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EVALUATION OF MMFX 2 STEEL CORROSION-RESISTANT DOWEL BARS IN JOINTED PLAIN CONCRETE PAVEMENT

FINAL REPORT

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16. Abstract
The performance of MMFX 2 steel dowel bars was compared to epoxy-coated steel dowel bars after five years of service in 9-in jointed plain concrete pavement (JPCP). Performance indicators included dowel bar corrosion, pavement smoothness and load transfer efficiency (LTE) at the transverse joints. Cores through dowel bars revealed that no corrosion had occurred on either type of dowel after five years in service. Results of IRI testing at several pavement ages indicated that pavement smoothness was similar for sections constructed with both types of dowels and was average for JPCP in Wisconsin. The LTE of epoxy-coated dowel bar sections (median value of 92 percent) was slightly higher than the median value of 87 percent for MMFX 2 dowel bar sections. However, these values indicate that both types of dowels have provided adequate load transfer for JPCP. Two life cycle cost analysis scenarios using a typical WisDOT rehabilitation schedule and analysis period illustrated that use of MMFX 2 steel dowels would be cost effective if they provided an additional 15 years of initial service for JPCP.

Results of this investigation did not suggest that either epoxy-coated steel or MMFX 2 steel dowel bars provide superior performance when used in the construction of JPCP. A detailed literature search of accelerated corrosion testing concluded that MMFX 2 steel demonstrated corrosion resistance that was close to or better than epoxy-coated steel with damaged coating but did not out-perform steel with intact epoxy coating. Given the inconclusive results of this field study and literature review, it is not recommended that MMFX 2 steel dowel bars be approved for use in future WisDOT JPCP construction.

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MMFX 2 steel, dowel bars, corrosion-resistant dowel bars, load transfer, jointed plain concrete pavement

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Table of Contents

1. Introduction

Use of steel dowel bars in jointed plain concrete pavement (JPCP) construction has been standard practice for the Wisconsin Department of Transportation (WisDOT) since the early 1980s. Smooth, round dowel bars are utilized at transverse joints to provide load transfer between adjacent slabs. Adequate load transfer is necessary to reduce faulting at transverse joints and results in a smooth riding surface.

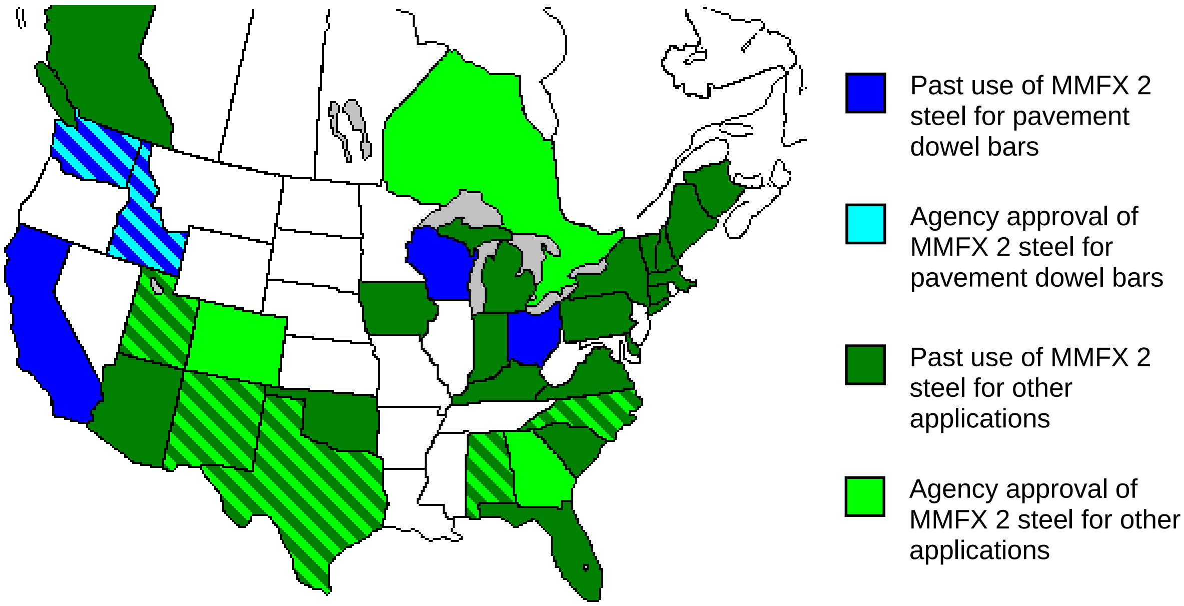
In areas where deicing agents are regularly applied to pavements during winter maintenance activities, corrosion of dowel bars is an important issue. The expansive properties of materials produced during corrosion can cause joint lock-up, which leads to cracking of the slabs. [1] Severe corrosion can also result in material loss in the dowel and thus reduced load transfer, which results in slab faulting. Epoxy-coating of dowel bars is a common method used to protect the steel from deicing agents that lead to corrosion. However, exposure of the steel dowel bar to these salts is still possible if slight imperfections occur in the epoxy layer during manufacture, transport or construction.

To further address the issue of corrosion, several new material technologies have been utilized for dowel bars including fiber-reinforced polymer composites, stainless steel, zinc-clad steel and microcomposite steel. Dowel bars made with these materials are generally more expensive than standard epoxy-coated dowel bars, but their limited or reduced tendency to corrode might result in longer service lives for JPCP and thus cost savings in the long term. This research project compared the in-service performance of JPCP constructed with epoxy-coated steel dowel bars to JPCP using dowel bars made of MMFX 2 steel, a microcomposite steel material manufactured by MMFX Steel Corporation of America.

2. Background

MMFX 2 steel is a low-carbon, chromium steel that is sold in both plain and deformed (reinforcing bar) lengths. This material conforms to ASTM A 1035, which specifies a minimum tensile strength of 150 ksi (1030 MPa) and a minimum yield strength of 100 ksi (690 MPa). [2] The allowable chromium content of ASTM A 1035 steel is 8.0 to 10.9 percent by weight, whereas stainless steel contains 11 percent or more chromium, and carbon steel typically contains less than one percent chromium. [2, 3] MMFX 2 steel is rolled under a controlled temperature range and cooled at a specific rate to produce a microstructure that gives the product its unique properties. [4]

Several state agencies have tested or approved use of MMFX 2 steel for pavement dowel bars, including California, Idaho, Ohio, Utah and Washington. Additional states and Canadian provinces have used MMFX 2 steel as reinforcement material for structures or pavements, as shown in Figure 1. [4, 5]



Note: Utah DOT has also approved use of MMFX 2 steel for pavement dowel bars.

Figure 1. State and province agencies with past use of MMFX 2 steel.

2.1 Corrosion Testing

The 1993 AASHTO pavement design guide indicates that dowel bars "should be resistant to corrosion when used in those geographic locations where corrosive elements are a problem." [6] However, determining a dowel bar's corrosion resistance is difficult because corrosion generally occurs slowly over the life of a concrete structure. Several accelerated corrosion tests have been developed so that steel corrosion resistance can be determined over a shorter period. In these accelerated corrosion tests, test specimens include bare steel or steel cast in concrete. Tests involving concrete samples with embedded steel (such as ASTM C 876 [7] and ASTM G 109 [8]) are expected to provide an environment for the steel that generally corresponds to an in-service environment. In corrosion tests with bare steel samples (such as ASTM B 117 [9]), the corrosive environment is much harsher than in tests involving concrete samples. Therefore, while neither test provides a direct correlation with field performance, testing of steel embedded in concrete specimens provides a more realistic indication of in-service corrosion properties.

Neither testing of bare steel nor embedded reinforcing steel provides a direct correlation to in-service corrosion performance of steel dowel bars. However, results from studies that used these methods will be discussed to provide a comparative idea of corrosion properties of different materials. In addition, several studies cited at the end of this section utilized customized methods to evaluate corrosion resistance of dowel bars.

In a study by Hartt et al. [10], bare reinforcing bars were subjected to wet-dry cycling for three months by immersion in NaCl solutions of varying concentrations (3 to 15 percent). Linear polarization resistance was used to determine the corrosion rate over time. Corrosion rates for bare carbon steel bars were approximately 5 and 15 mils per year (mpy) at 10 and 84 days, respectively. Corrosion rates for MMFX 2 steel bars were significantly lower, at approximately 0.2 and 1.0 mpy at 10 and 84 days, respectively. The corrosion rate of both MMFX 2 steel and bare carbon steel bars was found to increase with time. Corrosion rates for solid 316 stainless steel bars and 316 stainless steel clad bars were constant over time and were 0.004 and 0.3 mpy, respectively.

Results of another study [11] of wet-dry cycling of bare MMFX 2 steel reinforcing steel bars indicated that extensive pitting had occurred after 14,660 wet-dry cycles in 3.5% NaCl solution. The bar with the greatest damage had a 9.4 percent loss of cross-sectional area. Concrete blocks cast with #4 reinforcing bars were also subjected to wet-dry cycling in 3.5% NaCl solution as a part of this research study. Testing continued for 28,416 wet-dry cycles. This test regime resulted in minor corrosion staining and cross-sectional area loss for uncoated carbon steel, isolated corrosion on MMFX 2 steel, and no signs of corrosion on intact epoxy-coated steel and solid stainless steel bars. [11] The author of this study noted that "mill scale present on the MMFX 2 bars may be detrimental to corrosion performance." In addition, a life-cycle cost analysis of a reinforced concrete bridge deck indicated that, assuming a similar repair schedule as for concrete reinforced with epoxy-coated steel, use of MMFX 2 steel would result in 13 additional years of service. [11]

Trejo and Pillai [12, 13] conducted a series of studies using several types of reinforcing steel to determine the critical chloride threshold concentration before corrosion initiation. Concrete specimens cast with reinforcing steel were analyzed using the accelerated chloride threshold (ACT) test to determine the critical chloride concentration. A higher critical chloride concentration indicates greater corrosion resistance. Critical chloride thresholds for concrete made with carbon steel, microcomposite steel, 304 stainless steel and 316LN stainless steel were 0.9, 7.7, 8.5 and 18.1 lb/yd^3, respectively. [12] In the last part of their study, the authors noted that removal of the mill scale on as-received microcomposite reinforcement resulted in an increase in critical chloride concentration, but more variability among test results. [13]

Several studies made use of the rapid macrocell accelerated chloride test to investigate the performance of uncoated plain carbon steel, epoxy-coated steel and MMFX 2 microcomposite steel in reinforced bridge decks. Results showed that corrosion would proceed in all three types of steel [14], and that epoxy-coated steel had a lower corrosion rate than MMFX 2 steel [15, 16].

Several studies looked specifically at corrosion resistance of pavement dowel bars made with different types of steel. Snyder [17] investigated epoxy-coated, zinc clad, 316L stainless steel clad and microcomposite steel dowel bars. All but the microcomposite dowels had 0.125- to 0.5-inch holes drilled through the protective cladding layers to simulate damage due to poor handling and expose the inner steel to the salt solution. The dowels were immersed in 5 percent NaCl solution, and the solution was tested each week for iron content using atomic absorption spectroscopy. Microcomposite steel dowels exhibited corrosion rates greater than damaged epoxy-coated dowels and lower than damaged stainless steel and zinc clad dowels. However, the author cautioned that these materials could not be directly compared because the dowels with protective barriers were "damaged" only in a few areas, while MMFX 2 dowels were exposed in all areas. It was the author's opinion that MMFX 2 steel dowel bars would demonstrate lower corrosion protection than other dowels with undamaged barrier layers. [17]

Unpublished test results from the Minnesota Department of Transportation Office of Materials indicated that rust formed uniformly on both MMFX 2 steel and plain carbon steel dowels when subjected to ASTM B 117 conditions (continuous salt spray/fog). It was noted, however, that corrosion on the MMFX 2 dowel seemed to be contained mainly on the surface, and the depth of pitting was less than that of the plain carbon steel dowel. [18]

Research at the University of California-Berkeley utilized linear polarization resistance testing to determine corrosion rates of concrete samples with formed doweled joints subject to wet-dry cycling with 3.5 percent NaCl solution. Results indicated that microcomposite steel dowels provided greater resistance to corrosion than carbon steel dowels but less resistance than stainless steel clad dowels. [19] There was high variability in the linear polarization resistance results. Visual inspections showed light corrosion on the microcomposite steel dowels compared to heavy, uniform corrosion on carbon steel dowels, no visible corrosion on stainless steel dowels (clad and hollow) and localized corrosion on epoxy-coated dowels. [20]

Field testing was also performed in the UC-Berkeley study. Cores extracted from pavement that had been retrofitted with dowel bars showed that chloride concentrations in the concrete were much higher at the joints than at locations away from the joint. [20] This indicates that properly modeling the joint is critical for accelerated corrosion testing of dowel bars. Cores were also extracted from in-service transverse joints of 9-inch concrete pavement ranging in age from 25 to 45 years. The pavement test sites were located in Washington State and had therefore been exposed to deicing agents during winter seasons. Results showed that the chloride threshold for carbon steel was exceeded in five out of six locations, indicating that exposure to corrosive products is a significant problem for dowel bars. [20]

In summary, corrosion testing involving MMFX 2 microcomposite steel has produced variable results. In most studies, MMFX 2 steel demonstrated corrosion resistance that was close to or better than epoxy-coated steel with damaged coating but did not out-perform steel with intact epoxy coating. [10, 11, 12, 13, 19, 20] Accelerated corrosion test methods are variable and may not reflect field conditions. In addition, a repeatable accelerated test method to gauge the corrosion resistance of in-service dowel bars has not been standardized. Field studies, though time-consuming, are therefore the most reliable method to determine the relative performance of various types of steel dowel bars.

2.2 Mechanical Testing

A material's strength, capability to provide load transfer and pullout stress are important mechanical properties to consider in dowel bar selection.

2.2.1 *Strength*

Tensile strength testing was conducted at the WisDOT materials testing laboratory for MMFX 2 #6 reinforcing bar. The tensile and yield strengths were found to be approximately 183 ksi (1262 MPa) and 152 ksi (1048 MPa), respectively, which conform to the requirements of ASTM A 1035. [2, 21] In comparison, the corresponding strengths for Grade 60 steel are 90 ksi (620 MPa) and 60 ksi (414 MPa). [22] The Young's modulus of MMFX 2 steel reinforcing bar has been shown to be 29×10^6 ksi (200 GPa), which is equal to that of Grade 60 steel. [23]

2.2.2 *Load transfer efficiency and differential deflection*

To determine load transfer efficiency (LTE) between two slabs, deflection measurements are taken on either side of a pavement joint or crack. Falling weight deflectometer (FWD) test apparatus is typically used to obtain these measurements. A series of impulse loads are applied adjacent to the joint on the approach or leave slab. Deflection measurements are recorded for sensors positioned six inches on either side of the joint. Sensor D_0 measures deflection of the loaded slab and sensor D_1 measures deflection of the unloaded slab. LTE is calculated using the following equation:

$$LTE = \frac{D_1}{D_0} \times 100\% \,.$$

If adjacent slabs deform by the same amount under loading (i.e. $D_1 = D_0$), LTE is 100% and the load is shared equally by the two slabs. This is the ideal case. For doweled pavements, LTE greater than 70 percent indicates that there is sufficient load transfer at the joint. [6] No definite correlation has been noted between LTE and pavement age for long-term pavement performance (LTPP) JPCP sections. [24]

No previously published research was located that compared load transfer performance of MMFX 2 and epoxy-coated steel dowel bars. Unpublished LTE data for MMFX 2 dowels were provided by the Ohio Department of Transportation and will be discussed in Section 5.3.

The differential deflection (Δ_d) between two adjacent pavement slabs provides another indicator of the dowel bars' ability to transfer load at a transverse joint. Differential deflection is the difference between the deflections of the loaded and unloaded slabs, or

$$\Delta_d = D_0 - D_1 .$$

Differential deflection is an important parameter to consider because it, unlike LTE, is a function of the magnitude of slab deflection. It is possible for undesirably large slab deflections to occur along with a high LTE. Low differential deflection together with high LTE indicates that two adjacent slabs act together and without excessive deformation when loaded. Differential deflections on the order of 0.001 in (or 1.0 mil; 0.03 mm) are considered low. [25]

2.2.3 *Dowel pullout stress*

Dowel bars "should offer little restraint" to allow for longitudinal movement during expansion and contraction of pavement slabs. [6] For this reason, a bond release agent is often applied to dowel bars to prevent bonding between the dowel and concrete. A measure of a dowel's restraint is the dowel bar pullout stress; low pullout stress indicates that the dowel will allow free movement of slabs at the joint. Unpublished dowel bar pullout testing of MMFX 2 steel dowel bars performed at an independent laboratory indicated that MMFX 2 steel dowels with and without bond release had lower pullout stresses than epoxy-coated steel dowels with bond release. [26]

3. Problem Statement

The objective of this study was to determine if the in-service use of MMFX 2 steel dowel bars resulted in better pavement performance when compared to JPCP with standard epoxy-coated dowel bars. Performance indicators included dowel bar corrosion (tested via pavement coring), pavement smoothness and LTE at the transverse joints. Performance was evaluated five years after construction. Cost-effectiveness and construction issues were also evaluated.

4. Project Details

4.1 Test Site

An 833-ft (254-m) test section using MMFX 2 steel dowel bars was constructed as part of a JPCP new construction and expansion project on WisDOT's state trunk network. The construction project, built under WisDOT project I.D. 4015-06-70, included the expansion of STH 57 to a four-lane divided highway between I-43 and the village of Random Lake in Ozaukee and Sheboygan Counties. MMFX 2 steel dowel bars were used in the southbound lanes of STH 57 between Jay Road and Hickory Grove Road, approximately 3.5 mi (5.6 km) north of the town of Fredonia in Ozaukee County (Figure 2). See Figure A-1 in Appendix A for a detailed location of the project.

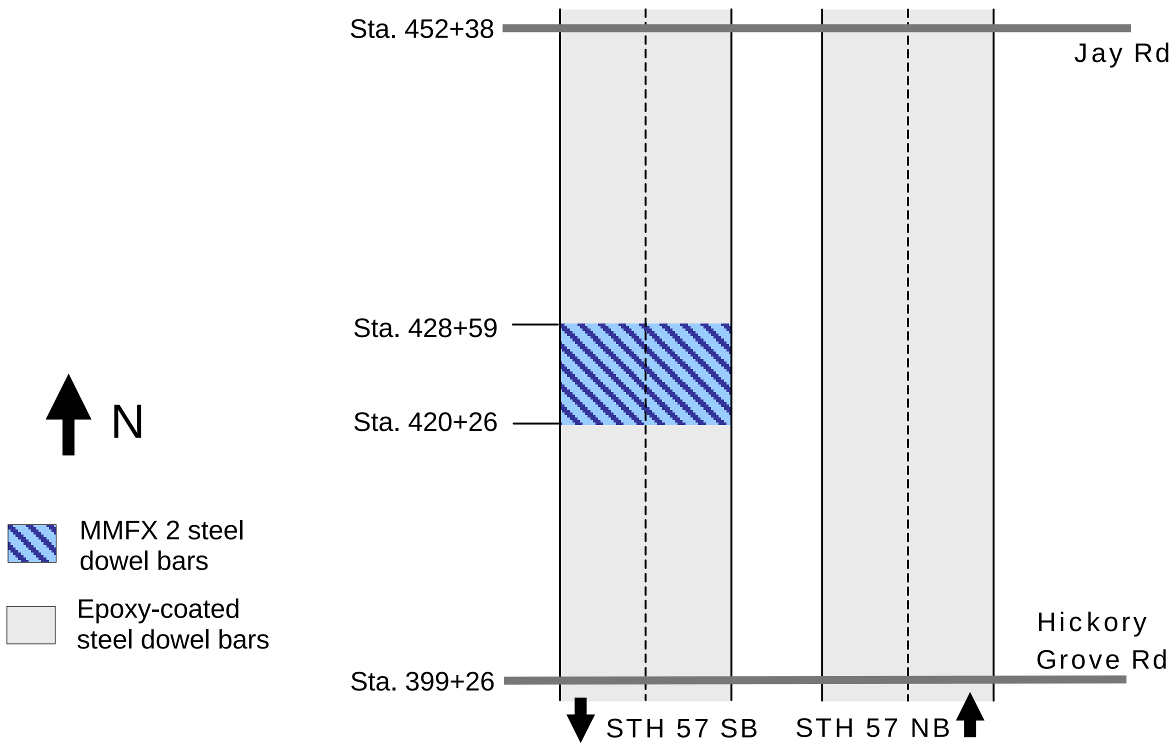


Figure 2. Location of test section.

4.2 Pavement Structure

The concrete pavement was constructed 9 in (225 mm) thick over 6 in (150 mm) crushed aggregate base course. The total paved width of concrete was 26 ft (7.8 m) with two percent crown (Figure 3). The pavement surface was pre-textured, and skewed transverse tining was applied with evenly spaced tining forks. Transverse joints were cut every 15 ft (4.5 m). Three-inch (80-mm) asphaltic concrete pavement shoulders were paved on both sides of the concrete driving lanes.

Both the epoxy-coated steel and the MMFX 2 steel dowel bars were 1.25 in (32 mm) in diameter and 18 in (455 mm) long. The plan depth for dowel bar placement was half the concrete thickness, or 4.5 in (112 mm), and the plan dowel bar spacing was 12 in (300 mm) on center. A total of 26 dowel bars were placed at each transverse joint (Figure 3). Dowel bars were inserted into the freshly placed concrete with dowel bar implanter equipment.

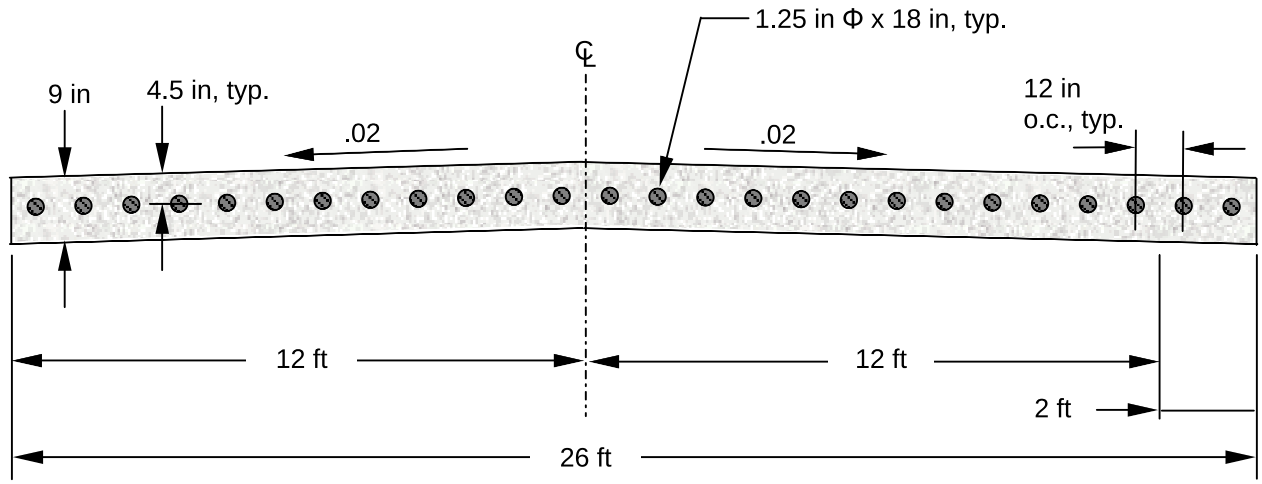


Figure 3. Typical concrete pavement cross section.

4.3 Construction

Streu Construction of Two Rivers, WI was the paving contractor for this project. Construction of the MMFX 2 steel dowel bar test section took place on August 7 and 8, 2002. MMFX 2 steel dowel bars were used for paving between stations 420+26 and 428+59 (Figure 2). Paving with these dowel bars went smoothly, and no problems were noted. [21]

5. Testing and Results

The test plan to evaluate performance of the MMFX 2 steel dowel bars involved taking pavement cores through dowel bars, testing the pavement for smoothness and ride quality using the international ride index (IRI), and testing for load transfer efficiency between adjacent slabs. The testing procedures and test results are described in the following sections.

5.1 Coring

To visually evaluate the two types of dowel bars' relative susceptibility to corrosion, four-inch diameter cores were taken though dowel bars within the test and control sections. Six cores were taken on October 15, 2007: two from the control section (epoxy-coated steel dowel bars) and four from the test section (MMFX 2 steel dowel bars). Coring locations were randomly selected; see Figure 4 for locations of the cores. All cores were taken from the center of the driving lane. An MIT Scan-2 unit manufactured by Magnetic Imaging Tools of Dresden, Germany was used to predict the location of the dowel bars to ensure a dowel was cored through on each attempt.

Cores were immediately inspected for signs of corrosion. None of the six cores taken exhibited any corrosion on the dowel bar. Two of the cored dowel bars are shown in Figure 5. For the two cores

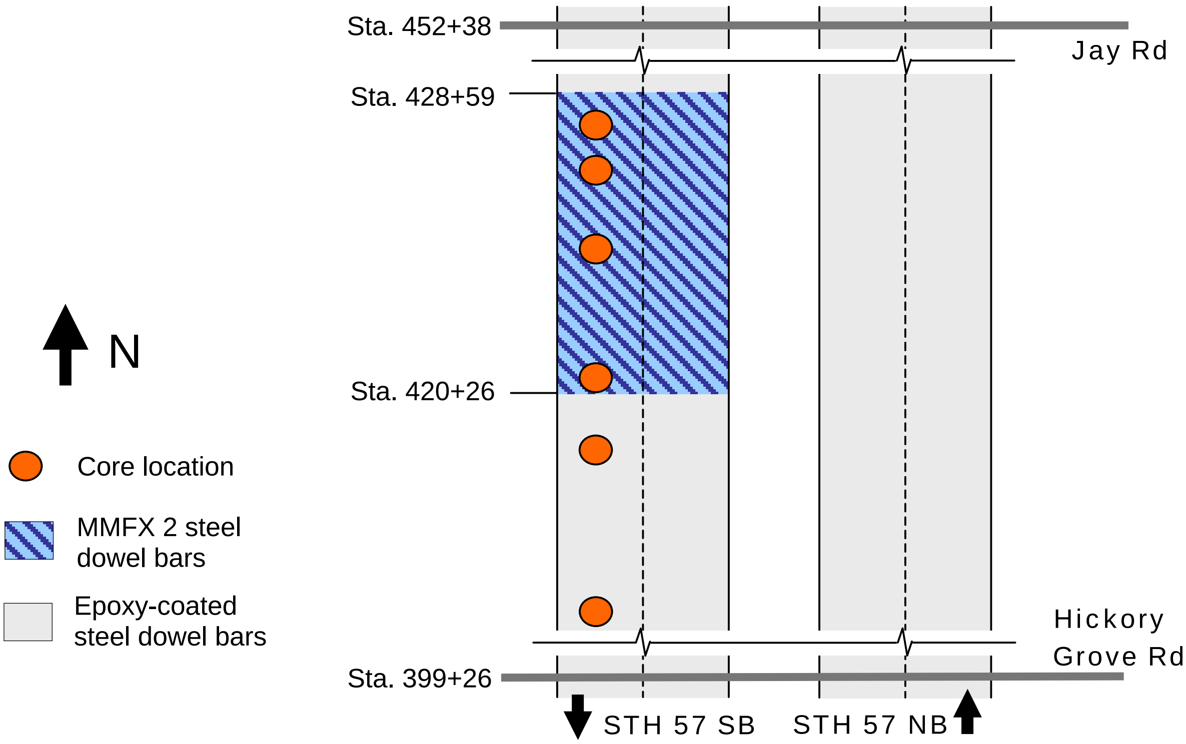


Figure 4. Location of cores.

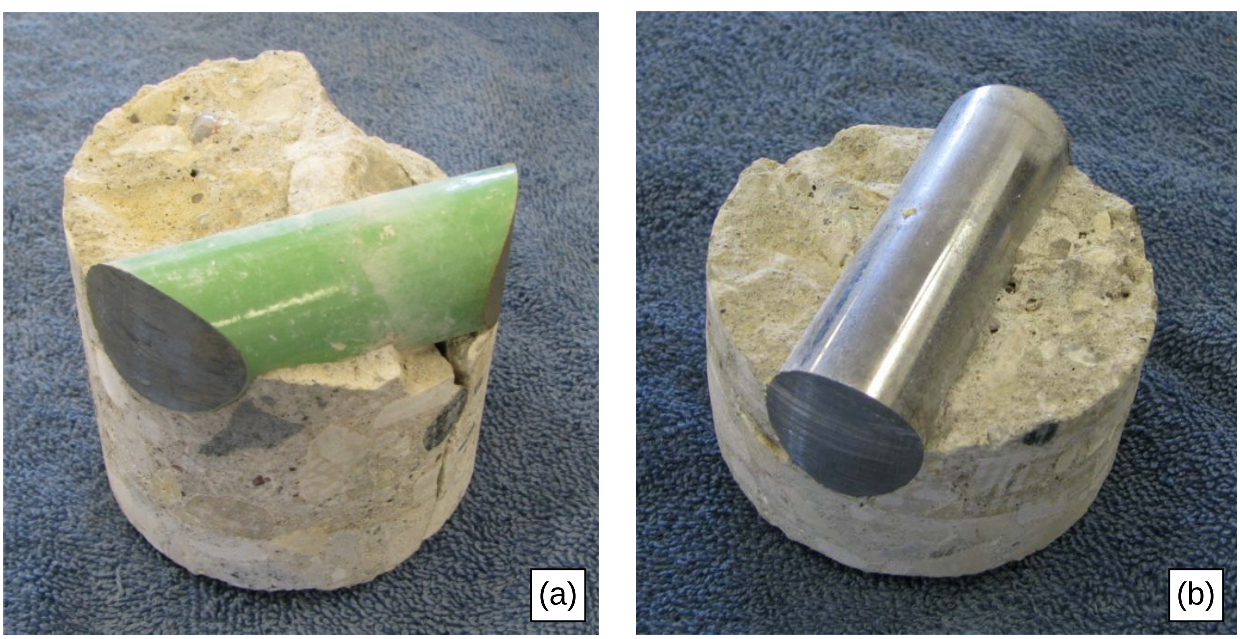


Figure 5. Epoxy-coated steel (a) and MMFX 2 steel (b) dowel bar cores removed after five years in service.

removed from the control section, the epoxy coating remained intact and did not exhibit any signs of blistering or other defects on the surface that would indicate corrosion was taking place in the steel. The four MMFX 2 steel dowel bars were also corrosion-free.

The absence of corrosion on all cored dowel bars indicates that epoxy-coated steel and MMFX 2 steel both resisted corrosion for the five-year period of this study. However, the duration of the test period was not long enough to draw a conclusion on which material exhibits greater in-service corrosion resistance for the life of a concrete pavement.

An additional observation is worth noting. Cores were stored indoors under ambient conditions after removal from the pavement. During the first six months after removal, the exposed steel surfaces of the epoxy-coated dowels began to corrode, while the exposed MMFX 2 steel remained free of corrosion. While in-service conclusions cannot be drawn from this observation, the MMFX 2 steel provided protection against corrosion when exposed to ambient conditions, while the carbon steel corroded when its protective epoxy coating was disrupted.

5.2 Pavement Smoothness

As part of its pavement management system inventory, WisDOT takes biennial international ride index (IRI) measurements on its state trunk network highways. IRI values are reported in units of inches per mile (or meters per kilometer) and represent the summation of the up and down motion experienced by a standardized vehicle at a specific speed over one mile (or one kilometer). Therefore, any occurrence of transverse joint faulting in JPCP is included in IRI measurements. An inertial profiler vehicle is used to record IRI measurements. The WisDOT state trunk network is divided into survey segments approximately 1.0 mi (1.6 km) in length, and one average IRI data point is reported for each survey segment.

Profile data were taken for the test project in 2002, 2004 and 2006 and are shown in Figure 6. The 833-ft (254-m) test section where MMFX 2 steel dowel bars were used was contained in one 1.0-mi (1.6-km) survey segment that also included epoxy-coated steel dowels. The IRI data points for this segment are shown in blue in Figure 6. The remaining length of the construction project, which was constructed entirely with epoxy-coated steel dowel bars, comprised eight survey segments; IRI data points for those segments are shown in green. A linear curve was fit through the MMFX data points (blue curve), and another linear curve was fit through the epoxy-coated data points (green curve). Table B-1 in Appendix B provides IRI data points.

The data indicate that over the time period monitored, IRI for the partial MMFX 2 steel dowel bar section was slightly lower than for the epoxy-coated steel dowel bar areas but did not differ significantly.

The average IRI for the MMFX 2 steel section was 79 in/mi (1.3 m/km) and the average for the epoxy-coated section was 90 in/mi (1.4 m/km). This minimal difference could be attributed to the relatively few data points available for MMFX 2 steel dowel bar construction. The average IRI for all sections increased slightly over the four years reported. Overall, pavement smoothness was very good for sections constructed with both types of dowel bars and is considered average for the first five years of Wisconsin JPCP service. [27]

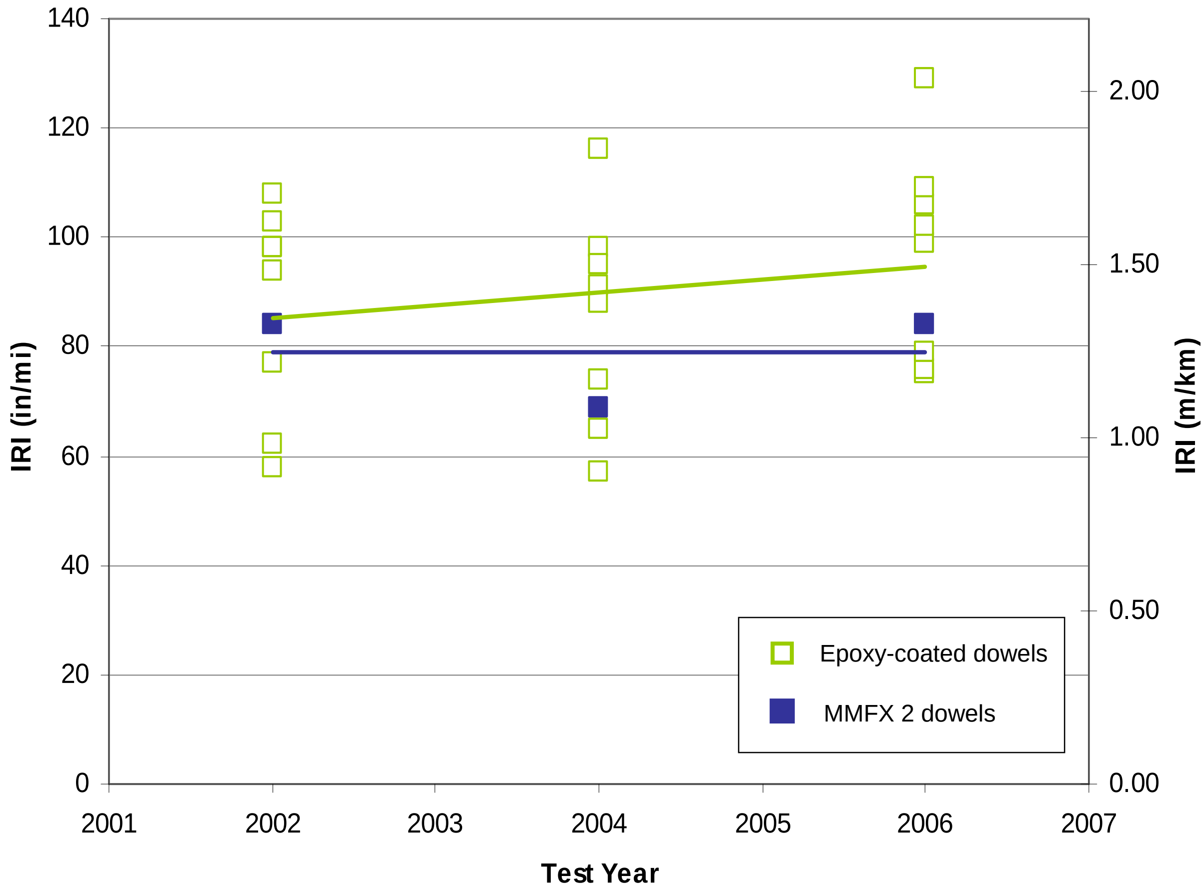


Figure 6. Pavement smoothness data for epoxy-coated and MMFX 2 steel dowel bars.

5.3 Load Transfer Efficiency

LTE was tested on approach slabs using WisDOT's KUAB 2m FWD. Testing took place on October 15, 2007, just prior to the coring operation. Weather was cloudy with an average air temperature of 53°F (12°C) and an average pavement surface temperature of 59°F (15°C). Every other joint was tested with two repetitions at each of three impulse load levels: 5500, 9500 and 13000 lbs (2500, 4300 and 5900 kg).

Results of LTE testing are shown in Figure 7. Each data point represents the average of six LTE values calculated at each joint from two test repetitions at the three load levels mentioned above, and the error bars show the high and low LTE value calculated at each joint. Trend lines show the median LTE value for each test section. Values for each joint and statistical information are provided in Table B-2 in Appendix B.

The median LTE values were 92 percent and 87 percent for joints constructed with epoxy-coated and MMFX 2 steel dowel bars, respectively. Both values are well over the 70 percent LTE level that is recommended for effective load transfer in doweled JPCP. [6] LTE values measured in the MMFX 2 steel test section were slightly more variable than those in the epoxy-coated steel section; the coefficients of variation for MMFX 2 and epoxy-coated steel dowel bars were 4.6 and 2.1 percent, respectively. Overall, both dowel bar types provided adequate load transfer, and the relatively small variations in LTE might be related to construction issues rather than material differences.

In August 2005 the Ohio Department of Transportation constructed test sections using several types of dowel bars, including epoxy-coated steel and MMFX 2 steel. Unpublished LTE results from these test sections were made available for comparison with results from this study. [28] A summary of results is provided in Table 1. For both dowel bar types, median values for LTE obtained from the Ohio test sections were nearly identical to those obtained in Wisconsin. Ohio data also indicated that median LTE values remained constant over the three years for which data was available.

Table 1. Median LTE for Approach Slabs at Mid-Lane (percent) [28]

	MMFX 2 Steel Dowel Bars	**Epoxy-Coated Steel Dowel Bars**
Wisconsin, 2007 Air temp. = 53°F (12°C) Pvmt. temp. = 59°F (15°C)	87	92
Ohio, 2006 Air temp. = 62°F (17°C) Pvmt. temp. = 74°F (23°C)	87	90
Ohio, 2007 Air temp. = 72°F (22°C) Pvmt. temp. = 86°F (30°C)	86	91
Ohio, 2008 Air temp. = 61°F (16°C) Pvmt. temp. = 73°F (23°C)	87	92

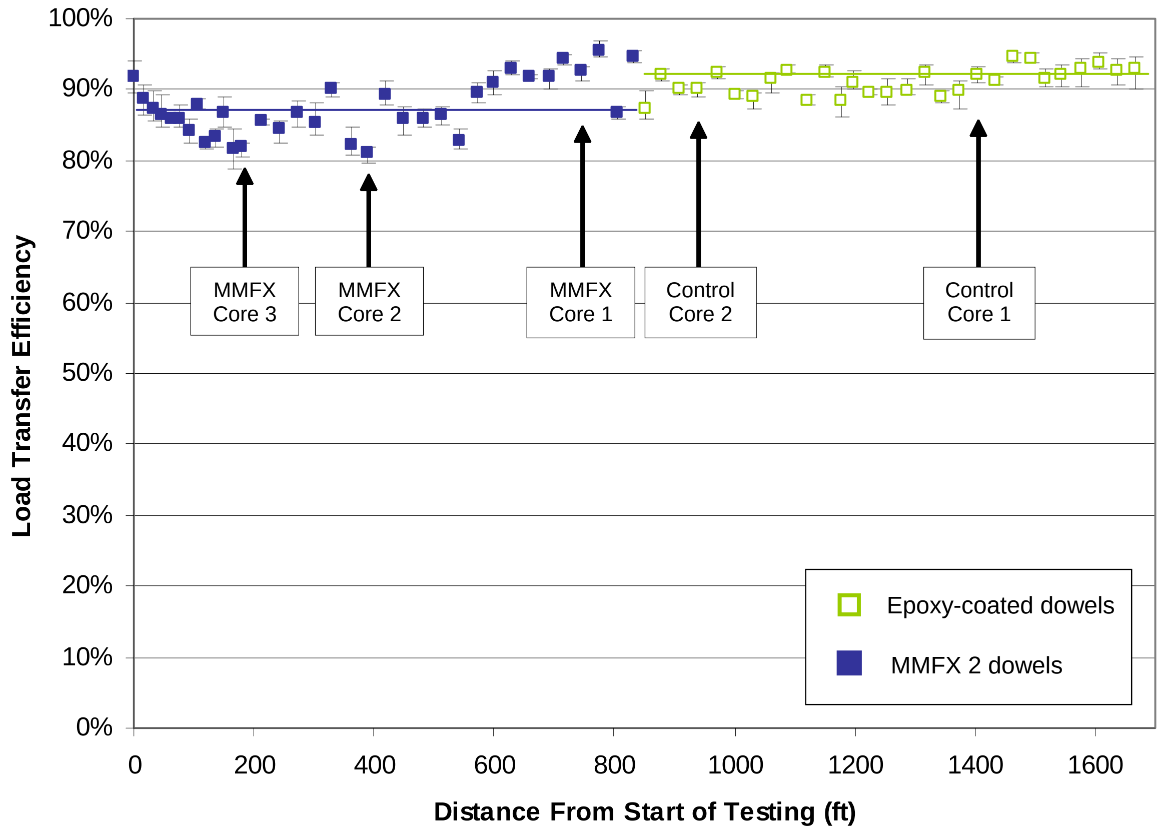


Figure 7. Load transfer efficiency data for epoxy-coated and MMFX 2 steel dowel bars.

5.4 Differential Deflection

To evaluate relative slab deflection under loading, differential deflections were calculated for each load drop (six per joint). A summary of differential deflection values for joints with MMFX 2 steel and epoxy-coated steel dowel bars is presented in Table 2. Values for individual joints are provided in Table B-3 in Appendix B.

Differential deflections were generally less than 1.0 mil (0.03 mm). These values, along with the high LTE values presented in the previous section, indicate that traffic loads transfer adequately between adjacent pavement slabs. Differential deflection values for MMFX joints were slightly higher and more variable than for epoxy-coated joints. Differential deflection values also closely followed the slight up and down trend in LTE noted for MMFX 2 steel dowel bars (Figure 7), with lower differential deflection values corresponding to higher LTE values. Ultimately, the differences in LTE and differential deflection were not significant for the two types of dowels. Both MMFX 2 and epoxy-coated steel dowels demonstrated adequate load transfer performance.

Table 2. Differential Deflection Summary (mils)

	MMFX 2 Steel Dowel Bars	**Epoxy-Coated Steel Dowel Bars**
Average	0.56	0.44
Median	0.56	0.42
Standard deviation	0.19	0.08
Coefficient of variation	34%	19%
Maximum	1.26	0.89
Minimum	0.08	0.15

5.5 Dowel Bar Depths

It should be noted that coring analyses revealed that dowels were placed at greater depths than specified in the project plan. The plan depth was half the slab thickness; for this study it was calculated as half the measured core thickness. Plan and actual dowel depths for each of the cores are reported in Table 3. The dowels were inserted 1.3 to 2.3 in (33 to 58 mm) deeper than specified, which means that in the worst case (MMFX core 1), the center of the dowel was only 1.75 in (44 mm) from the bottom of the pavement slab. This problem is also evident in Figure 5. Results from the MIT-2 Scan unit indicate that dowels were generally placed consistently along each pavement joint analyzed; thus the problem is not unique to these cores and could be an issue for the entire construction area.[1]

Dowel placement that deviates from mid-depth can affect LTE of the joint. Average joint LTE for each core location is also presented in Table 3. There is no correlation between depth deviation and average LTE. Therefore in this case, misplacement of the dowels did not appear to affect load transfer performance of the joint. It is possible, however, that aggregate interlock could deteriorate as the concrete ages, and at that point, dowel depth may become more critical.

[1] MIT-2 Scan unit results also showed that dowels were not horizontally or vertically misaligned; that is, they were placed perpendicular to the joint and would therefore allow free longitudinal slab movement.

Table 3. Dowel Depth Information for Pavement Cores (inches)

	Measured Core Thickness	Plan Depth (½ Core Thickness)	Measured Depth	Depth Deviation	Average Joint LTE
Control core 1 Sta. 413+90	8.5	4.25	5.75	1.5	92%
Control core 2 Sta. 418+69	8.5	4.25	6.25	2.0	90%
MMFX core 1 Sta. 420+53	8.125	4.06	6.375	2.3	93%
MMFX core 2 Sta. 424+23	8.5	4.25	5.75	1.5	81%
MMFX core 3 Sta. 426+37	8.125	4.06	5.375	1.3	82%
MMFX core 4 Sta. 427+71	8.5	4.25	5.625	1.4	*

*Core location was not noted in FWD data

6. Cost Analysis

6.1 Direct Cost Comparison

A cost comparison was performed using manufacturer dowel bar price estimates from June 2008. [29, 30] Cost details for 1.5-inch (38-mm) diameter dowel bars with a length of 18 inches (455 mm) are provided in Table 4. For calculations, construction parameters from this study's project were used: 15-ft (4.5-m) joint spacing with 26 dowels per joint. This cost comparison shows that with use of MMFX 2 steel dowel bars, the initial cost per project mile for two driving lanes is 32 percent higher than the cost to use epoxy-coated steel dowels.

Table 4. Cost Details for 1.5-inch (38-mm) Diameter by 18-inch (455-mm) Dowel Bars, 26 Dowels per Joint

Material	Cost per Dowel Bar	Cost per Project Mile (Project Kilometer)	
Epoxy-Coated Steel	$6.80	$63,200	($39,300)
MMFX 2 Steel	$9.00	$83,700	($52,000)

6.2 Life-Cycle Cost Analysis

A life-cycle cost analysis (LCCA) can give a better perspective of pavement cost over its entire service life. Therefore, a series of LCCAs were performed to better compare the dowel bar material costs. In a standard WisDOT LCCA, a new doweled JPCP over dense-graded base course is assigned an initial service life of 25 years. [31] A typical rehabilitation schedule consists of two cycles of concrete joint repair at five percent of joints (8-year service life each) and a final five-percent concrete joint repair with HMA overlay (15-year service life). The concrete joint repair operation includes full-depth replacement of concrete with drilled dowel bars inserted at the newly created joints. An analysis period of 50 years and a discount rate of 5 percent is typical for the LCCA.

In the first LCCA scenario, the rehabilitation schedule described above was applied for both dowel bar alternatives. Typical per project mile material costs for two driving lanes were used for initial pavement construction and each rehabilitation method. WisDOT's WisPave pavement design software tool was used to determine the total facility cost in the present year. Details of the first LCCA scenario are provided in Table 5, and a WisPave LCCA summary sheet is provided in Figure C-1 of Appendix C. Because of the higher initial cost, the MMFX 2 steel dowel bar alternative has a total facility cost that is 3.4 percent higher than the epoxy-coated alternative.

In the second LCCA scenario, the typical rehabilitation schedule was applied for the epoxy-coated steel dowel bar alternative. For the MMFX alternative, the initial service life was increased to 40 years, and one concrete joint repair rehabilitation effort was removed. Details of the second LCCA scenario are provided in Table 6, and a WisPave LCCA summary sheet is provided in Figure C-2 of Appendix C. With the 15-year increase in service life and fewer rehabilitation efforts, the total facility costs of the two dowel bar alternatives were approximately equal, with the epoxy-coated alternative 0.18 percent higher.

In conclusion, MMFX 2 steel dowel bars would be cost-effective if their use increased the initial service life of the JPCP by 15 years. This result is similar to the 13-year service life increase predicted by Kahl for concrete bridge decks reinforced with MMFX 2 steel. [11] A service life increase of 15 years or more could be possible if high performance concrete (HPC) materials were also used. This would further increase the initial cost of the pavement, and a separate LCCA would be required. However, for the intent of this research, the LCCA scenarios presented above provide a satisfactory indicator of cost differences for the two dowel bar types.

Table 5. Details of Life-Cycle Cost Analysis, Scenario Number 1, for
a. Epoxy-Coated Steel Dowel Bars and b. MMFX 2 Steel Dowel Bars*

a. Epoxy-Coated Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project Mile (2 Lanes)
0	Initial Construction	25		$573,839
25	Rehabilitation	8	Concrete joint repair (5%)	$19,129
33	Rehabilitation	8	Concrete joint repair (5%)	$19,129
41	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$185,559
			Total Facility Costs, Present Year	**$601,942**

b. MMFX 2 Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project Mile (2 Lanes)
0	Initial Construction	25		$594,308
25	Rehabilitation	8	Concrete joint repair (5%)	$19,129
33	Rehabilitation	8	Concrete joint repair (5%)	$19,129
41	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$185,559
			Total Facility Costs, Present Year	**$622,412**

*Metric data available in Table C-1 in Appendix C.

Table 6. Details of Life-Cycle Cost Analysis, Scenario Number 2, for
a. Epoxy-Coated Steel Dowel Bars and b. MMFX 2 Steel Dowel Bars*

a. Epoxy-Coated Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project Mile (2 Lanes)
0	Initial Construction	25		$573,839
25	Rehabilitation	8	Concrete joint repair (5%)	$19,129
33	Rehabilitation	8	Concrete joint repair (5%)	$19,129
41	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$185,559
			Total Facility Costs, Present Year	**$601,942**

b. MMFX 2 Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project Mile (2 Lanes)
0	Initial Construction	40		$594,308
40	Rehabilitation	8	Concrete joint repair (5%)	$19,129
48	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$185,559
			Total Facility Costs, Present Year	**$600,841**

*Metric data available in Table C-2 in Appendix C.

7. Summary

A detailed literature search was conducted to determine how epoxy-coated and MMFX 2 steels compare in accelerated corrosion tests. It was concluded that MMFX 2 steel demonstrated corrosion resistance that was close to or better than epoxy-coated steel with damaged coating but did not out-perform steel with intact epoxy coating. [10, 11, 12, 13, 19, 20]

The performance of MMFX 2 steel dowel bars was compared to epoxy-coated steel dowel bars after five years of service in nine-inch JPCP. Performance indicators included dowel bar corrosion, pavement smoothness and LTE at the transverse joints. Cores through dowel bars revealed that no corrosion had occurred on either type of dowel after five years in service. Results of IRI testing indicated that pavement smoothness was similar for sections constructed with both types of dowels. The LTE of epoxy-coated dowel bar sections (median value of 92 percent) was slightly higher than the median value of 87 percent for MMFX 2 steel dowel bar sections. However, these values indicate that both types of dowels have provided adequate load transfer for the JPCP. The initial cost per two-lane project mile is 32 percent higher for MMFX 2 steel dowel bars than for epoxy-coated steel dowels. Two LCCA scenarios illustrated that use of MMFX 2 steel dowels would be cost effective if they provided an additional 15 years of initial service for JPCP.

8. Conclusions and Recommendation

In conclusion, results of this investigation did not suggest that either epoxy-coated steel or MMFX 2 steel dowel bars provide superior performance when used in the construction of JPCP. Results of accelerated corrosion tests conducted in other research studies were variable and did not offer conclusive evidence that MMFX 2 steel would provide greater corrosion resistance than epoxy-coated steel in JPCP. After five years in service, the pavement is performing equally well in JPCP test sections constructed with both types of dowels.

Given the inconclusive results of this field study, the variability of corrosion testing noted in the review of previous literature and the higher initial cost of MMFX 2 steel, it is not recommended that MMFX 2 steel dowel bars be approved for use in future WisDOT JPCP construction. An additional evaluation may be warranted to determine if MMFX 2 steel dowels are appropriate for the construction of high performance concrete pavements.

9. References

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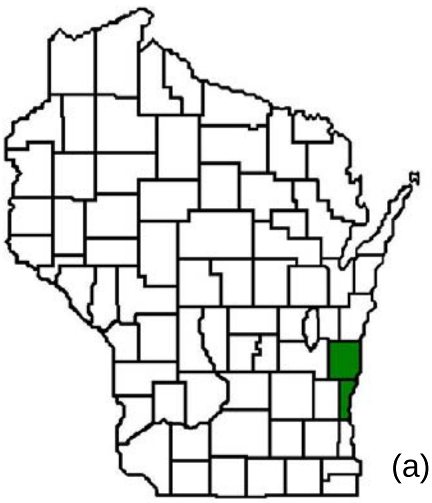
Appendix A

Test Site Location Figures



(a)

(b)

Figure A-1. Test site location: (a) Map of Wisconsin with Sheboygan and Ozaukee Counties shaded; (b) Sheboygan and Ozaukee Counties with test area denoted by box; (continued next page)

(c)

Figure A-1 cont. (c) Location of test section denoted by box.

Appendix B

IRI, LTE, and Differential Deflection Data

Table B-1 (a). International Ride Index (IRI) Data (in/mi)

Survey Segment	Dowel Bar Type	Test Year		
		2002	2004	2006
1	Epoxy-coated	94	98	106
2	MMFX 2	84	69	84
3	Epoxy-coated	58	65	75
4	Epoxy-coated	62	57	76
5	Epoxy-coated	77	74	79
6	Epoxy-coated	108	91	99
7	Epoxy-coated	98	88	102
8	Epoxy-coated	103	95	109
9	Epoxy-coated	98	116	129

Table B-1 (b). International Ride Index (IRI) Data (m/km)

Survey Segment	Dowel Bar Type	Test Year		
		2002	2004	2006
1	Epoxy-coated	1.48	1.55	1.67
2	MMFX 2	1.34	1.09	1.33
3	Epoxy-coated	0.93	1.03	1.18
4	Epoxy-coated	0.98	0.90	1.20
5	Epoxy-coated	1.22	1.17	1.25
6	Epoxy-coated	1.72	1.44	1.56
7	Epoxy-coated	1.56	1.39	1.61
8	Epoxy-coated	1.63	1.50	1.72
9	Epoxy-coated	1.56	1.83	2.04

Table B-2 (a). Load Transfer Efficiency Values for Joints Constructed with MMFX 2 Steel Dowel Bars

Dist. From Start		LTE Value		
m	**ft**	**Average**	**High**	**Low**
0	0	91.7%	94.2%	89.6%
5	16	88.7%	90.7%	86.3%
10	33	87.2%	89.7%	85.7%
14	46	86.5%	89.3%	84.8%
19	62	85.8%	86.2%	85.3%
23	75	85.9%	87.8%	84.7%
28	92	84.2%	85.9%	82.5%
33	108	87.8%	88.6%	87.2%
37	121	82.4%	83.4%	81.7%
42	138	83.3%	84.4%	81.9%
46	151	86.7%	89.1%	84.8%
51	167	81.7%	84.4%	78.8%
55	180	81.8%	82.5%	80.6%
65	213	85.5%	85.9%	85.1%
74	243	84.5%	85.7%	82.6%
83	272	86.7%	88.6%	84.8%
92	302	85.4%	88.0%	83.7%
101	331	90.2%	90.9%	89.0%
110	361	82.1%	84.7%	80.7%
119	390	81.0%	81.9%	79.6%
128	420	89.3%	91.1%	87.8%
137	449	85.7%	87.7%	83.5%
147	482	85.9%	87.2%	84.9%
156	512	86.4%	87.6%	85.1%
165	541	82.7%	84.5%	81.6%
174	571	89.6%	90.9%	88.1%
183	600	90.9%	92.6%	89.4%
192	630	93.0%	94.1%	92.1%
201	659	91.7%	92.0%	91.4%
211	692	91.9%	92.9%	90.1%
218	715	94.3%	95.0%	93.5%
227	745	92.8%	93.3%	91.3%
236	774	95.5%	96.8%	94.6%
245	804	86.7%	87.5%	85.8%
254	833	94.6%	95.3%	93.8%
	Median Value	**86.7%**		
	Standard Deviation	**4.0%**		
	Coefficient of Variation	**4.6%**		

Table B-2 (b). Load Transfer Efficiency Values for Joints Constructed with Epoxy-Coated Steel Dowel Bars

Dist. From Start		LTE Value		
m	**ft**	**Average**	**High**	**Low**
259	850	87.4%	89.8%	85.8%
268	879	92.1%	93.0%	91.2%
277	909	90.0%	90.7%	89.3%
286	938	90.0%	91.0%	89.1%
296	971	92.5%	93.2%	91.7%
305	1001	89.2%	89.7%	88.7%
314	1030	89.0%	89.6%	87.4%
323	1060	91.6%	92.4%	89.5%
332	1089	92.8%	93.5%	92.3%
342	1122	88.5%	89.3%	87.8%
351	1152	92.4%	93.6%	91.7%
359	1178	88.3%	90.4%	86.2%
365	1198	91.0%	92.7%	90.0%
373	1224	89.7%	90.0%	89.4%
382	1253	89.5%	91.5%	88.0%
392	1286	89.9%	91.6%	89.2%
401	1316	92.4%	93.4%	90.6%
410	1345	89.1%	89.7%	88.2%
419	1375	89.7%	91.2%	87.3%
428	1404	92.1%	93.2%	90.9%
437	1434	91.3%	91.9%	90.7%
446	1463	94.5%	95.1%	93.8%
455	1493	94.3%	95.3%	93.8%
462	1516	91.5%	92.9%	90.3%
471	1545	92.1%	93.5%	90.3%
481	1578	92.9%	94.3%	90.4%
490	1608	93.7%	95.3%	92.8%
499	1637	92.6%	94.2%	90.8%
508	1667	93.0%	94.8%	90.1%
Median Value		**91.5%**		
Standard Deviation		**1.9%**		
Coefficient of Variation		**2.1%**		

Table B-3 (a). Differential Deflection Values for Joints Constructed with MMFX 2 Steel Dowel Bars

Dist. From Start		Differential Deflection (mils)		
m	**ft**	**Average**	**Max**	**Min**
0	0	0.40	0.64	0.16
5	16	0.53	0.71	0.26
10	33	0.63	0.91	0.29
14	46	0.66	0.99	0.29
19	62	0.71	1.01	0.41
23	75	0.68	1.01	0.34
28	92	0.71	1.06	0.37
33	108	0.51	0.74	0.29
37	121	0.85	1.19	0.48
42	138	0.78	1.17	0.43
46	151	0.61	0.90	0.29
51	167	0.78	1.11	0.40
55	180	0.86	1.25	0.50
65	213	0.69	0.94	0.41
74	243	0.66	0.99	0.36
83	272	0.53	0.77	0.27
92	302	0.56	0.78	0.27
101	331	0.36	0.51	0.20
110	361	0.71	1.05	0.35
119	390	0.75	1.04	0.46
128	420	0.39	0.56	0.19
137	449	0.54	0.73	0.36
147	482	0.56	0.80	0.35
156	512	0.55	0.83	0.32
165	541	0.91	1.26	0.47
174	571	0.48	0.64	0.31
183	600	0.42	0.61	0.20
192	630	0.34	0.49	0.20
201	659	0.38	0.54	0.22
211	692	0.32	0.44	0.17
218	715	0.24	0.33	0.14
227	745	0.36	0.53	0.19
236	774	0.21	0.3	0.08
245	804	0.66	0.91	0.37
254	833	0.22	0.28	0.14
Median Value		**0.56**		
Standard Deviation		**0.19**		
Coefficient of Variation		**34%**		

Table B-3 (b). Differential Deflection Values for Joints Constructed with Epoxy-Coated Steel Dowel Bars

Dist. From start		Differential deflection (mils)		
m	**ft**	**Average**	**Max**	**Min**
259	850	0.60	0.89	0.27
268	879	0.39	0.56	0.2
277	909	0.58	0.86	0.33
286	938	0.49	0.71	0.27
296	971	0.39	0.56	0.24
305	1001	0.54	0.79	0.32
314	1030	0.58	0.81	0.31
323	1060	0.41	0.57	0.22
332	1089	0.36	0.53	0.19
342	1122	0.57	0.80	0.33
351	1152	0.41	0.62	0.19
359	1178	0.42	0.69	0.22
365	1198	0.38	0.57	0.17
373	1224	0.50	0.71	0.29
382	1253	0.50	0.71	0.23
392	1286	0.42	0.60	0.26
401	1316	0.35	0.49	0.18
410	1345	0.44	0.64	0.24
419	1375	0.55	0.76	0.32
428	1404	0.42	0.66	0.20
437	1434	0.44	0.67	0.23
446	1463	0.29	0.40	0.15
455	1493	0.31	0.45	0.19
462	1516	0.48	0.70	0.23
471	1545	0.41	0.62	0.23
481	1578	0.38	0.54	0.17
490	1608	0.37	0.57	0.15
499	1637	0.43	0.61	0.19
508	1667	0.34	0.47	0.15
	Median Value	**0.42**		
	Standard Deviation	**0.08**		
	Coefficient of Variation	**19%**		

Appendix C

Life Cycle Cost Analysis Summary

GENERAL LCCA RESULTS, WisPave 2.4

July 2008

Project ID: LCCA #1
Highway Name: STH 57
Designer Name: Irene Battaglia

C:\Program Files\State of Wisconsin\WisPave\dowel.mdb

PRESENT WORTH COSTS

(2008)

	ALT 1 Epoxy-Coated Steel Dowel Bars	ALT 2 MMFX 2 Steel Dowel Bars
Initial Construction Costs	$573,839.00	$594,308.00
Rehabilitation Costs	$34,575.04	$34,575.04
Rehabilitation Salvage Value	($6,472.54)	($6,472.54)
Total Facility Costs	$601,941.50	$622,411.50
	Lowest	**+ 3.40%**

Figure C-1. LCCA Summary Information for Scenario #1.
Costs are in dollars per project mile.

GENERAL LCCA RESULTS, WisPave 2.4

July 2008

Project ID: LCCA #2
Highway Name: STH 57
Designer Name: Irene Battaglia

C:\Program Files\State of Wisconsin\WisPave\dowel.mdb

PRESENT WORTH COSTS

(2008)

	ALT 1 Epoxy-Coated Steel Dowel Bars	ALT 2 MMFX 2 Steel Dowel Bars
Initial Construction Costs	$573,839.00	$594,308.00
Rehabilitation Costs	$34,575.04	$20,557.20
Rehabilitation Salvage Value	($6,472.54)	($14,023.83)
Total Facility Costs	$601,941.50	$600,841.37
	+ 0.18%	**Lowest**

Figure C-2. LCCA Summary Information for Scenario #2.
Costs are in dollars per project mile.

Table C-1. Details of Life-Cycle Cost Analysis, Scenario Number 1, for
a. Epoxy-Coated Steel Dowel Bars and b. MMFX 2 Steel Dowel Bars (metric values)

a. Epoxy-Coated Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project km (2 Lanes)
0	Initial Construction	25		$356,354
25	Rehabilitation	8	Concrete joint repair (5%)	$11,879
33	Rehabilitation	8	Concrete joint repair (5%)	$11,879
41	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$115,232
			Total Facility Costs, Present Year	**$373,806**

b. MMFX 2 Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project km (2 Lanes)
0	Initial Construction	25		$369,065
25	Rehabilitation	8	Concrete joint repair (5%)	$11,879
33	Rehabilitation	8	Concrete joint repair (5%)	$11,879
41	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$115,232
			Total Facility Costs, Present Year	**$386,517**

Table C-2. Details of Life-Cycle Cost Analysis, Scenario Number 2, for
a. Epoxy-Coated Steel Dowel Bars and b. MMFX 2 Steel Dowel Bars (metric values)

a. Epoxy-Coated Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project km (2 Lanes)
0	Initial Construction	25		$356,354
25	Rehabilitation	8	Concrete joint repair (5%)	$11,879
33	Rehabilitation	8	Concrete joint repair (5%)	$11,879
41	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$115,232
			Total Facility Costs, Present Year	**$373,806**

b. MMFX 2 Steel Dowel Bars

Year of Work	Type of Construction	Service Life	Description of Work	Cost per Project km (2 Lanes)
0	Initial Construction	40		$369,065
40	Rehabilitation	8	Concrete joint repair (5%)	$11,879
48	Rehabilitation	15	Concrete joint repair (5%) and HMA overlay	$115,232
			Total Facility Costs, Present Year	**$373,122**