Retrofit Dowel Bars in Jointed Concrete Pavement—Long-Term Performance and Best Practices

Thomas Burnham[1] and Bernard Izevbekhai[2]

ABSTRACT

As jointed concrete pavements age, they typically experience panel cracking, joint or crack faulting, and surface distress. To maintain user satisfaction and safety, the agency or owner must identify the causes of the distress and consider types of feasible repairs, if any. These repairs range from partial to full-depth concrete repairs for spalled or cracked panels, to load-transfer and ride-quality restoration schemes for faulted cracks and joints. Retrofitting dowel bars into a distressed and faulted concrete pavement has become a proven technique for restoring or improving the capacity of jointed concrete pavements. The backfill materials and installation techniques used in retrofitting dowel bars must, however, be carefully designed. Numerous field and laboratory trials have been carried out in Minnesota in the recent past, allowing engineers and contractors to refine the installation techniques and materials necessary to produce long-lasting and effective projects. This paper provides a history of the development of best practices for retrofitting dowel bars into jointed concrete pavements located in the extreme climate of Minnesota. The performance of field test sections, up to 13 years old, are discussed in relation to dowel bar location, long-term load-transfer capability, and durability of backfill materials. Implemented design changes based on results from accelerated loading laboratory studies are discussed. An effective installation method and materials testing process, required of contractors before constructing retrofit projects in Minnesota, is described. Retrofit dowel bar installation, in conjunction with restoration of the surface through diamond grinding, has been proven to significantly extend the capacity and serviceable life of many concrete pavements in Minnesota.

INTRODUCTION

This paper discusses the long-term field performance of four experimental retrofit dowel bar test sections in Minnesota. It also outlines the development of the current best practices used by the Minnesota Department of Transportation (Mn/DOT) for joint and crack load-transfer restoration, including those influenced by accelerated laboratory testing.

Background

Highway agencies typically expect long and relatively maintenance-free performance from jointed concrete pavements. However, due to age, increased traffic loads, older design standards, or poor construction, these pavements eventually will require some maintenance or rehabilitation.

As jointed concrete pavements age, they typically experience one of three distresses. Often the first distress to appear will be panel cracking, either across the middle of the panel, or

---

[1] Thomas Burnham, Senior Road Research Engineer, Minnesota Department of Transportation, Office of Materials and Road Research, 1400 Gervais Avenue, Maplewood, MN 55109; phone: 651-366-5452; email: tom.burnham@dot.state.mn.us

[2] Bernard Izevbekhai, Research Operations Engineer, Minnesota Department of Transportation, Office of Materials and Road Research; phone: 651-366-5454; email: bernard.izevbekhai@dot.state.mn.us

near the corners of the panels. Mid-panel cracking is most often caused by designs with panel lengths greater than 20 ft (6.1 m). These designs were common in Minnesota during the 1960s and 1970s, and often contained reinforcing steel near mid-panel to keep the expected crack tight. Corner cracking is often found in designs with skewed transverse joints, a design feature carried over from projects with undoweled joints.

The second distress to occur in jointed concrete pavement is faulting, or stepping, of the transverse cracks or joints. For longer panel length designs, the faulting often occurs at the mid-panel crack after the reinforcing steel has been weakened by rust, often to the point of rupture. Other designs will fault at the transverse joints if dowel bars become significantly deteriorated, or if they were never placed intially due to low design traffic volumes. In some cases, poor construction practices lead to joints with misaligned dowels bars, which can rapidly lead to joint faulting under heavy traffic volumes.

The final distress to occur in jointed concrete pavements is surface distress. This is often demonstrated by shallow surface spalling or delamination caused by material incompatibility, chemical attack, or environmental exposure (freeze/thaw).

Once a concrete pavement experiences some type of distress, the agency or owner must identify the cause and consider types of feasible repairs, if any. These repairs range from partial to full-depth concrete repairs for spalled or cracked panels, to load-transfer and ride-quality restoration schemes for faulted cracks and joints.

The use of retrofit dowel bars for load-transfer restoration has become a proven technique over the last two decades. Good information on other agency's experience with retrofit dowel bars can be found in references by Hall et. al. (*1*), Larson et.al (*2*), and Pierce et al. (*3*). Much of the research and development on this technique has been done with regards to the number and geometry of the dowel bars required to effectively transfer load across cracks or joints. Another important aspect to be studied however, is the backfill mortar material. This material needs to both secure the dowel bars to the pavement for transfer load, and demonstrate durability for long-term performance.

Load-transfer restoration using retrofit dowel bars has become a common pavement rehabilitation technique in Minnesota. Like many other states however, most of the early designs were experimental. Several dowel bar patterns and backfill materials were incorporated into test sections within rehabilitation projects, to investigate their performance in Minnesota's extreme climate. Mn/DOT first installed retrofit dowel bars into a distressed concrete pavement in 1994. To speed up the understanding of various retrofit dowel bar design features, Mn/DOT and the University of Minnesota teamed together in the late 1990's to develop an accelerated load test platform, known as the "Minne-ALF." Testing results from the device resulted in the implementation of several innovative retrofit dowel bar designs and installation techniques. More information on the Minne-ALF results can be found in references by Embacher et al. (*4*) and Popehn et al. (*5*).

LONG-TERM PERFORMANCE OF TEST SECTIONS

The following sections discuss the design and long-term field performance of four retrofit dowel bar projects constructed in Minnesota from 1994 to 1999.

TH 52, Zumbrota

Project Description

The first retrofit dowel bar project in Minnesota was constructed in 1994 on Minnesota Trunk Highway 52 (TH 52) near Zumbrota. The pavement on this project was originally constructed in 1984 of jointed reinforced concrete, 225 mm (9 in.) thick. After 10 years of heavy-truck traffic and extreme weather, the 8.2-m-long (27-ft) panels contained mid-panel cracks that demonstrated virtually no faulting. The mid-panel reinforcing steel appeared to be intact, and the original sawed transverse joints with dowels were in good condition. The objective of this project was to determine if retrofit dowel bars could prevent, or significantly slow down, the development of faulted mid-panel cracks, and thus extend the service life of the pavement. Since there was no faulting of the cracks (or sawed joints) prior to retrofitting, surface grinding was not included in this project.

Design Variables

The test sections in this project were designed to study the configuration, length, and number of retrofit dowel bars necessary to preserve long-term load transfer across transverse mid-panel cracks. Two types of backfill mortar material were used on this project to compare their load-transfer capability and durability. Except for three experimental slots, the retrofit dowel bars slots on this project were established using the saw-and-chip method. More information on this installation method will be discussed later in the best practices section of this paper.

The layout of the five test sections is shown in Figure 1. Retrofit dowel bar pattern variations included combinations of three, two, or no bars in the wheel tracks for both the driving and passing lanes. Dowel to dowel spacing in the wheel tracks was 300 mm (12 in.). For comparison, a control section containing no retrofit dowel bars, but sealed mid-panel cracks, was monitored as part of the study.

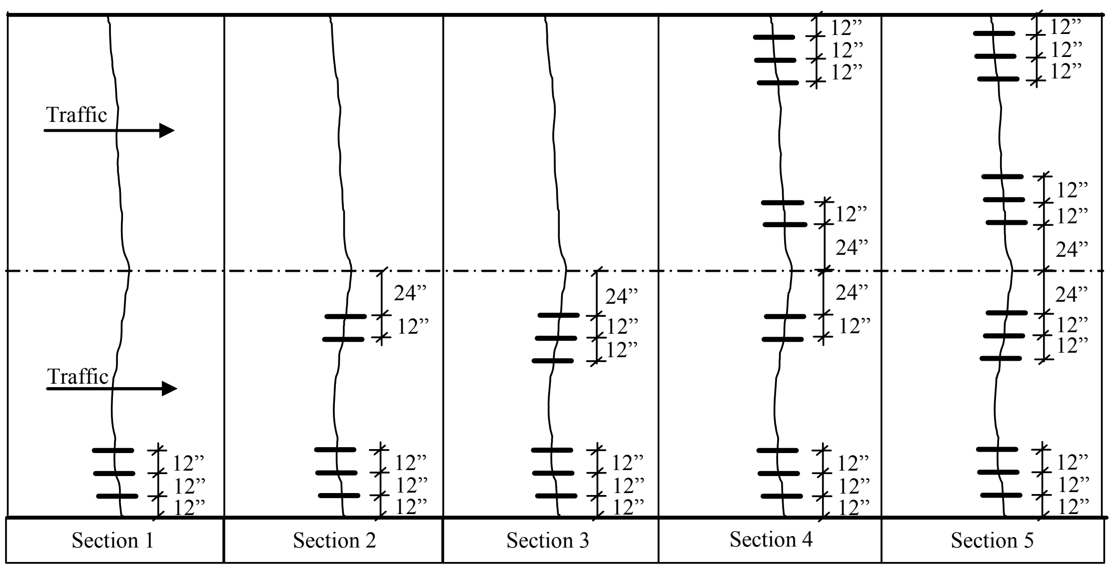

Figure 1. TH 52 test section retrofit dowel bar patterns.

Each test section is approximately 322 m (1,056 ft) long and is divided into two subsections. Transverse mid-panel cracks in the first subsection (containing approximately 20 panels) were retrofit with dowel bars 38 mm (1.5 in.) in diameter by 380 mm (15 in.) long. Transverse mid-panel cracks in the second subsection were retrofit with dowel bars 38 mm (1.5 in.) in diameter by 457 mm (18 in.) long. Each subsection also began with the first four mid-panel cracks retrofit using a polymer-modified quickset patching (PMQP) backfill mortar material. The remaining retrofit dowel bars in each subsection were installed using Mn/DOT's high early strength concrete repair patching material, designated as Mn/DOT 3U18. The primary reason for testing two types of backfill mortar is that Minnesota's extreme climate places severe demands on such materials. Pavement temperatures in Minnesota range from –40 °C to 55 °C (–40 °F to 131 °F), and frequent freezing and thawing conditions in the winter and spring necessitate the use of chemical deicers. In addition, retrofit dowel bar projects typically require minimal traffic disruption, therefore requiring early strength gain of the mortar. Discovering backfill mortars that meet early strength and long-term durability criteria is the key to developing best practices for this pavement rehabilitation technique. The performance of the retrofit mortars on this project will be discussed shortly.

Observed Performance

The retrofit dowel bar test sections on TH 52 were installed in 1994, and therefore to date have had over 14 years of exposure to traffic (heavy commerical average daily traffic [HCADT] = approximately 2,100)(*6*) and weather. Recent site visits took place in October 2006 and February 2007. During those visits, surface distress on the test sections was recorded as being minimal. Faulting of the transverse mid-panel cracks remains very low. There are a small number of distressed retrofit dowel bar groups, predominantly affected by longitudinal cracking in the panels (see Photo 1). Despite early concerns about shrinkage cracking in the many of the slots (unpublished report by Mn/DOT Geology Unit), there is little deterioration of the backfill mortar after 14 years of service. Photo 2 shows retrofit dowel bar slots with Mn/DOT 3U18 backfill mortar in very good condition. Several slots with PMQP backfill mortar experienced a loss of material of approximately 13 mm (0.5 in.) below the surface, however the integrity of the remaining material in the slot appeared to be sound (see Photo 3).

Photo 1. Distress in TH 52 retrofit dowel bars caused by longitudinal panel cracks.

Photo 2. TH 52 slots with Mn/DOT 3U18 backfill mortar after 13 years.

Photo 3. Loss of PMQP mortar near surface of slots on TH 52.

The objective of the research for the TH 52 test sections was to determine the long-term capability and durability of retrofit dowel bars placed across transverse mid-panel cracks. The two prominent performance measures to examine are the crack faulting and load-transfer efficiency. Periodic fault measurements of the mid-panel cracks were recorded throughout the life of the project. A randomly selected number of retrofit cracks were measured in October 2006 and revealed an average fault value of only 1.7 mm (0.067 in.). This low level of faulting is certainly barely perceptible to the traveling public. Therefore, in terms of reducing or preventing mid-panel crack faulting in reinforced concrete pavements in Minnesota, the installation of retrofit dowel bars across previously unfaulted mid-panel cracks has successfully achieved the objectives.

Although the retrofitted cracks in TH 52 have not begun to significantly fault, there is interest in understanding when they might began that process. One common measure of a crack or joint's condition is load-transfer efficiency (LTE). LTE is defined as the deflection of the unloaded side of a joint or crack, divided by the deflection of the adjacent loaded side, multiplied by 100 percent. To measure LTE, Mn/DOT uses a falling- weight deflectometer (FWD) device. LTE testing has been done several times on the TH 52 project since the installation of the retrofit dowel bars in 1994. Based on measurements taken in October 2006, a range of LTE from 60 to 80 percent was demonstrated by the various test sections. There are some indications from the data that LTE declines more rapidly in cracks retrofit with only three dowels in the outside wheel track of a panel. Additional data will be collected in the near future to confirm any such trend. Despite the low level of LTE (60 percent) in some sections, the cracks were still not appreciably faulting after 13 years of traffic. Perhaps this is not surprising, since the embedded supplemental mid-panel steel across the crack may still be providing resistance to faulting of the crack.

With regards to the various dowel patterns, it seems the performance in terms of ride quality at year 13 is insensitive to the number and length of the retrofit dowel bars as they were designed in this project. The benefit of retrofitting dowels across mid-panel cracks on TH 52 can clearly be seen by observing the faulting that occurred on a number of nearby unsealed mid-panel cracks that had not received retrofit dowel bars (see Photo 4).

Photo 4. Faulted mid-panel cracks without retrofit dowels on TH 52.

TH 12, Willmar

Project Description

In 1996, a retrofit dowel bar project was constructed on Minnesota Trunk Highway 12 (TH-12) near Willmar, Minnesota. The pavement on this project was originally constructed in 1981 of jointed plain concrete, 200 mm (8 in.) thick, with panels 4.6 m (15 ft) long and undoweled transverse joints. By 1996, the transverse joints were experiencing substantial faulting in the outside wheel tracks. Some of the joints had openings as wide as 32 mm (1.25 in.). The objective of this project was to determine if retrofit dowel bars and surface grinding could effectively extend the service life of this pavement.

Design Variables

This project was designed to study the performance of retrofit dowel bars installed across significantly faulted transverse joints. The project included two retrofit dowel bar patterns. The layout of the dowel bar patterns is shown in Figure 2. Short sections of tapering lanes contained transitions from three dowel bars in the outside wheel track, to three dowels in both the outer and inner wheel tracks. Otherwise the latter configuration (six dowels) were retrofit into both the driving and passing lanes. Dowel to dowel spacing in the wheel tracks was 300 mm (12 in.). The first dowel from the edge of the driving lane shoulder was placed at 300 mm (12 in.). The slots were formed using a milling machine, rather than the standard method of saw cutting and chipping. All retrofit dowel bars were 38 mm (1.5 in.) diameter by 457 mm (18 in.) long, and installed using Mn/DOT 3U18 patch mix backfill material.

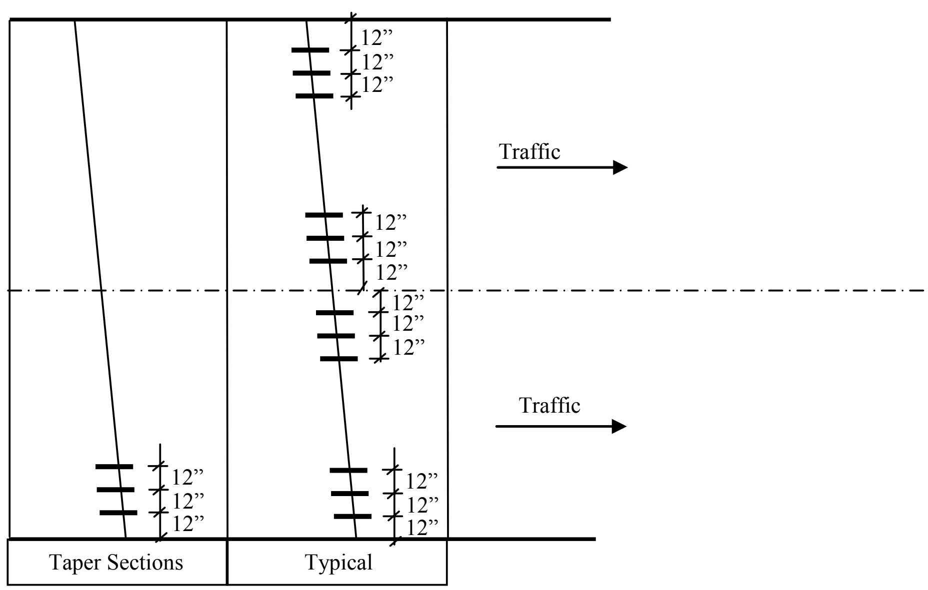

Figure 2. TH 12 test section retrofit dowel bar patterns.

Observed Performance

The retrofit dowel bars on TH 12 were installed in 1996, and therefore have been exposed to over 12 years of traffic (HCADT = approximately 600)(*6*) and weather. Recent site visits took place in October 2006 and February 2007. During those visits, minor surface distress on the retrofit dowel bar slots was noted to occur predominantly near the joints (see Photo 5). The distresses might be linked to the slot milling process, when material near the joint was weakened. Otherwise, there was little deterioration of the Mn/DOT 3U18 backfill mortar after 10 years of service.

LTE testing was measured for a select number of retrofitted joints in October 2006 and ranged from 51 to 65 percent. Initial LTE measurements from shortly after retrofit dowel installation could not be found, so trends could not be established. Despite the low LTE values, fault measurements recorded at the same time as the LTE testing revealed an average value of only 1.5 mm (0.059 in.). It is suspected that faulting levels may accelerate as the LTE continues to decline.

It appears that the installation of retrofit dowel bars on this project, in conjunction with surface grinding, has successful enhanced the performance and lengthened the life of the pavement.

Photo 5. Backfill mortar distress near joints on TH 12.

TH 23, Mora

Project Description

Another experimental retrofit dowel bar project was constructed in 1998 on Minnesota Trunk Highway 23 (TH 23) near Mora, Minnesota. The pavement on this project was originally constructed in 1952 of jointed plain concrete with a trapezoidal design of 225–175–225 mm (9–7–9 in.) thick. Panels were 4.9 m (16 ft) long, and the transverse joints were undoweled. After 46 years of traffic, the transverse joints were experiencing minimal faulting in the inside wheel track and substantial faulting in the outside wheel track. The objective of this project was to determine if retrofit dowel bars and surface grinding could effectively extend the service life of this very old pavement.

Design Variables

The test sections in this project were designed to study the configuration, length, and number of retrofit dowel bars necessary to restore load transfer across (previously undoweled) faulted transverse joints containing minimal aggregate interlock. Two types of backfill mortar material were utilized to compare their load-transfer capability and durability.

The retrofit dowel bar pattern variations in this project included combinations of three, two, or no bars in the wheel tracks for both the driving and passing lanes. The layout of the three test sections is shown in Figure 3. Test Section 1 consists of 160 total joints utilizing a repeating pattern of 20 joints of the sequences 1a, 1b, 1c, 1d as shown in Figure 3. Retrofit dowel bars were 380 mm (15 in.) long and 38 mm (1.5 in.) diameter. The backfill mortar type was Mn/DOT 3U18. Test Section 2 consists of 80 total joints, with 40 joints using rapid set mortar (RSM) backfill, and 40 joints using Mn/DOT 3U18 patch mix. The retrofit dowel bars in this section were 380 mm (15 in.) long and 38 mm (1.5 in.) diameter. Test Section 3 also consists of 80 total joints, utilizing a repeating pattern of 20 joints with 325 mm (13 in.) long retrofit dowel bars, then 20 joints with 380 mm (15 in.) long dowel bars. All of the dowel bars in this section were 38 mm (1.5 in.) diameter and the backfill mortar was Mn/DOT 3U18. Dowel to dowel spacing in the wheel tracks was 300 mm (12 in.). For comparison, a control section containing no retrofit dowel bars, but a diamond ground surface, was monitored as part of the study. Additional information on the layout and construction of TH 23 test sections can be found in a report by Embacher (*7*).

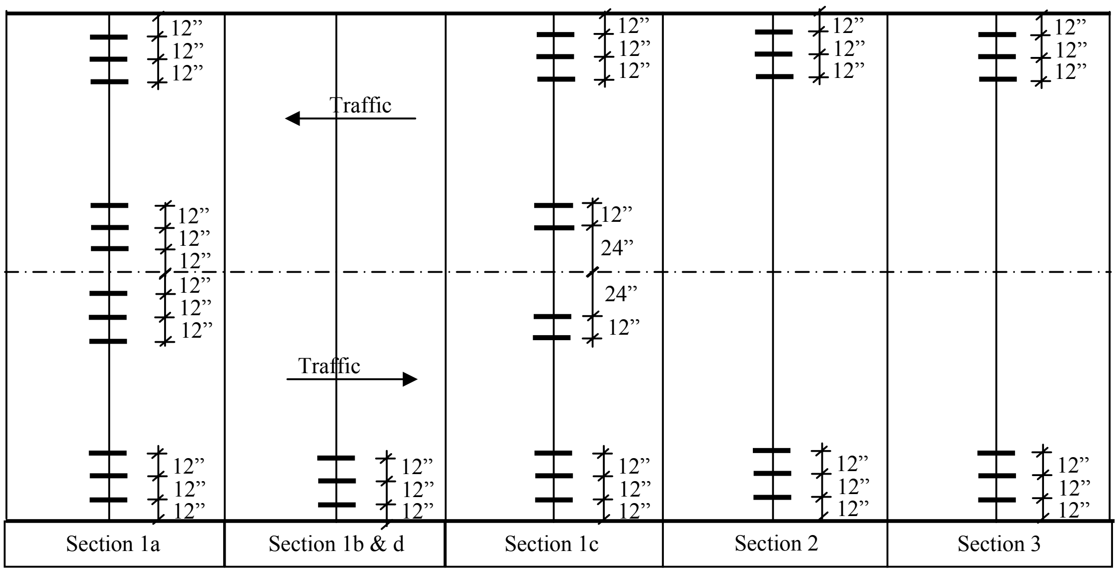

Figure 3. TH 23 test section retrofit dowel bar patterns.

Observed Performance

The retrofit dowel bar test sections on TH 23 were installed in 1998, and therefore to date, have had over 10 years of exposure to traffic (HCADT = approximately 500)(*6*) and weather. Recent site visits took place in October 2006, and February 2007. During those visits, surface distress on the test sections was recorded as being minimal. Photo 6 shows retrofit dowel bar slots with Mn/DOT 3U18 backfill mortar in very good condition.

Photo 6. TH 23 slots with Mn/DOT 3U18 backfill mortar after 8 years.

LTE testing was measured for a select number of retrofitted joints in October 2006 and ranged from 64 to 80 percent. Fault measurements recorded at the same time as the LTE testing revealed an average value of only 0.5 mm (0.02 in.). It appears that the installation of retrofit dowel bars on this project, in conjunction with diamond surface grinding, has successful lengthened the performance of this very old pavement.

The performance of the various dowel bar configurations indicates that three dowels in the outside wheel track only is adequate for long-term load transfer across a previously faulted transverse joint (for the traffic level on TH23). The difference in the performance of retrofitting a 380-mm (15-in.) versus a 325-mm (13-in.) dowel bar seems negligible at this time.

Laboratory testing of retrofit dowel bars 325 mm (13 in.) long on the Minne-ALF device by Embacher et al. (*4*), confirms the possibility of using a shorter, lower cost dowel bar, while still achieving long-term load-transfer performance. Shorter bars also provide the benefit of requiring shorter saw cuts, for additional cost savings.

I-90, Beaver Creek

Project Description

In 1999, a retrofit dowel bar project was constructed on Interstate 90 (I-90) near Beaver Creek, Minnesota. The pavement on this project was originally constructed in 1984 of jointed reinforced concrete 225 mm (9 in.) thick. After 15 years of heavy interstate truck traffic, the panels, 8.2 m (27 ft) long, contained mid-panel cracks that demonstrated enough faulting to affect ride quality. The objective of this project was to determine if retrofit dowel bars and diamond surface grinding could restore pavement performance and significantly slow down the redevelopment of faulted mid-panel cracks.

Design Variables

The test sections in this project were designed to study the configuration and number of retrofit dowel bars necessary to achieve long-term load transfer across faulted transverse mid-panel cracks. The layout of the two test sections is shown in Figure 4. Retrofit dowel bar pattern variations included combinations of two or three bars in both wheel tracks of the driving and passing lanes. Test sections 1 and 2 are each ten panels long (in both eastbound and westbound directions). All retrofit dowel bars were 38 mm (1.5 in.) by 380 mm (15 in.) long. Dowel to dowel spacing in the wheel tracks was 300 mm (12 in.). The first dowel from the edge of the driving lane shoulder was placed at 760 mm (30 in.).

All retrofit dowel bars on this project were installed using a PMQP mortar mixture. It was noted during construction that the existing reinforcing steel in the pavement was causing rapid wear of the saw blades used to form the slots. Therefore, many of the retrofit dowel bars on this project were placed 6 mm (0.25 in.) higher than the standard dimension of half the thickness of the pavement.

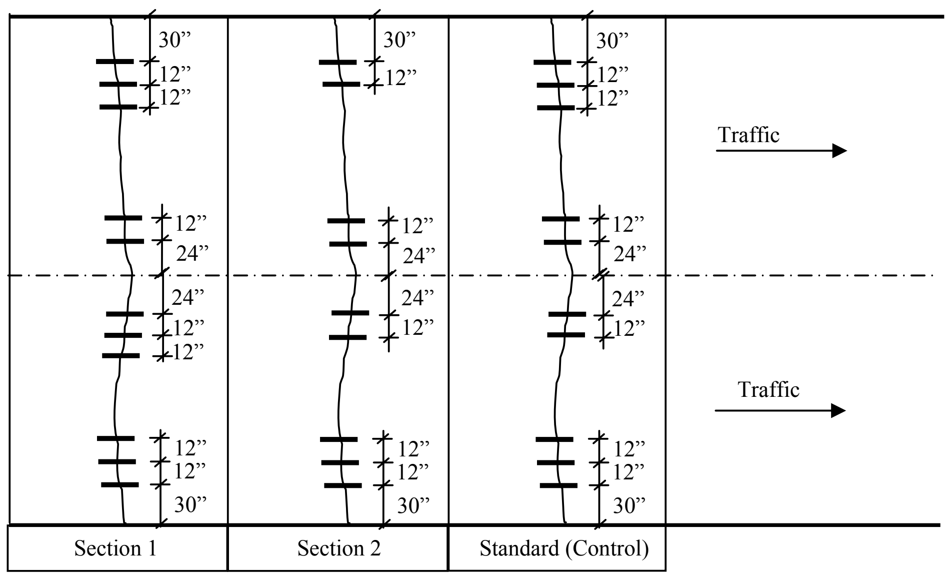

Figure 4. I-90 Test section retrofit dowel bar patterns.

Observed Performance

The retrofit dowel bar test sections on I-90 were installed in 1999, and therefore to date, have over 9 years of exposure to traffic (HCADT = approximately 1,200)(*6*) and weather. Recent site visits took place in October 2006 and February 2007. During those visits, surface distress on the retrofit dowel bars slots was recorded as being minimal. Photo 7 shows retrofit dowel bar slots with the PMQP backfill mortar in very good condition. Most of the current slot distresses are caused by longitudinal or transverse panels cracks that formed after the retrofit dowel installation.

The performance of the various dowel bar configurations indicates three dowels in the outside wheel track and two in the inner wheel track are adequate for long-term load transfer across a transverse mid-panel crack under the traffic loads experienced by I-90. A third dowel bar installed within the inside wheel track of the driving lane does not seem to add benefit to the performance and therefore is not cost beneficial in this case. Also, the performance of the retrofit dowel bars in the passing lane shows that the reduced pattern of two dowels in each wheel track is adequate to maintain performance for the reduced volume of traffic that this lane carries.

Photo 7. Typical condition of I-90 slots with PMQP backfill mortar after 7 years.

The objective of the research for the I-90 test sections was to determine the long-term capability and durability of retrofit dowel bars placed across previously faulted transverse mid-panel cracks. Fault measurements in October 2006 showed an average value of 0.3 mm, indicating that virtually no crack faulting has returned after 7 years of service. LTE tests taken at the same time revealed values ranging from 70 to 89 percent, indicating the retrofit dowel bars are continuing to contribute to load transfer across the crack.

Load-Transfer Efficiency Trends

Throughout each of the projects described previously, it is noted that several retrofit dowel bar patterns and lengths were being tested. Ideally, designers are interested in using the least amount of well-placed retrofit dowel bars, while still maintaining long-term performance. Most designs incorporate as a minimum, three retrofit dowel bars in the outer wheel track. It is believed that loads on the inner wheel track are carried in part by the adjacent lane (if tied with reinforcing steel). The question is whether adding bars in the inside wheel track (if even necessary to begin with) will simply carry local loads, or possibly benefit the bars in the outer wheel path. The only way to know is to monitor the LTE in both wheel paths.

It was discovered in preparation of this paper that, while various LTE tests were conducted at various times throughout the life of each project, the location assignments for individual joints or cracks was inconsistent. In addition, LTE testing of the inside wheel track was never conducted. Therefore, throughout this paper, only ranges of average LTE (based on measurement in the outside wheel track) could be presented. This prevented the determination of individual performance trends related to dowel bar patterns or lengths. It will be next step in this study to do more comprehensive LTE testing of the current projects, and to decode the past testing results.

Even though specific trends in LTE could not be determined, the observed uniform good performance of the projects in this study show that perhaps some of the design details considered are not as sensitive as once believed. These projects have demonstrated that using fewer and shorter dowel bars (AASHTO 1993 [*8*] recommends bars 457 mm [18 in.] long) can still provide long-term LTE performance for both joints and mid-panel cracks.

Ride Quality Trends

While adequate long-term LTE is important to the owners and maintainers of a retrofit dowel bar project, the traveling public is more interested in ride quality. Mn/DOT has a comprehensive pavement management program that frequently measures the pavement distress and ride quality of the entire road network operated by Mn/DOT. Through these measurements, long-term trends are established and pavement performance models can be determined.

For the time period covered in this study, Mn/DOT's pavement management system rated roads based on what is termed the PQI, or "Pavement Quality Index." The PQI is calculated based on a number of parameters defined as such:

$PQI = (SR * PSI)^{1/2}$ (Equation 1)

where PSI = "Present Serviceability Index", which is a function of the IRI (International Roughness Index), and SR, which is a surface condition rating. Recently Mn/DOT substituted the term Ride Quality Index (RQI) for PSI, but the latter term is retained for convenience in this paper.

Figure 5 shows a performance decay model for the TH 12 project. The rate of decay can be significantly influenced by the residual life and existing condition of the concrete prior to

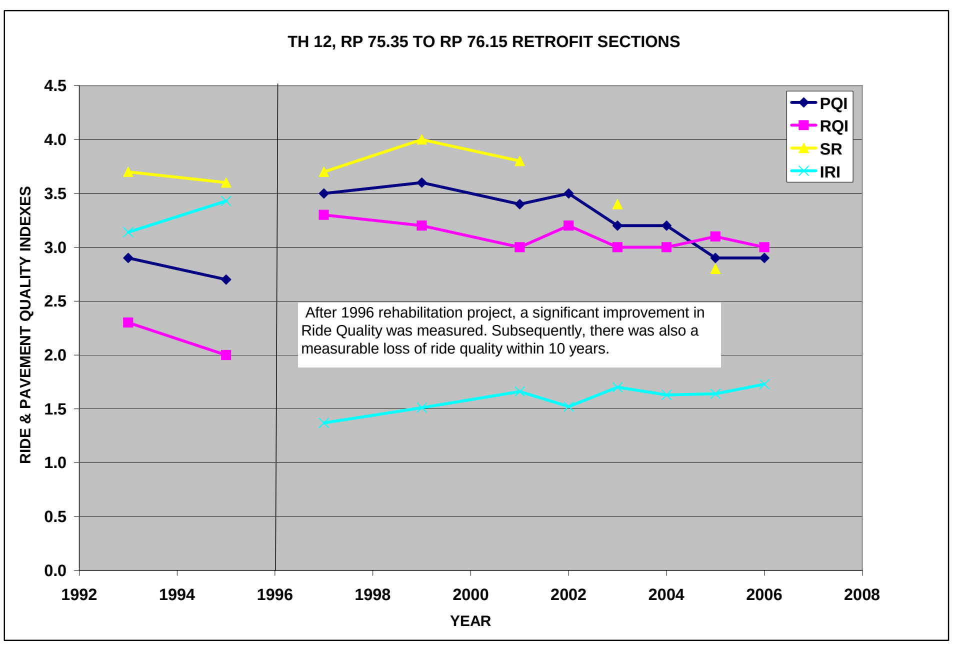

Figure 5. TH 12 pavement quality index trends.

rehabilitation. It is sufficient to note that there was a significant increase in ride quality after the retrofit project was completed, and after 10 years of service, the PQI is still above the value before the retrofit project was done. Unfortunately, the network-level data available for the other projects in this study did not allow for the establishment of similar decay curves at this time.

Backfill Mortar Performance

While the long-term performance of retrofit dowel bar projects is well accepted in terms of improved LTE, the materials used to anchor the bars to the existing pavement have often experienced problems. The projects in this study used various backfill materials to discover which ones could meet both the quick construction time criteria and long-term durability. The extreme climate of Minnesota often presents durability problems for rapid setting, high early strength grouting materials.

Recent site visits to the projects in this study revealed that all the backfill materials have demonstrated long-term strength and durability in Minnesota, when designed and constructed properly. There have been some minor problems with some of the PMQP materials on the TH 52 and I-90 projects, however long-term, the problems seem to be more cosmetic than structural in nature. Ironically enough, Mn/DOT's simple 3U18 repair material, even though not technically a nonshrink grout, has performed very well, despite sometimes displaying shrinkage cracks on the surface.

BEST PRACTICES

Development

Developing best practices for any design or construction feature comes from a combination of empirical field observation, analysis, and laboratory testing. The important issues related to the retrofit dowel bar technique in Minnesota revolve around economical construction and long-term durability in an extreme climate. The current best practices are based on the early performance of the projects in this study, results from laboratory load testing, and experiences learned from other States(*9*).

The successes and problems experienced on the projects in this study influenced much of the current design for retrofit dowel bars in Minnesota. Retrofit dowel bar slots are sawed, rather than milled, based on construction problems experienced on the TH 12 project. While the milled slots have performed reasonably well, they have experienced more distress than sawed slots. Successful milling or other slot- forming techniques may be developed in the future that could significantly improve construction efficiency and therefore reduce costs.

Minnesota's standard dowel bar length for new concrete pavement construction is 15 in. (380 mm). It was therefore desirable to know whether this length could provide long-term LTE when used in retrofitting joints and cracks. To accomplish this, an accelerated load-testing stand, developed in cooperation with the University of Minnesota, was used to test various retrofit design features (*4*). Design features tested included the number of retrofit dowels in a wheel track, the length of the dowel bars, and the type of backfill material used. It was determined that not only did dowels 380 mm (15 in.) long perform well, but even shorter bars, 330 mm (13 in.) long, performed just as well. Shorter bars not only reduce dowel cost, but also reduce sawing and chipping costs, due to shorter dowel-slot requirements. It was also demonstrated that two dowel bars in a wheel track can be as efficient long-term as three dowel bars in a wheel track, however joint deflections tend to be higher. Testing also revealed that Mn/DOT 3U18 patch mix performs just as well as some of the proprietary high-strength backfill mortar products.

Project Selection

When designing a joint or crack load-transfer restoration project utilizing retrofit dowel bars, the most important aspect is project selection. Mn/DOT currently expects a retrofit dowel bar project to increase the service life of a pavement by 12 to 15 years. Based on that expectation, Mn/DOT's recommendations when choosing a retrofit dowel bar project is that "the concrete is structurally sound and the main deficiency of the pavement is load transfer." This means the concrete near the transverse joints or mid-panel cracks must be capable of being sawed and chipped without growing in size due to cracked or weak material. Also, if faulting is significantly affecting the ride quality, it is recommended that diamond grinding or surface planing be done after the retrofit dowel bar installation. Grinding the pavement afterwards also allows for quicker retrofit dowel bar installation, since the backfill material in the slots does not need to be finished as smoothly.

Dowel Bar Placement

While much experimentation has been done with regard to the number and placement of retrofit dowel bars, Mn/DOT's experiences have led to the following recommendations. For two-lane roads with joint or mid-panel crack faulting predominantly near the outside edge of the pavement (near the shoulder), three retrofit dowel bars placed in the outside wheel track work well. For two-lane roads with joint or crack faulting across the entire lane width, three retrofit dowel bars placed in the outside wheel track and two dowels placed in the inside wheel track are the recommended option. For divided, multilane highways, the pattern of retrofit dowel bars should be based on the type of faulting that occurred. Full-lane-width faulting should be retrofit with three retrofit dowel bars placed in the outside wheel track and two or three dowels placed in the inside wheel track. Similar to two-lane roads, joints or cracks with faulting only near the shoulder should be retrofit with three dowels placed in the outside wheel track only. Since there is no rational design method established for retrofit dowel bars, design decisions should be based on the desired amount of heavy-truck traffic applications a particular lane will carry in the future.

Transverse alignment of the dowel bars within a lane can be flexible, however, the best performance is achieved when the center of a dowel bar group is centered in the wheel track. Dowel-to-dowel transverse spacing is recommended to be 305 mm (12 in.). When placed across transverse mid-panel cracks, retrofit dowel bars should be aligned longitudinally such that equal embedment length is realized.

Dowel Bar Design

Mn/DOT recommends epoxy-coated plain steel dowel bars 32 mm (1.25 in.) in diameter by 380 mm (15 in.) for retrofit dowel bar projects. Although shorter 330 mm bars, (13 in.) long, have been shown to work for retrofit dowel projects, 380-mm (15-in.) bars are very commonly used in conventional concrete pavement projects throughout Minnesota.

Each retrofit dowel bar is fitted with plastic end caps that allow for 6 mm (0.25 in.) of expansion movement at each end of the bar. They also contain nonmetallic support chairs that provide a minimum of 13 mm (0.5 in.) of clearance between the bottom of the dowel bar and the floor of the slot in the pavement. A compressible foam core board is also placed at the midpoint of the dowel to reestablish the joint or crack. Photo 8 shows Mn/DOT approved retrofit dowel bar assemblies.

Photo 8. Mn/DOT approved retrofit dowel bar assemblies.

Backfill Materials

Mn/DOT's special provisions to the specifications(*10*) state that: "The Contractor shall use a 'Mn/DOT Approved Non-Shrink Rapid Set Concrete Material for Dowel Bar Retrofit Repairs' conforming to ASTM C 928 and the requirements on file in the Mn/DOT Concrete Engineering Unit. This material may be extended with CA-80 as specified by the manufacturer, as backfill material." The Mn/DOT CA-80 designation represents an aggregate gradation as shown in Table 1.

Table 1
Gradation Specifications for Mn/DOT Designation CA-80 (Mn/DOT 2005)

Aggregate Designation	Percent by Mass (weight) Passing Square Opening Sieves	
	9.5 mm (3/8 in.)	4.75 mm (#4)
CA-80	100	55-95

Note: Not more than 5 percent shall pass the 300 um (#50) sieve.

Although not specifically designed to be a nonshrink retrofit dowel bar backfill material, Mn/DOT's 3U18 material has nevertheless performed very well in Minnesota when used for concrete rehabilitation repairs. The designation 3U18 can be decoded as follows:

3 = Air-entraining concrete for durability in freezing conditions,

U = Refers to cementitious content of the mix, where U $\geq$ 800 lb cement per cubic yard of concrete,

1 = Refers to slump level in inches,

8 = Descriptor for the aggregate gradation, which is the same as CA-80 (Table 1).

Despite some shrinkage problems observed along retrofit slot faces, Mn/DOT's 3U18 material demonstrates long-term strength and durability when used in retrofit dowel bar projects. Other States (*11*) have experimented with Mn/DOT 3U18 material for retrofit projects and report similar findings.

Several other proprietary, nonshrink, rapid-setting materials have been, and continue to be, successfully used for retrofit dowel bar projects in Minnesota.

Construction Method

Historically, the challenges faced during the installation of retrofit dowel bars have included the following:

- *Uniformity of placement.* The installation is often done quickly, and rapid-setting backfill materials can be improperly handled.
- *Avoidance of honeycombing and entrapped air*: The strength requirements for nonshrink grouts do not provide much tolerance for honeycombing.
- *Avoidance of unconsolidated concrete under the dowels.* With such small volumes of backfill material available to bond the dowel to the existing pavement, voids can significantly reduce the available load-transfer capacity of the retrofit dowel bar.
- *Compatibility at the concrete interface.* Retrofit slots must be rough and clean for the backfill materials to be able to bond. Also, the grout cannot shrink to the extent the bond with the slot is lost.
- *Vertical or horizontal misalignment.* Retrofit dowel bars must be aligned properly or they might cause binding of the joint, which may lead to further pavement distress.

To ensure that a contractor will be able to follow the recommended best construction practices on a retrofit dowel bar project, Mn/DOT requires that a small test section be constructed before commencing with a project. The details of this test section are summarized as follows:

1. There will be 24 retrofit dowels in the test operation.
2. Twenty-four hours after completion of the test operations, the Contractor shall take three 150 mm [6 in.] diameter full depth cores as directed by the Engineer to determine the completeness of the removal and installation operations.
3. If the placement is in accordance with the Plans, the Mn/DOT Standard Specifications, and these Special Provisions; and if the Contractor's retrofitting operation has not damaged the surrounding in place concrete; then, upon approval from the Engineer, the Contractor may begin production operations and shall proceed on a performance basis.
4. The work in this paragraph shall be paid at the unit price for dowel bar retrofit.

The (minimum) three core samples described above are taken to monitor the following:

- One core is taken through the dowel to observe that there is continuity at the dowel/ concrete interface and that there is consolidation beneath the dowel.
- One core is taken over the dowel supports to assure that there was no collapse that could result in vertical or horizontal misalignment.
- One core is taken to include both the retrofit backfill mortar and the existing concrete, to assure that compatibility and continuity exists at the interface of new and existing concrete.

Any problems identified during the examination of the cores must be addressed by the contractor before a project can proceed. One example of such problems on a project is described next.

A retrofit dowel bar project was constructed in 1994 on Minnesota TH 59. A contractor test site was constructed and the specified cores were taken and tested. Many of the core samples did not attain the required ASTM 928 prescribed strength. The cores also revealed severe honeycombing. This is shown in Photo 9. These results necessitated a switch from one approved backfill product to another.

Photo 9. Core from TH 59 test site showing honeycombed retrofit mortar.

The typical steps involved in the installation of retrofit dowels bars in Minnesota are as follows:

1. *Saw the slot for each dowel bar*. This is often accomplished by "gang saws," which provide cuts for multiple parallel slots at one time. Typical slot dimensions for a dowel 380 mm (15 in.) long are 650 mm (26 in.) long by 65 mm (2.5 in.) wide at the surface of the pavement, and 400 mm (16 in.) long by 65 mm (2.5 in.) wide at the bottom of the slot. Slots for mid-panel cracks may be longer to accommodate skew in the crack.

2. *Remove concrete to form kerf and rinse and dry.* Material between the saw cuts is typically removed using a chipping air hammer, limited to a weight of 13.5 kg (30 lb) or less. The bottom of the slots should be sufficiently cleaned to allow the dowel bar assembly to sit parallel to the pavement surface. Any water residue or saw slurry created by removal operations shall be contained and vacuumed immediately from the road surface.

3. *Sand blast and vacuum clean slot.* Sand blasting removes any loosened material and roughens the side faces of the slot. All exposed surfaces and cracks are then further cleaned with a "moisture and oil free" high-pressure air-blasting lance (690 kPa

[100 lbf/in^2] minimum pressure) immediately before beginning the sealing work. The contractor must protect nearby traffic from sand and air blasting operations.

4. *Seal bottom and sides of slot.* Prior to placement of the dowel bar and filler material, the contractor must seal the existing transverse joint or crack within the slot. Mn/DOT approved silicone joint sealant material is applied and allowed to cure for a minimum of 2 hours or until it is tack free (according to the manufacturer's recommendations) prior to placing the backfill material. This is done in a manner sufficient to keep the backfill material from leaking into the joint or crack.

5. *Place and align dowel bar and joint/crack filler material.* Just prior to installation, dowel bars are lightly coated with an approved release agent, fitted with the compressible foam or filler material, support chairs, and the expansion caps on both ends. The dowel bars are then placed in the slots, parallel to the centerline and pavement surface, all to a tolerance of 3 mm (0.125 in.). Figure 6 depicts a side view of a typical retrofit dowel bar within a slot. Photo 10 shows actual retrofit dowel assemblies placed in the slots prior to backfilling.

6. *Place backfill material, finish, and cure.* Approved non-shrink rapid set concrete material is placed within the slot. To ensure that backfill material fully surrounds the dowel and fills remaining voids in the slot, a "spud" type vibrator is inserted into the material prior to surface finishing.

   The slots are finished flush and smooth if surface grinding is not scheduled before traffic is allow on the pavement. Immediately after final finishing, all retrofit slots are coated with an approved membrane curing compound. Water based curing compounds are not permitted.

   Public or contractor traffic is not permitted on the newly placed backfill material until adequate strength has been achieved, according to the manufacturer's recommendations. If shrinkage cracks occur in the repair shortly after placement, the work is rejected and completely redone at the contractor's expense.

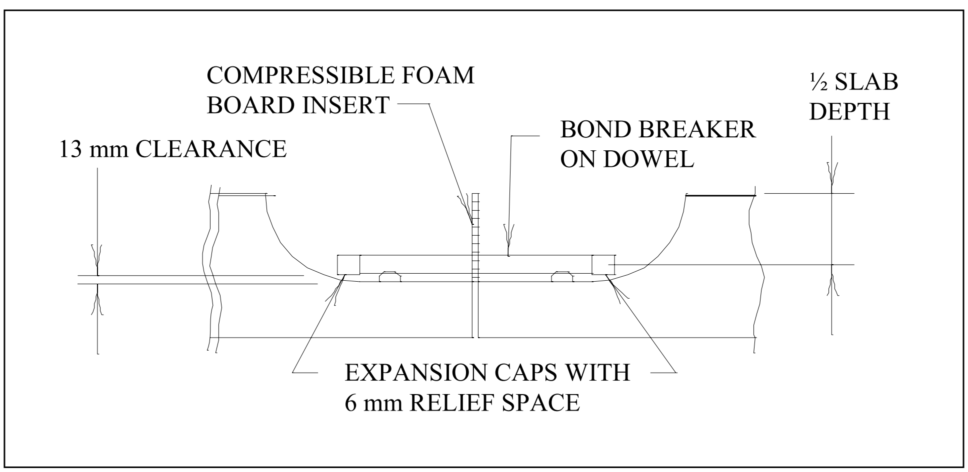

Figure 6. Side view of typical retrofit dowel bar in slot.

Photo 10. Retrofit dowel assemblies placed in the slots prior to backfilling.

7. *Seal joint or crack between slots.* Mn/DOT approved silicone joint sealant material is used to fill the joint or crack between the retrofit slots and any other areas disturbed by the construction process. Often the entire joint or crack within a lane is cleaned and filled as a standard preventative maintenance measure.

8. *Diamond grind or plane surface (optional).* Although this procedure is optional, it is very common to diamond grind or plane the surface of the pavement after retrofitting dowel bars. Typically retrofit projects are performed on pavement with significantly faulted joints or cracks that are impacting ride quality. Diamond grinding or surface planing not only restores ride quality, but also ensures that overbands of retrofit mortar and other sources of uneveness are removed and a uniform texture is imparted.

CONCLUSIONS

Retrofitting dowel bars into a distressed and faulted concrete pavement has become a proven technique for restoring or improving the capacity of jointed concrete pavements. The performance of this technique relies on proper project selection and the successful application of design features including dowel bar design and placement, backfill materials, and construction methods. Improved knowledge toward understanding the long-term performance of such techniques, especially in severe climate regions, is always of great interest. In this study, the successful long-term performance of four retrofit dowel bar projects in Minnesota has been described. After 14 years of heavy traffic and extreme weather, the mid-panel cracks on the TH 52 project still have an LTE ranging from 60 to 80 percent. Similar LTEs were found on retrofit dowel bar joints after 10 years of service on TH 23, a previously undoweled pavement now over 56 years old. Despite minor cosmetic problems, all of the retrofit dowel bar backfill materials used in the projects in this study are performing well in the Minnesota climate. The experiences from these projects, coupled with accelerated laboratory testing results, have resulted in the development of successful best practices for retrofit dowel bars in Minnesota. Retrofit dowel bar installation, in conjunction with restoration of the surface through diamond grinding, has been proven to significantly extend the capacity and serviceable life of many concrete pavements in Minnesota.

REFERENCES

1. K. T. Hall, M. I. Darter, and J. M. Armaghani. "Performance Monitoring of Joint Load Transfer Restoration." *Transportation Research Record No. 1388,* National Academy Press, Washington, DC, 1993.

2. R. M. Larson, D. Peterson, and A. Correa. *Retrofit Load Transfer Special Demonstration Project SP-204***.** Federal Highway Administration Report No. FHWA-SA-98-047, Washington, DC, 1998.

3. L. M. Pierce, J. Uhlmeyer, J. Weston, J. Lovejoy, and J. P. Mahoney. "Ten-Year Performance of Dowel-Bar Retrofit; Application, Performance, and Lessons Learned." *Transportation Research Record No. 1853*, Transportation Research Board, Washington, DC, 2003.

4. R. A. Embacher, M. B. Snyder, and T. D. Odden. "Using the Minnesota Accelerated Loading Facility to Test Retrofit Dowel Load Transfer Systems**."** *Transportation Research Record No. 1769*, National Academy Press, Washington, D.C., 2001.

5. N. A. Popehn, A. E. Schultz, and M. B. Snyder. *Performance Testing of Experimental Dowel Bar Retrofit Designs Part 2 – Repeatability and Modified Designs*. Minnesota Department of Transportation, St. Paul, 2003.

6. State of Minnesota 2004 Trunk Highway Traffic Volume Map, Minnesota Department of Transportation.

7. E. Embacher, *Construction Report on the Installation of Retrofit Dowel Bar Test Sections on TH 23.* Minnesota Department of Transportation, St. Paul, 2001.

8. AASHTO. *Guide for Design of Pavement Structures.* American Association of State Highway Transportation Officials, Washington, DC, 1993.

9. L. Pierce, *Dowel Bar Retrofit in Washington State; Summary of Findings.* Washington State Department of Transportation, Olympia, 1999.

10. Mn/DOT Specifications 2005, Minnesota Department of Transportation, 2005.

11. C. Dunn and B. Fuchs. *Experimental Study ND 95-03; Dowel Bar Retrofit for Load Transfer- Final Report.* North Dakota Department of Transportation, Bismarck, 2001.

ACKNOWLEDGMENTS

The authors would like to acknowledge the field data collection performed by Ted Snyder, Beverly Baron, and the Mn/DOT pavement management staff for this study.

DISCLAIMER

The contents and opinions presented in this paper are those of the authors, who are responsible for the facts and accuracy of the data. The contents do not neccesarily reflect the views or opinions of the Minnesota Department of Transportation.