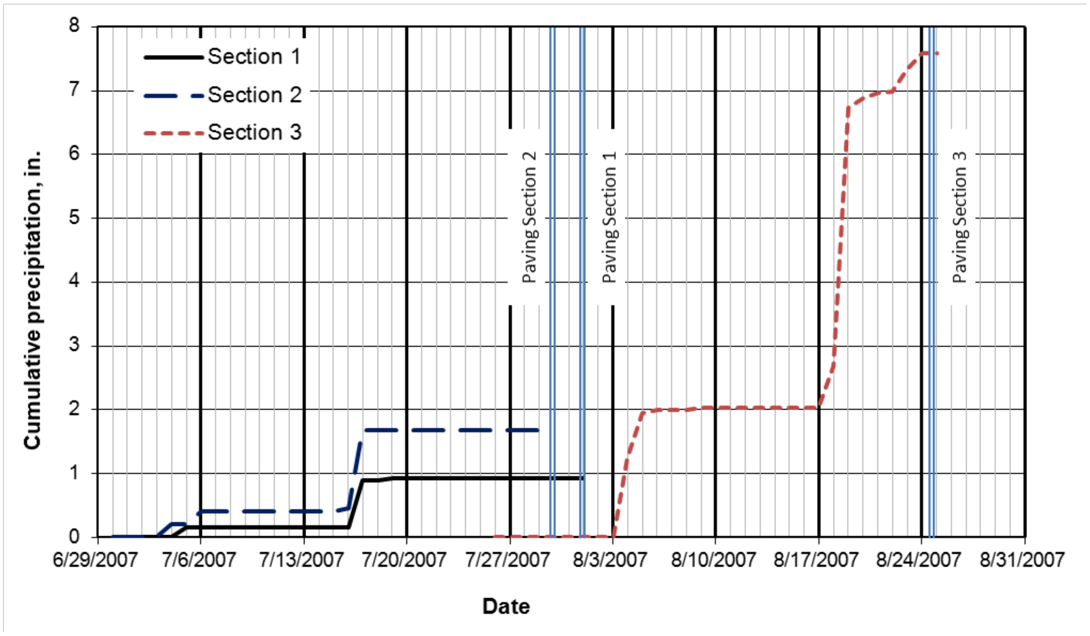


Figure 10. Precipitation Cumulative from 30 Days Prior to Paving.

<u>Construction</u>

On 31 July 2007, CSAH 5 south of Ivanhoe, Minnesota was overlaid with a single 2.5-in lift of asphalt. The HMA mixture design was a single lift 2.5-inch wear course designed with 29% RAP.

On 1 August 2007, paving progressed on Lincoln CSAH 15 from east to west in the eastbound lane. By 9:30 AM paving had progressed approximately 1.2 miles. The finish roller operator reportedly observed bumping for several cracks leveled with fine mix. It was the opinion of the finish roller operator that roller bumping response would not likely be observed by operators of the steel wheel breakdown or the pneumatic roller.

<u>Bump Formation Observations</u>

Pre-overlay distress patterns were found to differ by lane for Section 1 on CSAH 15. The general appearance of this road segment showed a greater amount of distress in the westbound lane. The westbound lane distress was generally limited to transverse thermal cracking. The eastbound lane distress included transverse thermal cracks continuing from the opposite lane as well as a large amount of fatigue and block cracking.

Eight transverse cracks were randomly selected for close observation and were marked with paint dots along the center stripe and lane edge prior to paving. Paving progressed with trucks dumping HMA on the ground in windrows. The HMA was placed by a paver using a pick up machine then compacted by a series of three rollers, described in Table 6. The project staff photographed the operation and also followed alongside the finish roller operator, who called attention to the bumping response of the roller.

Table 6. Lincoln CSAH 15 Roller Equipment, 1 and 24 August 2007.

Roller	Type	Complete Passes	Remarks
Breakdown	Vibratory steel drum	3	Vertical motion at end of drum when rolling over cracks
Intermediate	Pneumatic tire	3	Light tracking
Finish	Steel drum	2 minimum	Operator locates bumps with roller response

Stakes were set in the south ditch in order to locate the eight cracks observed prior to paving. Figure 11 and Figure 12 are images of bumps in the asphalt mat on the day of construction. The photos were taken after finish rolling was complete. Table 7 lists details of construction observations on CSAH 15 on 2 August 2007.

Figure 11. Bump Cracked Open over Unleveled Crack, Eastbound CSAH 15.

Figure 12. Bump Over Leveled Crack, Eastbound CSAH 15.

Table 7. Observations at the Lincoln County CSAH 15 Methods Site.

Crack	Location [a]	Length	Notes	Bumping [b]
	623.7			Bump cracked open
	2444, 2449.7, 2458.7			Set of post-paving bumps, no pre-existing transverse cracks
8	3116.7	12	Leveled sealed crack	Dip 1/16-in
7	3260.6	12	Sealed crack	1/4-in bump near cold joint
6	3323.9	12	Leveled sealed crack	None
5	3420.5	12	Sealed crack	None
4	3448.4	12	Sealed crack	1/32-in
3	3475.9	6	Sealed crack	None
2	3527.3	6	Sealed crack – near station 247+00	1/32-in
1	3589.6	6	Sealed crack	1/32-in
	5450.1		Leveled crack	Dip
	5526.0		Leveled crack	Dip
	6196.3		Leveled crack	Dip
	6613.3		Sealed crack	Bump
	6869.5			Bump cracked open
	8647.5		Leveled crack – near station 298+00.	Bump cracked open. Patch material extends past overlay into shoulder.
	9863.3		Leveled crack – near station 310+00.	Bump cracked open

[a]Feet east of intersection with 160th Ave. as measured with Ames LISA system.
[b]Measured with level and ruler.

Paving at the methods sites continued to progress throughout August. Additional monitoring occurred on 23 to 24 August 2007. Observation of the completed CSAH 15 Section 1 near 160 – 180th Ave. (north side of Section 31 in Ash Lake township and Section 36 in Shaokatan township) – found scrapes in the new HMA at transverse crack locations. Stakes were installed on Section 1 for the following day's work. Shadows provided by the setting sun facilitated the identification of pavement surface features.

Visual observations of Section 1 showed that segregation of recently placed aggregate shoulder material had routinely occurred near severe bump/dips due to the diversion of rainwater runoff. It was found that scraping of the HMA surface was isolated to bump locations. It is likely that a spreader blade caused the scrapes during placement of aggregate shoulder material. The westbound lane of Section1 generally had less severe bumps, and the bumps formed in the eastbound lane did not necessarily transfer to the westbound lane. Figure 13 through Figure 16 show the presence of scrape marks and several hairline cracks. Hairline cracks were generally less than 6 feet long. Figure 15 shows how the HMA mixture appears folded over in the direction of rolling at a bump location.

Figure 13. CSAH 15 – Section 1, Paved 1 August 2007.

Figure 14. CSAH 15 – Section 1, Paved 1 August 2007.

Figure 15. CSAH 15 – Section 1, Paved 1 August 2007.

Figure 16. CSAH 15 – Section 1, Paved 1 August 2007.

On 24 August 2007 the construction methods Section 4 was established at the junction of CSAH 7 and CSAH 15 east of Arco, MN (NW corner of section 33 in Lake Stay Township). Prior to paving, GPS equipment was used to store the latitude and longitude of start point, midpoint, and end point of a total of approximately ten transverse cracks on either side of the culvert bridge along the north side of Section 33. The transverse cracks were full width, and included both sealed and sand-leveled treatments. The contractor applied an emulsified tack coat to the eastbound lane at midday and began paving within 15 minutes.

Thermal Imaging

Thermal conditions were monitored for two cracks using an infrared camera. One crack was patched and leveled and the other crack had been sealed. Infrared data was also collected in a more extensive area of blade leveling. The leveling work had been performed prior to paving, and was generally similar to the pavement temperature. In this area it was possible to identify the path of transverse cracks below the road-temperature blade-leveled material.

Figure 17 through Figure 18 are infrared images collected during the paving operations on Lincoln CSAH 15 on 24 August 2007 near the junction of CSAH 7 and CSAH 15 east of Arco, MN (NW corner of Section 33 in Lake Stay Township). The section is typical of a two-lane rural highway. Crack A was untreated prior to overlay, but contained old crack sealant. Crack B was treated with a leveling patch prior to overlay and also contained old crack sealant. The two cracks were approximately 70 feet apart along CSAH 15.

Each figure shows Crack A at the left and Crack B at the right. The overlay construction occurs in the upper portion of the image. A lane of non-overlaid pavement is located in the lower portion of the image. The images show the thermal condition of each crack at similar time in the paving process.

Figure 17 shows the pair of cracks after tack coat application. It was observed that both crack sealant and leveling patch treatments could be detected below the emulsified tack coat, and that the tack coat appeared cooler than the pavement surface. In the thermal signature graphs the presence of sealant material appears as a spike, and the leveling patch is shown by a length of elevated temperatures.

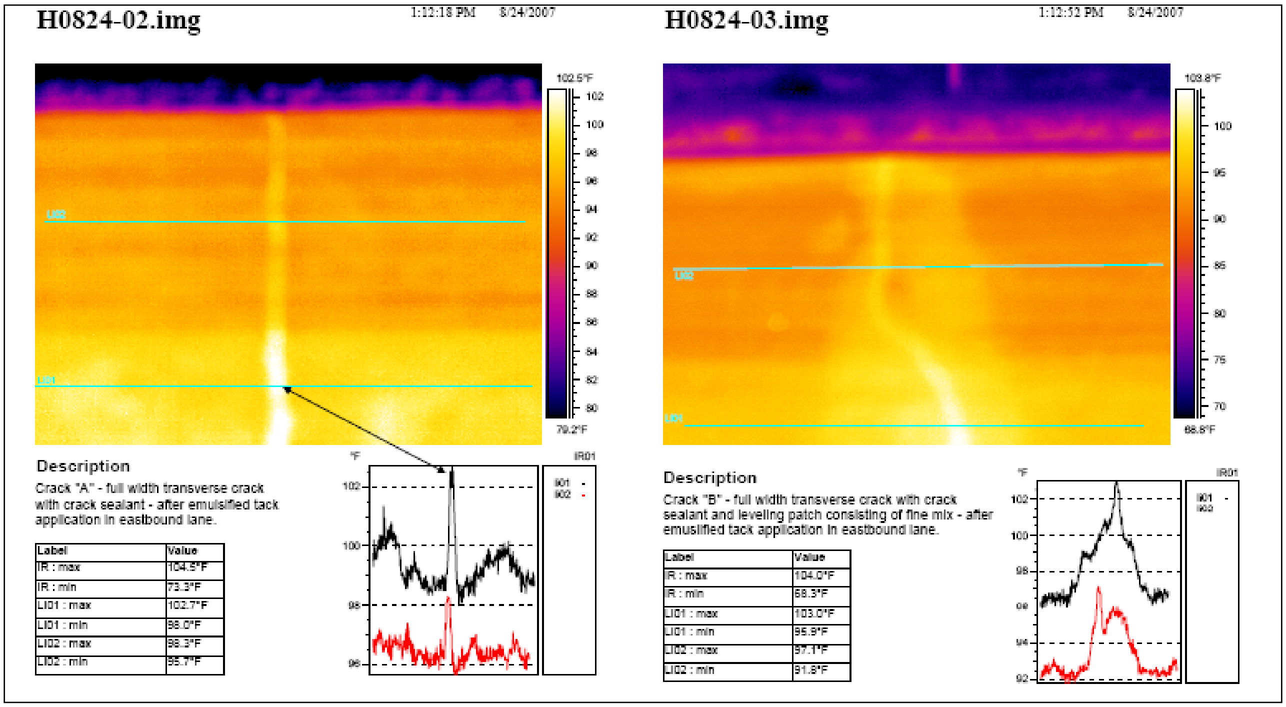


Figure 17. Thermal Signature of Tack-Coated Transverse Cracks on Lincoln CSAH 15.

During the time between mat placement and breakdown rolling there was no detectable thermal signature that indicated the presence of a material other than the hot asphalt mat. Conditions were monitored as the mat cooled and rolling continued. At the start of finish rolling (20 minutes after the paver pass) a 2-°F thermal spike was observed in the region of the treated cracks. At this point it was possible to identify the location of the treated crack below the HMA mat. Figure 18 shows the thermal spike increased to 4° F when the final observation was obtained approximately 40 minutes after the paver pass.

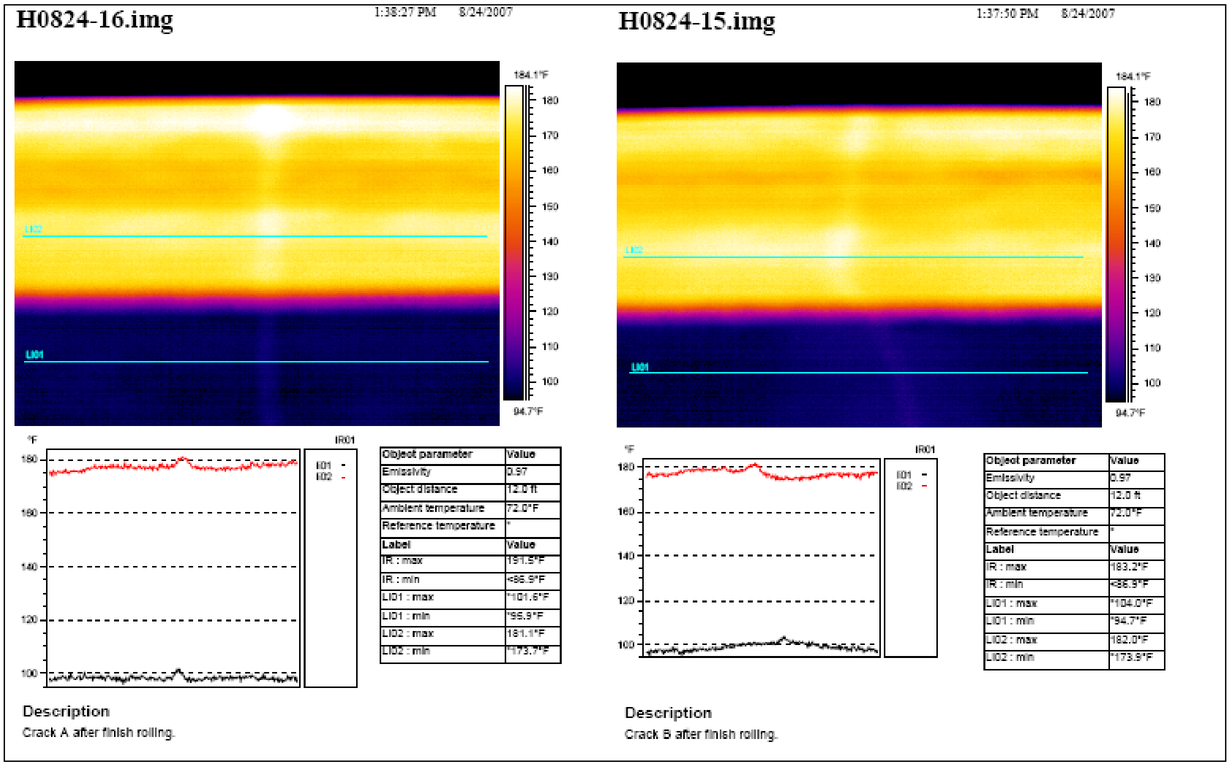


Figure 18. Thermal Signature of Transverse Cracks after Finish Roller on Lincoln CSAH 15.

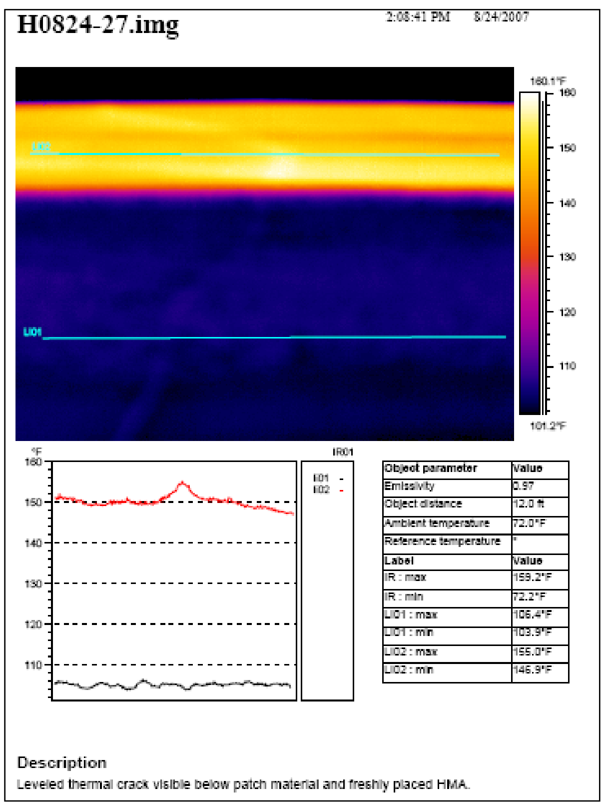


Figure 19. Thermal Signature of Blade-Leveled Treatment and Fresh HMA.

The infrared camera was also used to obtain several images in an area of blade leveling. The leveling work had been performed many days prior to paving, and was generally similar to road temperature. Figure 19 shows that in these areas it is possible to identify the path of transverse cracks below the road-temperature blade-leveled material. Bumps in the overlay did not develop at locations where the thermal camera was used.

Analysis of Observed Bumps

The bumps observed at the sealant site were quantified and analyzed, as discussed in this section.

Sealant Materials and Methods

The relative performance of sealant and installation type is shown in Table 8 through Table 12. In this summary both reflected and non-reflected bumps were considered with respect to the number of treated cracks in a sealant section. Table 8 shows all pre- and post-paving bumps and cracks identified along CSAH 5, including several outside of, or between specified test section segments. The post-paving GPS survey identified 151 bumps that had formed over the 420 cracks identified prior to construction.

The tables in this section describe the percentage of bumps that occurred during overlay construction. Bump severity levels were adopted early in the project for the purposes of comparing the bump formations with respect to height differences as measured with a level and ruler. The bumps that developed were classified as Low, Medium, or High Severity bumps. The severity levels were determined by the vertical deviation of the bump as follows:

- Low severity bumps are slightly raised, but less than 1/8” from the surface.
- Medium severity bumps are raised 1/8-in or more, but less than 1/4-in above the surface.
- High severity bumps are raised 1/4-in or more above the surface.

As described in previous sections, the overlay construction took place over two days. By coincidence, the air temperature (and thus the surface temperature of the existing pavement) was significantly different on the two days. The weather on the first day of overlay paving (in the southbound traffic direction) is termed “Low air temperature” since the weather was overcast and about 60 °F. On the second day, the paving proceeded in the northbound direction, and is termed “Higher air temperature” due to the sunny weather and 80 °F air temperatures.

As can be seen in Table 8 and in the tables below, there is a significant increase in the formation of bumps with higher air temperatures. Table 9 presents the results of bump formation with respect to sealant material and temperature at the time of overlay construction. When accounting for bumps of all severity levels, treatments using the elastic extra-low modulus specification (3725) formed bumps at a substantially higher rate than other materials within both air temperature categories. The crumb rubber (3719) and elastic sealants (3723 and 3725) exhibited similar rates of bump formation within the air temperature categories. Cracks which received no sealant treatment also formed no bumps, in either of the air temperature categories. Considering only bumps of high severity, as defined above, Table 10 shows that these bumps primarily developed in cracks treated with the extra-low modulus (3725) material.

Table 8. Cracks and Bumps at Sealant Site, September 2007.

Jackson CSAH 5		**Pre-Overlay GPS Crack Survey**		**Overlay Bumps at Crack**		**Overlay Bumps Away From Crack**	
Sealant	Treatment	SB	NB	SB	NB	SB	NB
3719	A	11	11	2	4	1	1
	B	10	10	5	7	0	1
	C	10	10	1	7	1	0
	D	10	10	2	7	0	0
	E	11	10	6	9	1	0
	F	11	11	0	1	0	2
	G	1	1	0	0	0	0
	Subtotal	**64**	**63**	**16**	**35**	**3**	**4**
3723	A	10	10	2	2	0	0
	B	10	10	2	7	0	0
	C	10	10	0	8	1	0
	D	10	11	1	10	1	2
	E	7	7	1	7	1	0
	F	10	10	1	3	2	2
	G	11	11	0	2	0	0
	Subtotal	**68**	**69**	**7**	**39**	**5**	**4**
3725	A	10	10	4	6	0	1
	B	10	10	1	8	0	0
	C	10	10	3	2	0	1
	D	10	10	9	9	2	0
	E	11	11	11	10	2	0
	F	6	6	0	0	0	0
	G	7	6	0	0	0	0
	Subtotal	**68**	**63**	**28**	**35**	**5**	**6**
Control	G	10	10	0	0	1	0
	G	10	10	1	0	2	0
	Subtotal	**20**	**20**	**1**	**0**	**3**	**2**
TOTAL		**220**	**215**	**52**	**109**	**16**	**16**

Table 9. All Bump Severities (L, M, and H) by Sealant Type.

Sealant Type	**CSAH 5 – Southbound (Low air temperature)**	**CSAH 5 – Northbound (Higher air temperature)**
No Treatment	0.0%	0.0%
3719	6.5%	14.8%
3723	5.3%	14.3%
3725	22.8%	40.9%

Table 10. High Severity Bumps by Sealant Type.

Sealant Type	CSAH 5 – Southbound (Low air temperature)	CSAH 5 – Northbound (Higher air temperature)
No Treatment	0.0%	0.0%
3719	0.0%	0.0%
3723	0.0%	0.0%
3725	1.8%	16.1%

Table 11 presents bump formation by reservoir geometry and air temperature at the time of overlay construction. Between air temperature categories there was little difference with respect to bump formation rates for geometries A, B, C, or F. With the increased air temperature, the bump formation rates for all severities showed an increase of more than 250% and 150%, respectively. These findings concur with the general conclusions by Hearne (2004) in North Carolina. The practice of minimizing the reservoir width and depth, and the overband on the surface of the pavement, is also recommended by Crafco (1995) and Flexible Pavements of Ohio (undated). When only high severity bumps are considered, as in Table 12, bump formation is only evident in Geometry E in the higher air temperature category. The 3.3% high-severity bump formation for geometries A and D represent only one bump formed per 30 original crack locations, and may not be a significant response.

The practice of minimizing the reservoir width and depth, and the overband on the surface of the pavement, is also recommended by Crafco (1995) and Flexible Pavements of Ohio (undated). The general finding in this section also concur with the recommendations in the *Best Practices Handbook on Asphalt Pavement Maintenance* (Johnson, 2000), specifically that proper crack sealant practices can help alleviate the occurrence of bumps in a subsequent overlay.

Table 11. All Bumps (L, M, and H) by Reservoir Geometry / Routing Treatment.

Routing Treatment		CSAH 5 – Southbound (Low air temperature)	CSAH 5 – Northbound (Higher air temperature)
A	No Rout	13.3%	16.7%
B	Routed ¾” x ¾”, normal overband	13.3%	13.3%
C	Routed ¾” x ¾”, no overband	0.0%	0.0%
D	Routed 1” wide x ¾” deep, normal overband	13.3%	46.7%
E	Routed 1½” wide x ½” deep, normal overband	23.4%	59.2%
F	Saw and seal	0.0%	0.0%

Table 12. High Severity Bumps by Reservoir Geometry / Routing Treatment.

Routing Treatment		CSAH 5 – Southbound (Low air temperature)	CSAH 5 – Northbound (Higher air temperature)
A	No Rout	3.3%	0.0%
B	Routed ¾" x ¾", normal overband	0.0%	0.0%
C	Routed ¾" x ¾", no overband	0.0%	0.0%
D	Routed 1" wide x ¾" deep, normal overband	0.0%	3.3%
E	Routed 1½" wide x ½" deep, normal overband	0.0%	29.6%
F	Saw and seal	0.0%	0.0%

Construction Methods

The preconstruction pavement management video log of Lincoln County roads, maintained by Mn/DOT, was used to subjectively identify full- or nearly full-width transverse cracks likely to produce bumps in an overlay. The following table shows the number of transverse cracks with potential to produce bumps.

Table 13. Crack Counts at Methods Sites – 2007.

Section	Pre-overlay Crack Count
1	220
2	223
3	275
4	37

Cracks identified with high potential to produce bumps were 6 – 12 feet wide cracks that showed little wander. The bumps that were located again in 2008 frequently bore minor scrapes that were assumed to result from snow plows. As shown previously, in Table 6, there was little difference between the methods sections regarding overlay preparation, materials, paving methods, and densification techniques used by the contractors. The major difference was the temperature conditions. Table 14 shows the air temperatures that occurred during paving of the methods sections.

Table 14. Air Temperature for Methods Sites – 2007.

Section	Paving Date	High/Low air temperature, °F
1	8/1/2007	90/71
2	7/31/2007	89/69
3	8/24/2007	74/53
4	8/24/2007	74/53

Measurement of bump formation at the methods site was performed immediately after paving. Follow-up measurements were performed on the sections in 2008. Only low severity bumps were observed for the methods sections. Table 15 shows the distribution of bumps occurring within the various sections. The data also showed that over 85% of the bumps resulted on the sections paved by “Contractor A”, where daily air temperatures were elevated relative to the sections paved by “Contractor B”.

Table 15. Bump Severity Summary for Methods Sites – 2008.

Section	Low	Medium	High
1	22	0	0
2	20	0	0
3	7	0	0
4	0	0	0
Total	49	0	0

Table 16 summarizes the paving conditions and amount of bumps formed at all of the sites in the study. The table also shows variables for the air temperature differences at the time of paving (AirDiff) and for the interaction of air temperature differentials and bump formation (AirDiff * Bumps/mi). Air Diff for the methods sections was calculated as the difference between the daily high air temperature during construction for the first methods section 1 and that of the other methods sections. For the sealant site, the AirDiff was computed as the difference between the daily high temperature during construction on the northbound direction and that of the southbound direction.

Table 17 shows the coefficients of correlation for the data in Table 16 with respect to the number of bumps formed per mile.

Table 16. Paving Conditions and Bump Formation for all Test Sites.

Location	Section	Length, miles	# Bumps	Bumps per mile	7-day Precip.	Air Temp.	Air Diff	Breakdown Temp.	Air Diff * Bumps/mi
Methods Site	1	2	20	10	0	90	0		0
	2	2	22	11	0	89	-1		-11
	3	2	7	3.5	0.86	74	-16	235	-56
	4	0.2	0	0	0.86	74	-16	235	0
Sealants Site	SB	1.1	52	47	1.63	61	-9	212	-423
	NB	1.1	109	99	1.63	70	0	202	0

Table 17. Correlation Coefficients for Bump Formation.

	30-day Cum. Precip.	7-day Precip.	Air Temp.	AirDiff	Breakdown Temp.	Bumps/mile
Bumps/mile	0.692	0.709	-0.499	0.472	-0.973	--
Air Diff * Bumps/mile	-0.531	-0.538	0.683	0.197	0.296	-0.193

Other Observations

Additional evaluations were collected on two projects that were paved during the 2010 construction season. The projects were constructed for the Minnesota Department of Transportation, and were located in the Twin Cities metropolitan area. Both projects were two-lift bituminous overlays of concrete pavements (BOC), used similar hot mix asphalt (HMA) mixtures, and developed bumps. Table 18 provides a brief description of the two projects.

Table 18. Mn/DOT Projects Observed.

Highway	Location	Construction Type
US 52	RP 119 SB	BOC, Mn/DOT Level 5 HMA wear mixture using PG 64-28 asphalt binder
US 52	RP 117.2 NB	BOC, Mn/DOT Level 5 HMA wear mixture using PG 64-28 asphalt binder
I-35W	RP 27.4 SB	Bituminous mill and BOC, Mn/DOT Level 5 HMA wear mixture using PG 64-28 asphalt binder

The evaluations included

- Locating joints prior to paving,
- Collecting data on HMA temperatures and construction practices, and
- Measuring any bump formations that developed near the area.

Construction began on US Highway 52 near Rosemount, MN in April, 2010. The design called for two 2-inch lifts of HMA over concrete. Observations were made on US 52 after bumps were reported to develop in the lower lift. Additional visits were also performed by personnel from the Mn/DOT Metro District and Bituminous Office. Figure 20 shows the project limits and the location of the field observations.

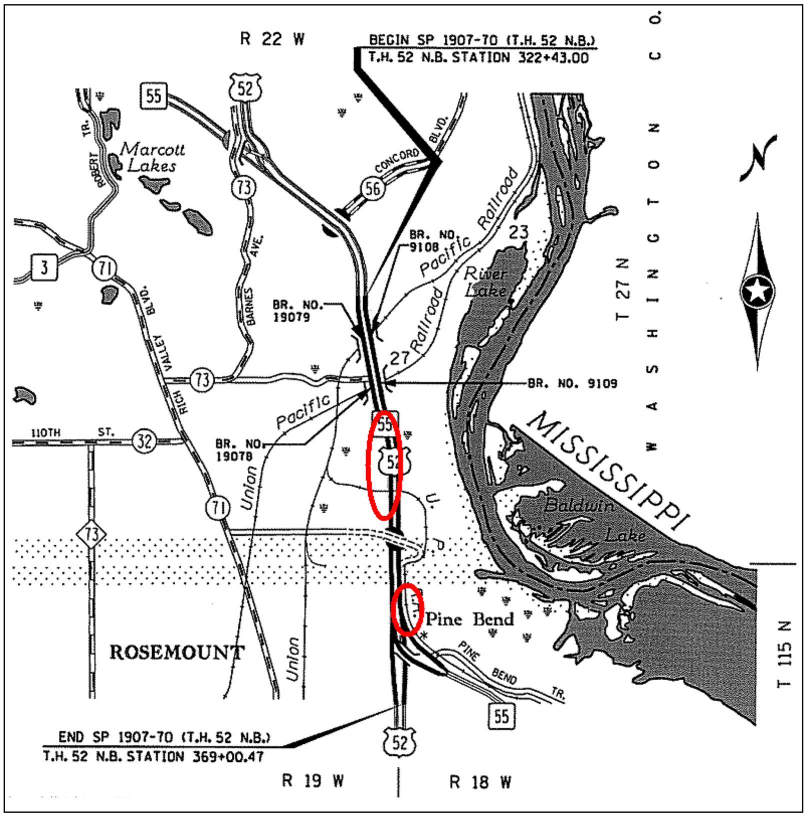


Figure 20. Bumps Observation Sites on US 52.

The surface of US 52 was concrete prior to the 2010 overlay, and the Mn/DOT pavement management video log revealed that transverse joint repairs had been performed on an as-needed basis. Field observations found that a hot-pour type crack sealant had been applied to the joints and joint repairs. Many of the sealed joints appeared in good condition and were in compression at the time of construction, but some of the wider, more severe joints were either unsealed or contained deteriorated sealant. Time constraints did not permit an evaluation of joint load transfer efficiency. Several feet of the hot-pour sealant and backer material were removed from the pavement. The sealant was evaluated for expansive behavior by placing several pieces of the material in a laboratory oven at 290 °F (130 °C) for approximately half an hour. A comparison of pre- and post-heated volume measurements showed that no change had occurred.

Figure 21 shows the lower lift of HMA and a bump that formed in the lift. The bump was approximately ½-inch tall and contained visible hairline cracking. Such bumps were found often during the initial field visit. Cases of mixture shoving and instability were also located, indicating that compaction equipment had operated while the HMA temperature was in a tender zone.

Figure 21. Severe Bump in Lower Lift on US 52.

Field evaluations occurred near US 52, mile 119 southbound during paving of the final lift of HMA. Nine locations were selected prior to final lift paving, and were labeled A-I.
Six of the locations had bumps in the lower lift that had developed over transverse joints similar to Figure 22.

Three locations had shallow dips in the lower lift, and were not over transverse joints
The nine locations were monitored for bump development and temperature as the final lift was constructed.

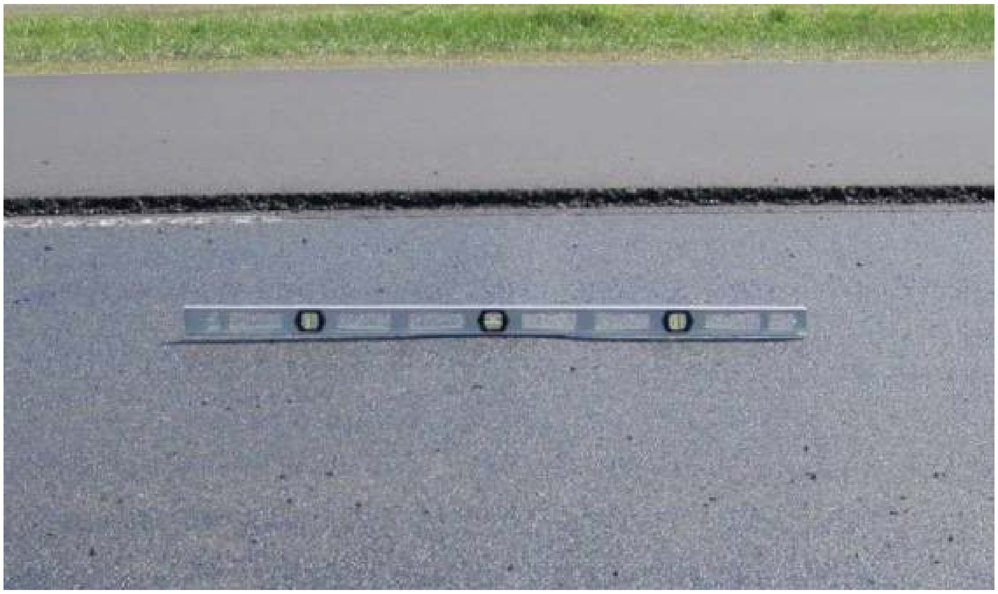


Figure 22. Bump Location "A" in Lower Lift of HMA on US 52.

Bumps developed in the final lift in five of six cases. No bumps developed over the shallow dip locations. The bumps labeled C1 through C4 developed after paving over smooth areas in the lower lift. Bumps developed while HMA temperatures were between 180 and 135 °F. Formations generally occurred after vibratory rolling ceased, about 180 °F, and they appeared to increase in size until the temperature was approximately 150 °F. Figure 23 and Table 19 show bump formation temperatures and construction observations.

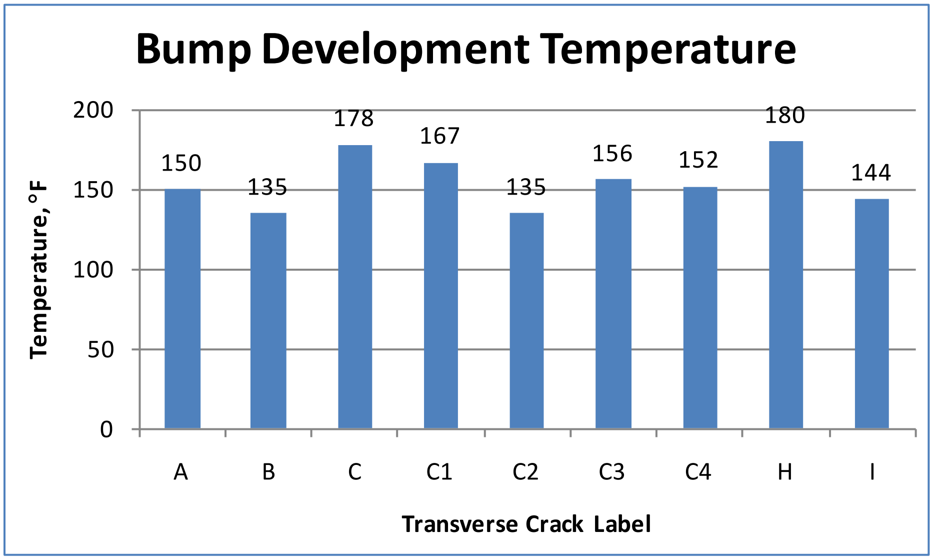


Figure 23. Bump Formation Temperatures Observed on US 52.

In some cases the bump formations had a folded-over, or shoved appearance that coincided with the motion of the compaction equipment, as seen in Figure 24.

Figure 24. Bump in the Final Lift of HMA on TH 52.

Table 19. Bump Formation Details on US 52.

Mark	Temp (F)	Vibratory Passes	Non-vibratory Passes	Remarks	Bump, in.
A	245			Windrow	0
	250	0		Paver stopped 18 min.	0
	218	1			0
	180	3			0
	180	5			0
	155		1		0
	150			Set PK nail	1/8
	141				1/8
B	267	0		Windrow	0
	235	1			0
	235	2			0
	232	3			0
	220	5			0
	168		1		0
	150				0
	135				1/8
C	236	1			0
	236	2			0
	230	4			0
	223	5			0
	178			Set PK nail	1/4
	154		1		1/4
	135			Right WP	1/2
C1		5			
	167			Set PK nail	1/4
	156				3/8
	135		1		1/2
C2		5		Set PK nail	
	135		1		1/4
C3		5			
	156				1/2
			1		1/2
C4		5			
	152			Set PK nail	1/2
	136				1/2
H		5			
	180			Bump LWP	1/4
	149			Set PK nail	1/4
	130		1		1/4
I		5			
	144			Set PK, Bump LWP	1/2
	133		1		1/4

A second set consisting of 13 joints was located on US 52, mile 117.2 northbound prior to paving of the first lift of HMA. The set included a range of sealant conditions, joint widths, and concrete conditions. Location measurements were obtained with a rolling wheel relative to permanent landmarks. A review was performed after the final lift of HMA was placed, and it was found that no bumps had developed.

Construction began on I-35W near Arden Hills, MN in June 2010. The design called for removal of the existing 4-inch HMA down to the concrete surface followed by placing two 2-inch lifts of HMA. Observations were made on I-35W after bumps were reported to develop in the lower lift. Additional visits were also performed by personnel from the Mn/DOT Metro District and Bituminous Office. Figure 25 shows the location of the field observations, near mile 27.4 at the onramp from CSAH 96.

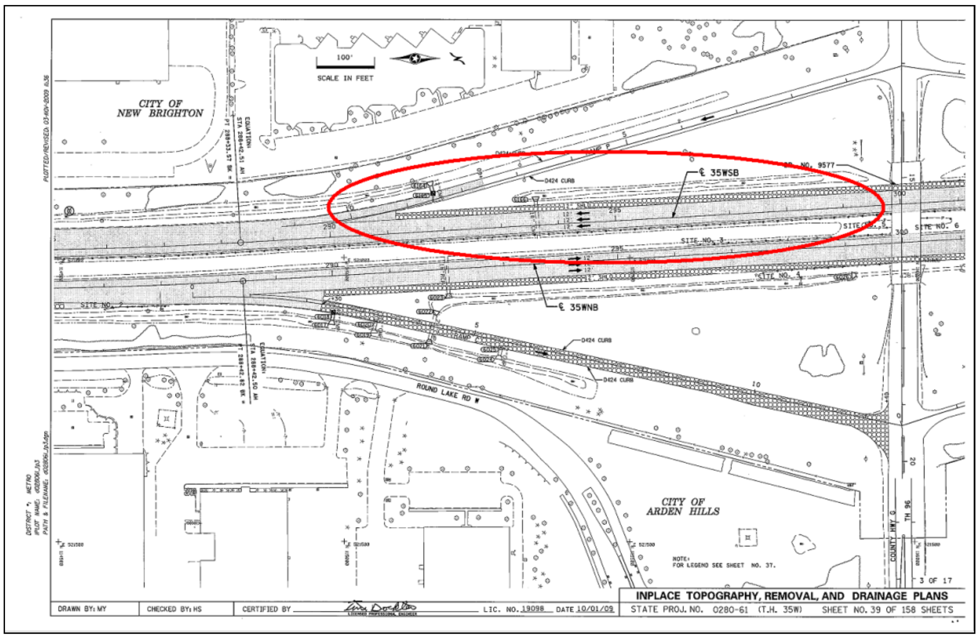


Figure 25. Roller Pattern Observation Site on I-35W.

Once the bump formations were detected on I-35W the paving contractor made alterations in the rolling patterns and choices of compaction equipment. The first seven configurations were unsuccessful in preventing the formation of bumps.

- Configuration #1 (4 rollers)
    - Pneumatic breakdown
    - Two steel rollers (before tender zone)
    - Steel finish

- Configuration #2 (4 rollers)
    - Steel as breakdown
    - One pneumatic roller (before tender zone)
    - One steel roller (before tender zone)
    - Steel finish

- Configuration #3 (4 rollers)
    - Two steel for breakdown
    - One pneumatic roller (before tender zone)
    - Steel finish

- Configuration #4 (4 rollers)
    - Three steel breakdown
    - Steel finish

- Configuration #5 (3 rollers)
    - Two steel breakdown
    - Steel finish

- Configuration #6 (5 rollers)
    - Pneumatic breakdown
    - Two steel (before tender zone)
    - One pneumatic (before and after tender zone)
    - Steel finish

- Configuration #7 (4 rollers)
    - Two pneumatic tire breakdown
    - One steel (before tender zone)
    - Steel finish

It was noted that configuration 1 – 7 used steel vibratory rollers early in the compaction process. An eighth configuration was devised in order to limit the presence of vibratory compaction and emphasize rubber tire densification.

- Configuration #8 (3 rollers)
    - Two pneumatic tire breakdown (into tender zone, to 200 degrees)
    - Density was achieved
    - Steel finish (tender zone, 200 degrees and below)
    - Observed mix shoving and bump formation

Two pneumatic tire rollers were used for breakdown densification. The rollers closely followed the paving machine. Pneumatic rollers made 16 or more passes before moving ahead. A non-vibratory steel roller followed the pneumatic tire rollers. The steel roller was allowed to make four or more passes, until bumping or tenderness was observed. Several joints were selected, marked using paint, and located with a rolling wheel. Four of these joints (labeled J1 through J4) were also marked with wooden stakes. Table 20 is a chronological list of the observations taken on joints 1 through 4. The joint locations were monitored for bump development and temperature as the initial lift was constructed on the concrete surface. Table 21 summarizes the location of the joints.

Table 20. Construction Observations on I-35W, Mile 27.4.

Joint	Time	Temp (F)	Remarks
J1	7:23	328	Belly dump up to J2
		270	2 pneumatic tire passes
		266	4
		260	6
		250	8
		226	10
		206	12
	7:50	196	14 pneumatic tire, begin slower speed.
			18
		165	4 steel roller passes
J2	7:25	330	Belly dump past J4
		282	2 pneumatic tire passes
		267	4
		258	6
		250	8
		242	10
		218	12
	7:50	200	14 pneumatic tire, begin slower speed.
			18
		198	Hairline cracking observed over joint.
			Steel roller
J3	7:25	330	Belly dump past J4
		282	2 pneumatic tire passes
		267	4
		258	6
		250	8
		242	10
		218	12
	7:50	200	14 pneumatic tire, begin slower speed.
			18
			Steel roller
			3/4-inch bump found downstream
		150	Mix tender, 1.5-inch bump. 6 steel passes.
			Transverse roller pass shoves mat. Rolling stopped.
	8:50	115	Tenderness past
J4	7:25	330	Belly dump past J4
		267	2 pneumatic tire passes
		258	4
		252	6
		241	8
		228	10
	7:50	210	12 pneumatic tire, begin slower speed.

Table 21. Joint Locations on I-35W, Mile 27.4.

Location	Feet north of Mile 27.4	Crack Width, in.	Condition
Joint J1	321	3 – 3.5	No sealant
Joint J2	211	1.5	Old repair, some sealant in cracks, dirty
Joint J3	202	2	Some sealant in crack, dirty
Joint J4	163	0.25 – 4	No sealant, widest at mid-lane

Nuclear density readings with Configuration 8 resulted in achieving of over 92 % of theoretical maximum density using the rubber tires alone. Application of the vibratory steel caused shoving and bump formation as the HMA temperature dropped to 150 °F.

A ninth configuration was devised as a compromise that would achieve satisfactory density and avoid bump formation (working the HMA while temperature remains within the tender zone). Configuration 9 was field tested on a segment of I-35W and found satisfactory, without bump formation.

- Configuration #9 (3 rollers)
  - Two pneumatic tire breakdown (before tender zone)
  - Steel finish (after tender zone)

In summary, greater rates of bump formation were associated with construction circumstances where air temperature was warmer in comparison to corresponding locations that formed few bumps. This relationship was observed for both the construction methods and the sealant materials and methods test sections. Construction situations involving tender mixtures were found to frequently develop bumps. The conclusions regarding the number of roller passes and the types of rollers used confirms recommendations by Crafco in a 2003 technical bulletin.

An analysis that included all of the county test sites showed that a moderate positive correlation was found to exist between temperature differences and the rate of bump formation. Much stronger correlations were found to exist for breakdown temperature and recent precipitation history with respect to the rate of bump formation. Note that the breakdown temperature data was incomplete and that factors such as temperature in paver, time between placement and breakdown, and temperature at bump formation were unknown, and may be useful to more completely describe bump formation. The effect of these bumps in terms of smoothness is discussed in chapter 4.

Chapter 4. TEST SITE MONITORING

In this chapter, the early field performance history of the test sections is documented, and included the use of the same data collection methods as described in Chapter 3 – collection of profile data, and measurement of bumps.

Test Section Monitoring

The project work plan established that measurements and observations would be obtained prior to overlay construction, immediately following construction, and after the overlay had been in service for approximately one year. The monitoring phase began immediately following completion on construction activities in 2007. Table 22 shows when particular sections were monitored during the project, along with the methods that were used.

Following the first winter of service, the partnering county highway departments found reflective cracking in all of the thin overlay sections. The departments performed routine preventive maintenance on the sections that included routing and sealing cracks and also applying a chip seal. The maintenance treatments were applied early in the 2008 season, prior to the monitoring activities of the bumps project. The project staff subsequently decided to supplement the 2008 data with another round of monitoring in 2009 in an attempt to account for the effect of the maintenance activities.

Table 22. Chronology of Project Activities.

Date	Section(s)	Manual Bump Measurements	Profile Measurements	Other
7/17/2007	5, 6		X	Inspection
7/27/2007	1, 2, 3		X	Inspection
8/1/2007	1	X	X	Photos, inspection
8/1/2007	2		X	Inspection
8/24/2007	1	X	X	Photos, inspection
8/24/2007	4			Photos, thermal
9/1/2007	3, 4	X	X	
9/13/2007	5, 6	X	X	Photos, thermal
5/23/2008	5, 6			Inspection
7/1/2008	5, 6		X	Photos
7/2/2008	1, 2, 3, 4	X	X	Inspection, photos
5/13/2009	1		X	Inspection, photos
5/13/2009	2		X	Photos
5/13/2009	3, 4		X	
5/14/2009	5, 6		X	Inspection, photos

Manual Measurements

In 2008 visual inspections of the four methods test sections were conducted from a vehicle traveling at approximately 10 mph. Distance was monitored with a measuring wheel. When any feature that presented a bump-like appearance was encountered, the location was recorded and the height measurement of the bump height was taken using a 4-ft carpenter’s level and ruler.

A similar visual inspection of the sealant site was performed after overlay construction in 2007. At that time county forces assisted in recording bump locations using county-owned GPS equipment. Results from the 2007 surveys are summarized in Chapter 3. Results from the 2008 methods sections inspections are presented in Table 23 through Table 24. Table 23 shows results for Sections 1 and 3, and Table 24 shows results for Sections 2.

Section 4 also received a field inspection in the east and westbound lanes during this time frame. During the inspection a total of 70 locations from the two lanes were identified as potential locations for bumps, including 68 rout-and-seal transverse cracks. The inspection found that all of the locations had a very level appearance. Bump severity measurements were performed with a level and ruler, and all bump heights were approximately zero.

Table 23. Methods Sections 1 and 3 Inspection Log.

Distance	Lane	Crack length, ft	Centerline Offset, ft	Test Section	Measurement, in.[a]	Remarks
0				1	1/8	Section 1, intersection CSAH 15 and CR103 (160th), eastbound
623	EB	6	3	1	1/8	
2442	EB	12	0	1	1/8	Picture, set of 2
2444	EB	12	0	1	1/8	Picture, set of 2
3120	EB	12	0	1	0	C8, R/S
3264	EB	12	0	1	0	C7, R/S
3327	EB	12	0	1	0	C6, R/S
3423	EB	12	0	1	0	C5, R/S
3452	EB	12	0	1	0	C4, R/S
3480	EB	12	0	1	0	C3, R/S
3597	EB	12	0	1	0	C1, R/S
5450	EB	12	0	1		R/S
5526	EB	12	0	1		R/S
6196	EB	12	0	1	1/8	R/S, picture
6623	EB			1		
6869	EB	12	0	1		R/S, picture
6890	WB	6	3	1	1/8	
8607	EB	6	3	1	3/16	Picture
8647	EB	12	0	1		R/S
9863	EB			1		Did not find.
10798	EB			1		End section 1
-	EB	12	0	1	0	C2, R/S. Did not get wheel distance.
0				3		Section 3, intersection 260th, eastbound.
1079	WB	6	0	3	3/16	
5300				3		Section 3, mile 1
				3		Found at least one low severity (< 1/8) bump each 0.1 mile.
0				3		Section 3, mile 2 "CR15" sign in EB lane, eastbound.
1987	EB	6	3	3	1/8	no crack
5200				3		End section 3.
				3		Found at least one low severity (< 1/8) bump each 0.1 mile.

(a) Measurement performed with ruler marked with 1/16-inch gradations.
(R/S) Rout-and-seal.

Table 24. Methods Section 2 Inspection Log.

Distance	Lane	Crack length, ft	Centerline Offset, ft	Test Section	Measurement, inch[a]	Remarks
0				2		Section 2, Intersection CSAH 5 and 24th St., northbound.
2450	SB	12	0	2	1/4	Bumps "shaved off" full width over 3ft
2550	SB	3	3	2	1/4	Bump scraped off.
2554	SB	3	3	2	1/4	Bump scraped off.
2760	SB	3	3	2	3/16	Bump scraped off.
2764	SB	3	3	2	1/8	Bump scraped off.
2930	NB	6	0	2	1/8	
2930	SB	6	0	2	1/4	Near transverse crack.
3100	SB	3	3	2	1/8	Over shaved point.
3580	SB	3	0	2	1/4	At crack, shaved
3663	NB	3	12	2	1/8	Edge of pavement
3663	SB	3	3	2	1/8	Left wheel path
3882	SB	3	0	2	3/16	At centerline
4125	SB	12	0	2	3/16	Full width
4135	SB	12	0	2	1/8	Full width
4835	SB	4	2	2	1/8	Set of 2
4836	SB	4	2	2	1/8	
5280	SB	12	0	2	3/16	
5295	NB	4	4	2	1/8	
5775	SB	3	0	2	1/4	At centerline
6653	SB	6	0	2	1/8	Another mark around 6663
6985	NB	3	9	2	3/16	
7130	SB	12	0	2	1/8	Set of 2
7132	SB	12	0	2	1/8	
7313	SB	6	0	2	1/4	Set of 2
7315	SB	6	0	2	3/16	
7920	SB	9	0	2	1/8	Set of 2
7922	SB	9	0	2	1/8	
8360	SB	6	3	2	1/8	
8790	SB	6	0	2	1/16	Transverse crack between set of 2 bumps
8792	SB	6	0	2	3/16	Transverse crack between set of 2 bumps
9452	SB	3	3	2	1/8	
9671	SB	6	3	2	1/8	
10592				2		End section 2

(a) Measurement performed with ruler marked with 1/16-inch gradations.

Smoothness Measurements

In an effort to evaluate the effect of overlay bumps on smoothness, an inertial profiler was employed on each of the test site segments prior to and after the overlay construction. This section describes the results of these measurements and presents an analysis of the results.

Sealant Materials and Methods

Pavement profile measurements were taken within one week after the overlay had been constructed on the sealant site. This post-construction IRI was computed and compared with the pre-overlay IRI, and was used to attempt to quantify the effect of bumps on ride measurements. The IRI improvement results with respect to pavement surface temperature are shown in Table 25 and those for surface smoothness versus reservoir geometry are presented in Table 26. Improvement in IRI averaged 49% or more for each reservoir type, when comparing by sealant type and temperature category. On average Geometry B (Routed ¾" x ¾", normal overband) showed the greatest IRI improvement, and D (Routed 1" wide x ¾" deep, normal overband) showed the least.

Under cooler temperature conditions Geometry E (Routed 1½" wide x ½" deep, normal overband) produced the greatest improvement (54%), followed by Geometry B, with 53%. The analysis of higher temperature conditions showed that Geometry B produced the greatest level of improvement (57%) followed by F (saw and seal). The geometries showing the least amount of improvement were A for lower temperatures and D for higher temperature conditions.

Table 25. IRI Improvement vs. Sealant Material (L, M, and H Severity).

Sealant Type	IRI Improvement Southbound (Lower Air Temp)	IRI Improvement Northbound (Higher Air Temp)
No Treatment	56%	54%
3719	56%	49%
3723	50%	54%
3725	49%	51%

The greatest levels of IRI improvement were obtained for the cooler construction condition on cracks with "No Treatment" and for cracks treated with the crumb rubber (3719) sealant material. During the warmer construction condition the elastic (3723) and extra-low modulus (3725) materials produced the greatest levels of IRI improvement. Their percent improvements were just slightly less than for the percent improvement in the lower air temperature case.

It should be noted, however, that the variation in percent IRI improvement was negligible in almost all of the comparisons. The only two that may be significant are the percent improvement vs. sealant material in the low air temperature condition (range of 7%) and vs. reservoir geometry in the high air temperature condition (range of 13%). Further investigation into the improvement in surface smoothness is recommended.

Table 26. IRI Improvement vs. Reservoir Geometry (L, M, and H Severity).

Routing Treatment		IRI Improvement Southbound, % (Lower Air Temp)	IRI Improvement Northbound, % (Higher Air Temp)
A	No Rout	50%	52%
B	Routed ¾" x ¾", normal overband	53%	57%
C	Routed ¾" x ¾", no overband	52%	53%
D	Routed 1" wide x ¾" deep, normal overband	51%	44%
E	Routed 1½" wide x ½" deep, normal overband	54%	49%
F	Saw and seal	51%	53%

Since the sealant site contained a greater variety of installation types than the methods sections it was deemed valuable to perform duplicate or triplicate data collection runs for the same lane-wheel path combinations when possible. Table 27 shows the average smoothness in terms of IRI, in in/mi, for the sealant site prior to, immediately after, and at one and two years after construction.

Table 27. Average Smoothness Data (IRI, in/mi) – Sealant Site.

Direction	Wheel path	Pre-Construction	Post-Construction	After 1 Year	After 2 Years
Northbound	Right	110.0	58.5	54.4	59.9
	Left	80.6	38.4	42.4	43.6
Southbound	Right	112.2	61.7	57.6	66.1
	Left	81.0	39.8	46.3	47.6

The roadway received preventive maintenance after the first winter of service, including crack filling followed by a chip seal, in the spring of 2008. Figure 26 is a photo of the site at the time of the 2008 profile evaluation.

During profile data collection it was also found that a variety of unbound chip thicknesses were encountered throughout the site. When the 2008 profile trace was later evaluated, a number of events were found that were not visible on the 2007 post-overlay trace. These deviations were interpreted as small piles of chip that might occur as a result of transferring aggregate from a dump truck to a chip spreader. This prompted the researchers to perform a follow-up profile evaluation in 2009. Satisfactory conditions were encountered for the 2009 profile collection, and the specific deviations were not observed.

Figure 26. Chip Seal on Sealant Site.

Figure 27 and Figure 28 compare the IRI collected over the full length of the site between July 2007 and May 2009. From the figures it is apparent that the IRI improves dramatically on all sections after construction of the HMA overlay. After one year it appears that the IRI of the right wheel paths may have improved slightly, perhaps due to the chip seal, while the left wheel paths show deterioration of at least 12 percent.

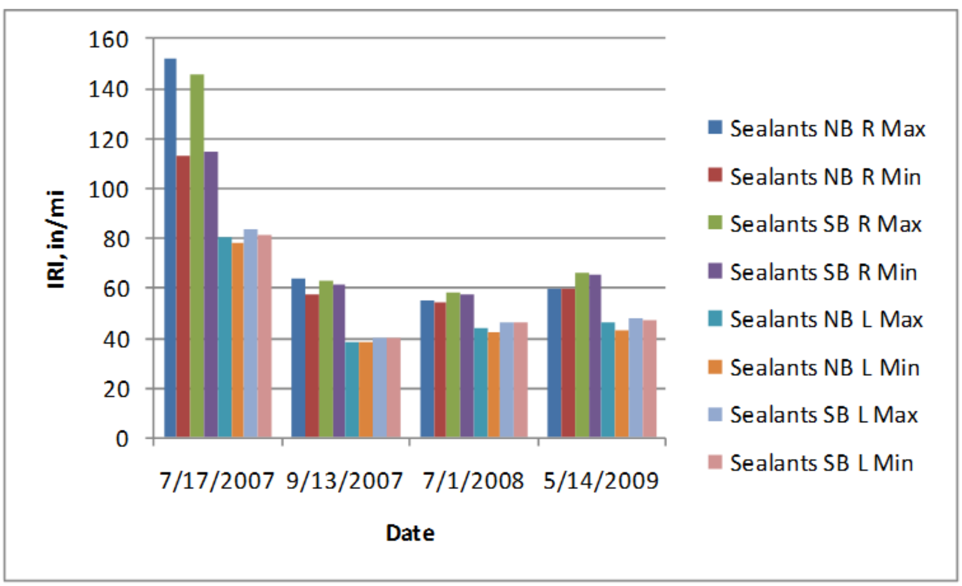


Figure 27. Smoothness Data for Sealant Site.

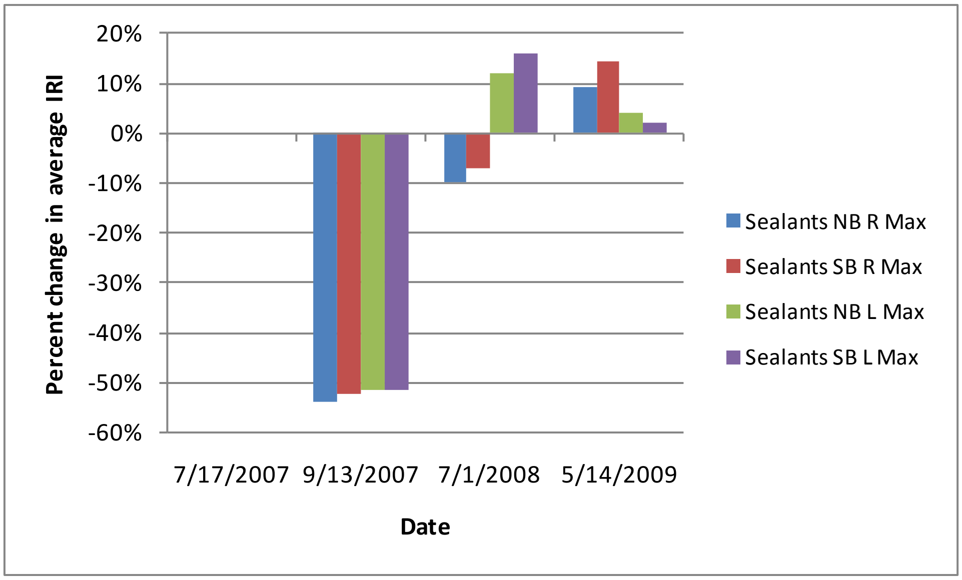


Figure 28. Percentage Change in Smoothness on Sealant Site.

A statistical test of equal means for the IRI data suggests the sealants site ride condition was similar in 2007 and 2008, and the condition in 2009 was more like 2008 than 2007. The results, summarized in Table 28, support the idea that the chip seal applied one year after overlay had an additional benefit of maintaining ride quality, especially for the right wheel path. After one year in service the chip seal and overlay combination began to show a measurable deterioration in ride quality.

Table 28. Paired T-Test For Equal Means – Sealant Site.

Paired IRI Data	2007 and 2008	2007 and 2009	2008 and 2009
P(T<=t) two-tail	83%	4%	9%

Construction Methods

The project team collected profile measurements of the paving performed on the methods section on 1 August 2007. Data was collected in the right wheel path of the northbound and southbound lanes between 240th and 260th Streets. Profile measurements were collected, and analysis of ride quality was reported in terms of IRI. Summary values for the methods sites are listed in Table 29, in inches per mile. All measurements were taken in the right wheel path.

Table 29. Average Smoothness Data (IRI, in/mi) – Methods Sites.

Section	Direction	Pre-Constsruction	Post-Construction	After 1 Year	After 2 Years
1	Eastbound	96.9	57.8	56.0	59.8
1	Westbound	121.4	58.3	56.3	58.8
2	Northbound	108.2	53.9	58.4	59.4
2	Southbound	113.1	57.1	55.0	62.8
3 part 1	Eastbound	110.0	55.4	55.0	63.4
3 part 1	Westbound	100.4	53.6	54.7	67.0
3 part 2	Eastbound	91.1	43.1	46.4	56.2
3 part 2	Westbound	113.2	49.7	49.6	49.9
4	Eastbound		72.4	76.1	80.4
4	Westbound		66.5		77.0

Figure 29 and Figure 30 compare the IRI collected over the full length of the construction materials sections between July 2007 and May 2009. From the figures it is apparent that the IRI improves dramatically on all sections after construction of the HMA overlay, as would be expected. These sections received maintenance crack filling, without routing, after the first winter of service. Collection of profile data occurred after crack filling.

Profile analysis results from 2008 were similar to the post-overlay condition in 2007. By 2009 the IRI of all sections showed deterioration, with an average increase in roughness of 10 percent.

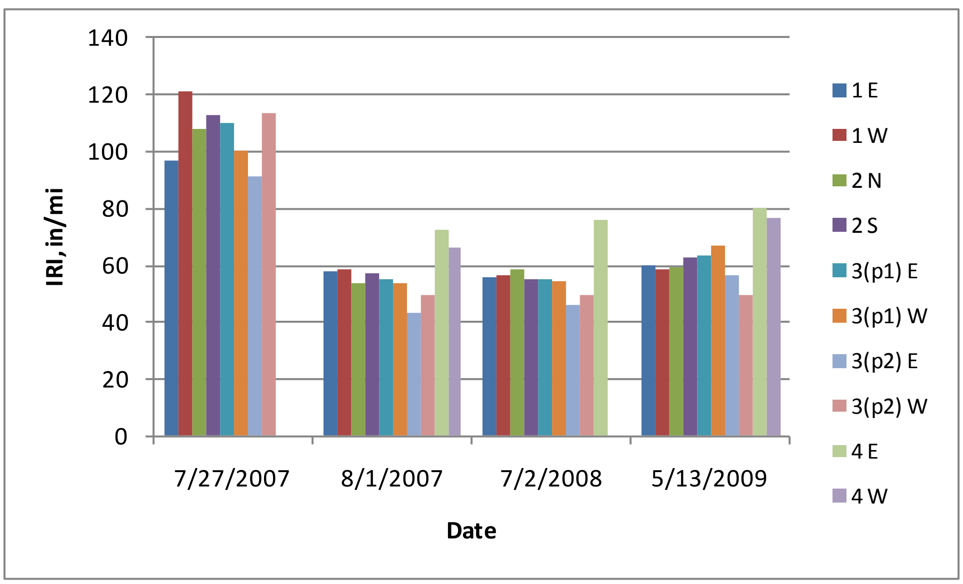


Figure 29. Ride Condition Range for Methods Sites.

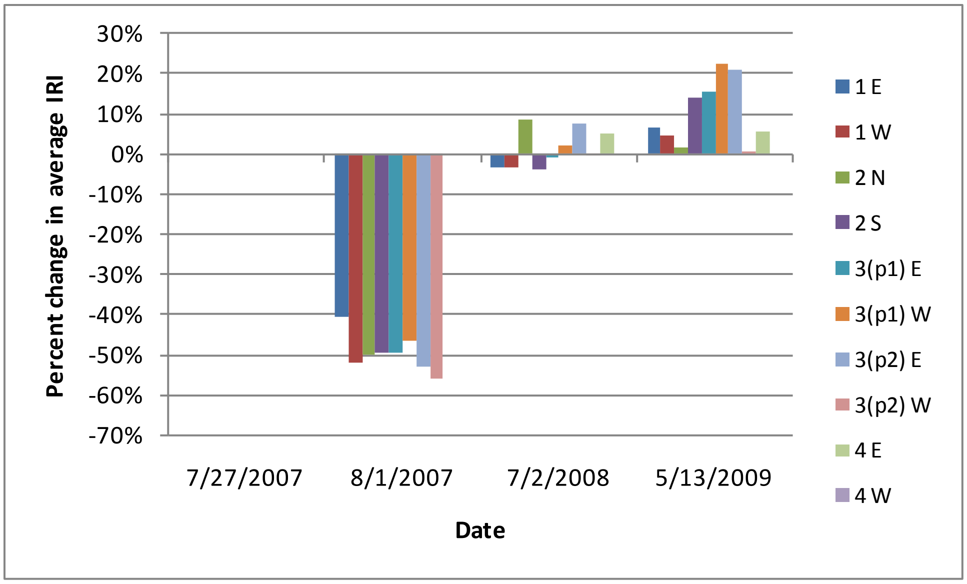


Figure 30. Percentage Change in Ride, Methods Sites.

A statistical test of equal means for the IRI data, summarized in Table 30, supports that the ride quality of the methods sites was fairly constant through the first year of service, with measurable deterioration in the second year of service.

Table 30. Paired T-Test for Equal Means – Methods Sites.

Paired IRI Data	2007 and 2008	2007 and 2009	2008 and 2009
P(T<=t) two-tail	45%	0.2%	0.4%

Chapter 5. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents conclusions and recommendations based on the results of the research conducted under this project. The effectiveness of the various sealant materials and methods, as well as the construction methods test sites are discussed. The recommendations contained in this chapter are included in the updated *Common Practices for Avoiding Bumps in Overlays* booklet prepared under the original INV-802 project, in Appendix A of this report.

In many cases the occurrence of bumps in overlays can be directly related to sealant type and/or reservoir. More often the cause is related to rolling techniques (type of rollers, vibratory or static, temperature at which various stages of compaction are conducted, etc.). Recommended actions, both before construction (sealing cracks) and during construction (rolling techniques) are discussed in this chapter.

Conclusions

Monitoring was performed on single-lift HMA highway overlay projects that were constructed in 2007. The test sections were located in two counties in southwestern Minnesota, and are referred to as the methods sites (constant materials, variable construction methods), and the sealant site (constant construction methods, variable materials) The duration of post-overlay monitoring activities was from August 2007 to May 2009. Monitoring activities included:

- measuring bump height with a carpenter's level and ruler,
- recording bump locations with a measuring wheel or GPS equipment, and
- collecting profile data.

Pavement profile measurements were performed on all sections prior to construction and profile monitoring continued to May 2009. Over 70 individual profiles were collected on the methods and sealant sites during the course of this project. The FHWA ProVAL software was used to analyze the data and to report ride quality in terms of IRI. The methods sites were analyzed in their entirety for ride quality and bumps. The sites were analyzed in their entirety for ride quality, but were also divided into short test section lengths in order to compare bump formation versus material type and rout configuration.

The profile analysis showed that ride conditions improved dramatically on both the methods and sealants sites immediately after construction of the single-lift overlay, as would be expected. After one winter both sites received preventive maintenance crack filling without routing. The sealant site also received a chip seal treatment. Profile data was collected shortly after the maintenance activities and again one year later.

Comparison of the sealants and methods ride quality trends showed that the sealant site profiles collected just after chip sealing would be valid for a network level evaluation. However, the presence of fresh chip material introduced too much interference for the data to be used at the research level. Analysis of profile data from the final collection in 2009 showed that the effect of the chip seal had diminished on the sealants site, and indications were that future performance would be similar to the methods sites.

Construction Methods Site

Visits to bituminous overlay construction at the county test sites and several projects in the Twin Cities area produced observations that were collected for a variety of conditions. Variables included a range of transverse crack/joint conditions, ambient temperatures (60 – 90 °F), number of asphalt lifts (single-lift over bituminous construction or multiple-lift over concrete), design (high- and low-traffic volume mixtures), and equipment use (variety of equipment combinations and roller patterns).

Bump development occurred at most of the construction sites, but was more frequent, and more severe, at certain sites. Although most of the bump formations occurred at or near transverse cracks, some formations were found at locations between cracks. In some cases bump formations were perceived to be the result of expansive crack sealant, however, laboratory testing for volume change of sealant subjected to high temperatures did not provide evidence that any expansion occurred, contradicting the theory. Mild statistical relationships were found to exist between the occurrence of bumps and precipitation and changes in ambient temperature.

Mixtures designed for high traffic volumes typically receive a greater amount of compaction effort. Single-lift overlays of low traffic volume bituminous roads developed bumps less frequently than did initial lifts placed on high volume concrete roads. Observations showed that formations occurred more frequently on projects where roller equipment provided a greater number of roller passes, especially vibratory roller passes.

Thermal imaging equipment showed that during overlay construction a difference exists between unsealed cracks and cracks that contain sealant or patching mixture. Thermal evaluations showed that at sealed and leveled crack locations the temperature readings remain several degrees higher than the rest of the cooling asphalt mat. These non-homogeneous conditions, combined with the fact that asphalt has greater workability at higher temperatures, support the theory that some bump formations may be due to slippage within an asphalt layer.

Based on the observations of this project it is recommended that bumps will be reduced by the following activities.

- Preparing the surface prior to overlay construction with activities such as patching and leveling.
- Monitoring pavement temperature to avoid conditions that promote slippage within the asphalt mat. Be watchful for tender mix behavior such during late stages of breakdown rolling and intermediate rolling. If tender behavior occurs, suspend rolling operations until the mat will support finish rolling.
- Sweeping the road prior to overlay construction. Locate and remove pieces of partially-attached and loose sealant protruding from cracks/joints.
- Using a pneumatic tire roller. In the event of bumps, alter the roller equipment pattern and use the rubber tire or a non-vibratory steel roller for breakdown rolling.

Sealants Site

From the data analysis and construction observations on the sealants site it was found that among treated sections various combinations of air temperature at time of construction, geometry, and sealant type affected the rate and severity of bump formation. With respect to sealant material, the low modulus sealant (3725) performed the least favorably, in both air temperature conditions. The cracks without sealant at all produced the best results, but only somewhat better than the other two Mn/DOT types (crumb rubber – 3719 and elastic – 3723). With respect to reservoir geometry, those with the largest width dimensions (1x¾-recessed and 1½x½-normal) performed the least favorably in both air temperature conditions. The best-performing geometries were ¾x¾-no overband and saw and seal – primarily those with narrow width and no overband.

Since the sealants site was established in both directions (northbound and southbound) the overlay paving was conducted in the area of the site on two different days. The air temperature on the second day was significantly greater than on the first, and the same segments that had exhibited some bumps on the first day produced many more bumps, and of higher severity on the second day. This is likely due to the effect of either the "slipping" or "sticking" effects (two of the possible causes identified in the INV-802 report). Essentially, the crack sealants were hotter on the second day, and the discontinuity in the area of the sealant produced an enhanced effect as the paver and rollers passed by the existing cracks.

Summary

This section summarizes the sealant materials and methods as well as the construction methods that are more highly correlated with the occurrence of bumps in overlays. These materials, methods, and activities are incorporated into the updated *Common Practices for Avoiding Bumps in Overlays* booklet prepared under the original INV-802 project, in Appendix A of this report, and also provided as a standalone file for ease of printing and publishing.

Sealant Materials and Methods

In higher ambient air temperature conditions, bumps were more prevalent. In INV-802, it was found that at existing pavement temperatures greater than 125°F and air temperatures greater than 80°F, bumps were more prone to occur. Table 31 shows the relative amount of bumps that occurred on the sealants site compared to the ambient air and existing pavement temperatures.

Table 31. Bump Observations vs. Air and Pavement Temperature.

Temperature of Ambient Air and Existing Pavement	All Bump Severities	High-Severity Bumps
Low	Few	Few
High	Few	Many

Table 32 shows the relative performance of the sealant materials at the sealants site. As can be seen, cracks without sealant exhibited no bumps, while those with sealants exhibited few to many bumps. High-severity bumps are those that could be felt by the traveling public. Some of these were found in the hot-poured elastic section of the sealants site.

In Table 33, the reservoir geometry is compared with the relative rate of bumps in the overlay. As can be seen in the figure, cracks without routing, and those with narrow routing, performed the best. The saw and seal section is also included in this grouping. Those with wider routing performed worse than the others.

Table 32. Bump Observations vs. Crack Sealant Type.

Sealant Type	All Bump Severities	High-Severity Bumps
No sealant	None	None
Hot-poured, crumb rubber (Mn/DOT 3719)	Few	None
Hot-poured, elastic (Mn/DOT 3723)	Few	None
Elastic, extra-low modulus (Mn/DOT 3725)	Many	Few

Table 33. Bump Observations vs. Reservoir Geometry.

Reservoir Geometry	All Bump Severities	High-Severity Bumps
No Rout	Few	Very Few
Routed ¾” x ¾”, normal overband	Few	None
Routed ¾” x ¾”, no overband	None	None
Routed 1” wide x ¾” deep, normal overband	Many	Very Few
Routed 1½” wide x ½” deep, normal overband	Many	Many
Saw and seal	None	None

In Table 34, roller configurations at various times during the cool-down phase of the asphalt are compared to the effectiveness in preventing bumps. The two configurations that avoided steel vibratory rollers while the asphalt was at its highest temperatures performed the best. It is recognized, however, that compaction at higher temperatures is often critical to achieving the density required, and that lower density asphalt concrete pavement could result in rutting, shoving, and other distresses due to traffic after construction is complete. Contractors should keep this in mind as they plan their roller configuration and their response to bump formation.

Table 35 shows that there is a correlation between the temperature of the asphalt mat at the time the breakdown rollers begin compaction and the effectiveness in preventing bumps. This correlation was shown to be fairly weak, and additional investigation into this effect should be conducted.

Table 34. Bump Observations vs. Roller Configuration.

Roller Configuration	Success in Preventing Bumps?
#1 Pneumatic Breakdown 2 Steel (before tender zone) Steel Finish	No
#2 Steel Vibratory Breakdown Pneumatic (before tender zone) Steel (before tender zone) Steel Finish	No
#3 2 Steel Vibratory Breakdown Pneumatic (before tender zone) Steel Finish	No
#4 3 Steel Vibratory Breakdown Steel Finish	No
#5 2 Steel Vibratory Breakdown Steel Finish	No
#6 Pneumatic Breakdown 2 Steel (before tender zone) Pneumatic (before and after tender zone) Steel Finish	No
#7 2 Pneumatic Breakdown Steel (before tender zone) Steel Finish	No
#8 2 Pneumatic Breakdown (into tender zone, to 200 °F) Achieve Density Steel Finish (200 °F and below)	Yes
#9 2 Pneumatic Breakdown (before tender zone) Steel Finish	Yes

Table 35. Bump Observations vs. Mat Temperature at Breakdown.

Asphalt Mat Temperature at Breakdown	Success in Preventing Bumps?
Low	Yes
High	No

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APPENDIX A. UPDATED BUMP AVOIDANCE BOOKLET

Front Cover

Common Practices for Avoiding Bumps in Overlays

(and what to do if they occur)

Minnesota Local
Road Research Board

updated
August 2010

Back Cover

August 2010
LRRB Publication No. %%%

Common Practices for Avoiding Bumps in Overlays

(and what to do if they occur)

This booklet is intended to aid local and state highway construction, maintenance, and design staff understand the potential causes and possible remedies for bumps that occur during overlay construction.

It comprises the actual experiences and of those familiar with overlay paving in Minnesota – county engineers, contractors, and paver and roller operators, as well as the results of research experiments and long-term monitoring in the field. The strategies contained herein have provided good results for those who have used them.

The Local Road Research Board does not specifically endorse any particular method described in this booklet, but encourages local agencies to experiment with those that seem promising and to implement those strategies that work best for them.

Further information can be obtained by contacting the Minnesota Local Road Research Board at www.lrrb.org.

Crack Sealing

- **Avoid sealant overbanding**
  Many agencies recommend applying the smallest overband possible with the equipment available. This usually means using a two-inch wide wand or simply filling a routed crack with no overband at all.

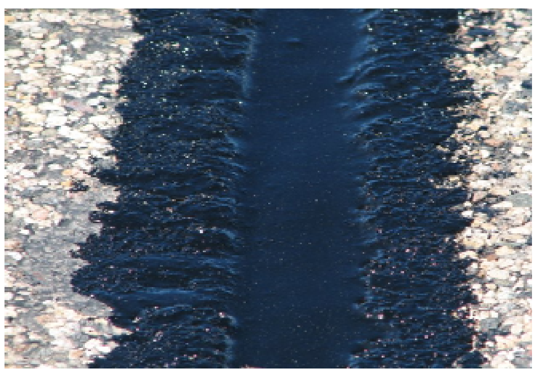
Crack Sealing

- **Let the sealant material age**
  A common practice is to avoid overlay placement until the sealant has aged for at least one year in the field. There may be some benefit to a stiffer sealant material when placing an overlay.

Crack Sealing

▷ Minimize Sealant Reservoir Size

Wider and deeper routing operations can induce large volumes of sealant, essentially using more material than necessary, and increases the probability that bumps will form in a subsequent overlay.



Crack Sealing

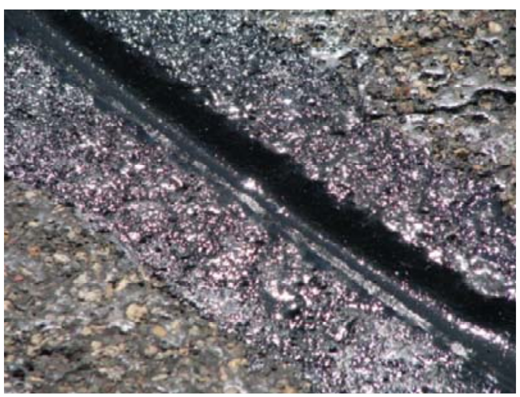
▷ Choose Sealant Type Carefully

Not all sealant materials perform the same. While sealant type is chosen for specific properties during placement and for long-term benefits in preventing water from infiltrating a crack, some sealants can increase the probability of bump formation in an overlay, including those with extra-low modulus properties.

Crack Sealing

▷ **Leave sealant material below pavement surface**

Another sealant material option is to rout and seal, and fill the rout so that the surface of the material is about ¼ inch below the surface of the existing pavement. When the overlay material is pressed into the rout and onto the sealant material, there will be some space available for the material to go without forming a crack.



Remove the Sealant Material

▷ **Remove sealant material**

One way of removing the sealant material is by ripping it out with a small backhoe and hook attachment. In most cases, the sealant "ropes" can be pulled from the cracks and removed from the pavement.

Once the sealant material is removed, there is little probability of bumps occurring.

This method is labor-intensive, especially if the sealant does not come out of the cracks in long ropes. There is usually some residual sealant material that must be either removed before overlay placement or left in the cracks.

Remove the Sealant Material

▷ Mill before overlaying

Another way of removing the sealant from the roadway is to mill the project prior to overlaying. Care must be taken, however, with the milling equipment and the type of sealant material. Some types of material may be detrimental to the operation of the equipment.

If the milled asphalt is intended to be used as recycled material, it must not contain used crack sealant. In this case, the sealant must be removed prior to milling, as described in the previous section.

Remove the Sealant Material

▷ Mill and fill a narrow path

Another suggestion for removing the sealant material is to mill a 1-inch deep, 12-inch wide path transverse to the roadway centerline. This will remove the sealant and much of the raveled crack edges, if any.

Immediately fill the milled section with hot mix to restore the roadway surface until the overlay is placed.

Care should be taken when employing this method, however, because sealant material can become hot and render the milling apparatus inoperative.

Temperature Management

Appropriate timing of rolling
Some indications are that a short delay in the rolling operations can decrease the severity of bumps once they occur. By delaying the application of breakdown rollers, the overlay mat will cool slightly and the sealant below will heat up, thereby becoming softer.

Temperature Management

One potential problem with this practice is that the longer rolling is delayed, the less likely that the density requirement can be met. Often agencies that employ this method waive the density requirement.

It is strongly suggested that when using this method, the contractor or engineer make use of Mn/DOT's software "PaveCool" to estimate asphalt temperatures and to avoid detrimental effects on density.

Additional Compaction

▷ Use a small roller transversely

If bumps are observed, one practice to mitigate their severity is to use a small "walk-behind" roller to apply additional compaction to the specific area needed. Applying additional compaction with full-size vibratory rollers generally results in worsening the bumps and pushing the overlay material back and forth above the crack.

Roller Operations

▷ Use single vibratory drum

After noticing the formation of bumps, some roller operators have reported fewer bumps by using the lead drum as the drive roller and setting it to static operation. The following drum is then left as to provide the vibratory compaction.

While this may not remove bumps that have already formed, it is reported that this practice can sometimes reduce the probability of further bumps forming.

Roller Operations

- **Use pneumatic breakdown roller**
  Often the use of a pneumatic roller for breakdown operations can be used in preventing bump formation. This practice, together with temperature management options, is often effective.

Roller Operations

- **Use two pneumatic rollers**
  The use of two pneumatic rollers down to temperatures of 200°F and one steel finish roller soon afterward has been observed to stop bumps from occurring after they had been noticed.

Roller Operations

▷ Overlap roller types

If bumps are observed, a method that works for some roller operators is to overlap vibratory and pneumatic rollers. By alternating passes between steel-drum vibratory and rubber-tire pneumatic rollers, the kneading process seems to work the bumps back down in some cases.

Roller Operations

▷ Hold back finish roller

Another method used in some cases to recompact bumps that have formed is to hold the finish roller until the mat has cooled to between 120 and 200° F. At lower temperatures, the finish roller may still be able to compact the overlay material further in the area of the bump, and keep it down.

Roller Operations

▷ Don't over roll

A common rule of thumb from roller operators is not to over roll the mat when bumps have occurred. As mentioned previously, addition rolling to compact the bumps often results in worsening the situation by pushing the overlay material back and forth above the crack.

Pre-Overlay Preparation

▷ Tight-blade leveling

Place a thin-lift, grader-placed, fine-aggregate layer on the surface of the existing pavement prior to overlay placement. Some agencies suggest that the motor grader scrape the surface of the pavement when conducting this operation to place a very thin layer. Other agencies suggest placing a slightly thicker layer. All those who suggest this method recommend compaction of the thin layer with rubber-tire rollers.

Traffic may be allowed on the roadway between the application of the tight-blade leveling course and the overlay.

Pre-Overlay Preparation

▷ Paver-laid leveling course

As an alternative to tight-blade leveling, the placement of a thin-lift, paver-laid overlay prior to the primary overlay, can also minimize the possibility of bump formation. This type of overlay should be approximately ½ to 1 inch thick, and compacted with rubber-tire rollers.

There may be concerns with measuring the density of such a thin layer. Density of this layer is important, and care should be taken ensure that it is compacted properly.

After this leveling course, a single 1½- to 2½-inch overlay may be placed. A two-lift primary overlay may also be placed.

As with the tight-blade leveling operation, traffic may be allowed on the surface between placement of the leveling course and the primary overlays.

Physically Remove Bumps

▷ Grind surface smooth

Some paving contractors have taken a more direct approach to removing bumps after they have formed – grinding them smooth. One drawback to this is that the overlay material in the area of the bumps may not be compacted well enough, and may be further compacted by traffic after being ground smooth. If this occurs, a dip in the surface may result.

Construct Two-Lift Overlay

- **The second lift is usually better**
  When constructing a two-lift overlay, the first lift bears the effects of the crack sealant, and the second lift is almost always bump free. Some of the previous suggestions are almost equivalent to the two-lift recommendation. Many overlays thicker than two inches are designed to be constructed in two-lifts.