ALTERNATIVE DOWEL BARS FOR LOAD TRANSFER IN JOINTED CONCRETE PAVEMENTS

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ABSTRACT

Concerns over the long-term effectiveness of epoxy coatings of dowel bars have motivated some agencies to investigate the use of alternative dowel bar materials. Alternative dowel bars are either constructed of a non-corrodible material or contain a non-corrodible cladding for protection against corrosion. The need for a long-lasting dowel bar design has become even more acute as many highway agencies are exploring the development of long-life portland cement concrete (PCC) pavements, ones that are capable of providing service lives of 40, 50, or even 60 years.

Under Test and Evaluation Project 30 (TE-30), *High Performance Concrete Pavements* (HPCP), the Federal Highway Administration (FHWA) is exploring the applicability of innovative PCC pavement design and construction concepts, including the use of alternative dowel bars. Several projects incorporating alternative dowel bars have been constructed under that program, and interest in these projects is high. At the same time, the Highway Innovative Technology Evaluation Center (HITEC) is sponsoring an evaluation the HPCP projects that specifically compare the performance of 38-mm (1.5-in) diameter fiber reinforced polymer (FRP) composite or Type 304 solid or concrete-filled tubes to standard epoxy-coated steel dowels.

This paper summarizes some of the types of alternative dowel bars currently available for use in jointed concrete pavement (JCP) construction, describes some of their advantages and disadvantages, and reviews some of the recent field projects constructed under the TE-30 or related programs that incorporate alternative dowel bars. In addition, a brief summary of related laboratory or accelerated pavement testing on alternative dowel bars is provided. Recommendations for additional research and field testing are also presented.

INTRODUCTION

Load transfer is the mechanism through which wheel loads are conveyed across joints and cracks in PCC pavements. In JCP, it is an important design consideration because effective load transfer significantly reduces the magnitude of stresses and deflections at transverse joints, which in turn helps reduce or prevent distresses such as pumping, faulting, and corner breaks, as well as the roughness associated with those distresses. Load transfer across transverse joints is provided through aggregate interlock, mechanical load transfer devices (dowel bars), and

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foundation (base/subbase/subgrade) support, with dowel bars providing the most effective and reliable means of long-term load transfer. Conventional JCP construction uses smooth, round steel dowel bars commonly conforming to AASHTO M31 or ASTM A615 for load transfer across transverse joints.

Unfortunately, the performance of some JCP has been compromised by the corrosion of the steel dowel bars. This is a particular problem on pavements in wet climates that are exposed to deicing salts. Although steel embedded in hydrating cement paste forms a thin passivity layer of oxide providing protection from reaction with oxygen and water, this passivity film can be easily broken down under the action of chloride ions (Neville 1998). The primary source of the chloride ions is from the application of deicing salts (which have direct access to the dowel bars at the joints), although it can also come from other sources such as seawater or the presence of a calcium chloride accelerator in the PCC mix (Van Dam et al. 2002).

If significant corrosion of the dowel bars occurs, the transverse joint may "lock up" and no longer be capable of accommodating horizontal movements. Locked or frozen joints can cause cracking or spalling at the joints, or may contribute to the development and further deterioration of mid-panel transverse cracks (because the cracks must now open to accommodate the slab movements). And, in advanced stages of corrosion, the effective diameter of the dowel bar is reduced, often to the point where joint load transfer is adversely affected. In some cases, it is believed that the expansion of the dowel due to corrosion (combined with stresses due to thermal curling or moisture warping) causes excessive tensile stresses that result in a horizontal delamination in the concrete slab at the dowel bar level. However, delaminations in the concrete at the dowel bar may also be due to built-in construction curling/warping, heavy loadings, poor base/subgrade support conditions (such as provided by some unstabilized permeable bases), or a combination of all three. It should also be noted that joints can also lock up due to misalignment of the dowel bars.

The corrosion of dowel bars has long been recognized as a problem in JCP. New Jersey was one of the first states to adopt a means of corrosion protection for dowel bars in their JCP, experimenting in the 1940s with both monel and stainless steel sleeves placed over steel dowels to prevent corrosion (Van Breemen 1955). These clad dowel bars were very successful, and although costly New Jersey reasoned that their use was warranted because they would have a life expectancy on the order of the 30 or 40 years that the pavement structure was providing (Van Breemen 1955). Over the years, several research studies investigated clad bars and other dowel coatings in efforts to identify suitable means of providing corrosion protection (Mitchell 1960; Wood and Lavoie, 1963; Ramey 1968; Minkarah and Cook, 1976; Arnold 1980; Vyce 1987).

Beginning in the mid-1970s, many agencies began using epoxy-coated dowel bars. This material was cheaper than other coatings or cladding materials, and the short-term performance was promising (Kelleher and Larson, 1989). By the mid-1980s, most highway agencies had adopted epoxy-coated steel dowel bars as their design standard. However, recently some concerns have arisen regarding the long-term effectiveness of epoxy coatings in preventing corrosion; moreover, there is concern that any nicks or scratches on the epoxy-coated dowel bar at the time of construction may create a concentration point for the intrusion of caustic chloride ions, which could result in the rapid development of corrosion. Although there is currently insufficient documentation of the extent of the epoxy-coated steel dowel bar corrosion problem nationwide, a survey in the late 1990s showed that 78 percent of the responding states were interested in the use of alternative dowel bar materials (Porter and Braun 1997). As such, additional research on the long-term performance and cost-effectiveness of alternative dowel bars is needed.

A recent assessment of dowel bar research was prepared by Iowa State University researchers that identified the more significant gaps in technology for dowel bar design and analysis. Of the gaps identified, the authors recommended that universal testing procedures for both laboratory and field conditions first be determined so that a correct, consistent comparison between dowel bars can be made (Porter and Guinn 2002). And, the need for better tools is addressed under Task 6 ("Innovative Concrete Pavement Joint Design, Materials, and Construction") of the proposed *Long-Term Plan for Concrete Pavement Research and Technology* (FHWA 2004).

Because of some of the concerns associated with epoxy-coated dowel bars, some highway agencies have been exploring the use of alternative dowel bars that are either constructed of a non-corrodible material or contain a more durable non-corrodible cladding. Several projects incorporating alternative dowel bars have been constructed under the FHWA's TE-30 Project *High Performance Concrete Pavements* (HPCP), and interest in the use of these materials is high. At the same time, HITEC is sponsoring an evaluation of 38-mm (1.5-in) FRP and Type 304 solid stainless steel or concrete-filled tubes compared to epoxy-coated mild steel dowels (HITEC 1998). Several other related laboratory or accelerated pavement testing research studies are also underway.

This paper summarizes some of the types of alternative dowel bars currently available for use in JCP construction, describes some of their advantages and disadvantages, and reviews some of the recent field projects constructed under the TE-30 and other related programs that incorporate alternative dowel bar materials. Recommendations for further research to improve guidance in this area are also provided.

TYPES OF ALTERNATIVE DOWEL BARS

As previously described, a variety of alternative dowel bars have been used over the years in attempts to combat potential corrosion. These may be broadly classified as follows:

- Fiber reinforced polymer (FRP) composite dowel bars.
- FRP composite tubes filled with cement grout.
- Plastic-coated dowel bars.
- Solid stainless steel dowel bars.
- Stainless steel clad dowel bars.
- Stainless steel tubes filled with cement grout.

A summary of some of the characteristics of these materials is provided in table 1, along with characteristics of conventional epoxy-coated dowel bars. Additional information on these materials is provided in the following sections.

Fiber Reinforced Polymer (FRP) Composite Dowel Bars. FRP composites are a matrix of polymeric material that is reinforced by fibers or other reinforcing materials (HITEC 1998). A description of the specific constituent materials in FRP composites is given below (RJD 1999):

- The *matrix binder* is made up by a homogenous resin or polymer material such as polyester, vinyl ester, or epoxy. The binder holds the reinforcing elements together and acts as a corrosion barrier.
- The *reinforcing element* consists of a strong material (such as fiberglass, carbon fiber, or graphite fiber) bonded into the matrix binder to improve its mechanical properties.
- *Fillers*, which are relatively inert materials (such as calcium carbonate, clay, or hydrated alumina), are added to improve specific properties of the composite or to lower its costs.

FRP composite dowel bars constructed of polyester resin and fiberglass reinforcing elements are the most common type of FRP bars, although both vinyl ester resin/fiberglass and epoxy resin/fiberglass bars are also available. These materials are often manufactured in a pultrusion process, in which the reinforcing elements are pulled continuously through a resin impregnation bath and through a shaping die, where the resin is cured to hardness.

As shown in table 1, the primary advantages of FRP composite dowel bars are their resistance to corrosion, their light weight, and their greater relative closeness in stiffness to that of the PCC; this latter characteristic may reduce the build-up of critical stresses at the interface of the dowel and PCC, which could lead to "socketing" around the dowel bar and eventually reduced LTE. However, recent Manitoba research shows that the greater flexibility of the dowel results in higher stresses at concrete interface (Murison 2004; Murison et al. 2005). The primary disadvantages are their increased initial costs and a lower modulus of elasticity.

Laboratory testing of FRP composite dowel bars generally have shown that they exhibit higher deflections than conventional steel or stainless steel dowel bars (Cable and McDaniel, 1998; Cable and Porter 2003; Crovetti 1999). A theoretical analysis of the dowel bar response to loading showed that the deflection of the FRP composite dowels was about 1.6 times that of a steel dowel, suggesting that either dowel bar diameter must be increased or the dowel spacing must be decreased in order to achieve the same performance (Davis and Porter 1998). In that vein, a laboratory study showed similar performance (in terms of joint LTE) between 44-mm (1.75-in) diameter FRP bars spaced at 203 mm (8 in) and conventional 38-mm (1.5-in) steel dowels spaced at 305 mm (12 in) (Porter et al. 1996). Another laboratory study indicated that 38-mm (1.5-in) FRP bars performed as well as 25-mm (1-in) steel dowel bars when subjected to cyclic loadings across jointed specimens (Melham 1999). Also, a recent laboratory accelerated pavement testing study evaluated both new and retrofitted dowel materials and recommended evaluating 50-mm (2-in) FRP composite tubes filled with concrete as a cost-effective alternative to the 38-mm (1.5-in) solid FRP or epoxy-coated steel dowels (Popehn et al. 2003).

The first FRP composite dowels used in pavement applications were placed in Ohio on several sections of State Route 7 in Belmont County (as part of a new PCC paving project) and on I-77 in Guernsey County (as part of a full-depth repair project that was given a sawed and sealed HMA overlay) in 1983 and 1985, respectively (MDA 1999; McCallion 1999). Deflection testing conducted periodically after the construction of these projects indicated that the LTE of the FRP composite dowel bars was equal to, or greater than, conventional steel dowel bars installed on the projects. However, a number of the LTE test results were 70 percent or less for all the types of dowels used (McCallion 1999). Inspection of several of the FRP composite dowels removed from the transverse joints of these projects after nearly 15 years of service showed no signs of deterioration, other than mechanical erosion on a few FRP dowels caused by excessive joint movement (MDA 1999). Deflection testing was performed using the Dynatest device up to 1998, and an FWD thereafter. All deflection testing of the I-77 full-depth repairs were taken on top of the HMA overlay.

Extensive FRP research has been conducted at West Virginia University as the result of a congressionally mandated study. The main objectives of the FRP dowel studies were: (1) construct FRP-doweled pavement sections and evaluate performance, and (2) study moisture diffusion in FRP dowels. Various sizes and spacings of both FRP and epoxy-coated steel dowels were evaluated theoretically and in the laboratory and installed on new or rehabilitated pavement sections. Larger diameter dowels or closer spacing improved LTE as expected. Poor base conditions resulted in less than desirable LTEs for the experimental sections (GangaRao 2004; Gupta 2004).

Researchers at the University of California-Davis have performed fatigue and durability testing on three types of FRP dowels. Accelerated testing on a section with FRP and other dowel types has been performed, along with theoretical modeling studies. The goal is to develop design criteria and material specifications for FRP dowels. The results are expected to be available in mid-2005 (Bian 2003).

FRP Composite Tubes. A variation on the use of solid FRP composite bars for load transfer devices employs an FRP composite tube filled with high-strength cement grout. These tubes are manufactured using the same types of materials and the same process as with the solid FRP bars. The cement grout that is added to the bars serves to increase the strength and deformation resistance of the tube (Murison 2004; Murison et al. 2005). However, some problems have been noted in getting suppliers to fill the tubes with grout.

The primary advantages of these types of load transfer devices are their corrosion resistance (same as solid FRP bars) and their lower costs (compared to solid FRP bars). Costs on one project were noted to be about $8 to $9 per bar (for a 51-mm [2-in] diameter bar, 457-mm [18-in] long), but these represent costs from experimental projects in which limited quantities were used (Wojakowski 1998).

Plastic-Coated Dowel Bars. Plastic-coated dowel bars are steel dowels coated with a thin layer (0.5 to 0.8 mm [0.020 to 0.030 in] thick) of plastic, most commonly polyethylene. A thin mastic bonding coat is often placed between the bar and the plastic coating. Plastic-coated dowel bars first came into widespread use in the 1960s, and several highway agencies constructed experimental PCC pavements containing plastic-coated dowels during that time period (Minkarah and Cook, 1976; Arnold 1980; Vyce 1987).

The primary advantages of plastic-coated dowels are their relatively low cost (compared to other alternative dowel bars) and corrosion resistance. Moreover, the plastic coating is effective in preventing bond to the concrete, so a bond breaker may not be required.

The historical literature suggests that the performance of PCC pavements containing plastic-coated dowel bars has generally been good. For example, Michigan reported excellent performance after up to 10 years of service (Arnold 1980). However, after 30 years, the plastic coating was debonded while the epoxy-coated dowels were in pristine condition; as a result, Michigan now allows only epoxy coating (Smiley 2005).

The I-75 Michigan European Demonstration Project contains polyethylene-coated dowels at reduced spacing in the wheel paths and epoxy-coated dowels at 305-mm (12-in) spacings on the Michigan control section. Only the initial construction report and a 5-year evaluation are available; however, the LTEs on both the sections are reported to be less than 70 percent which raises questions about their long-term performance capabilities (Weinfurter et al. 1994; Buch et al. 2000). Additional evaluations of this project are needed to determine the probable cause of the low observed LTEs.

New York and Ohio also have experience with plastic-coated dowel bars. New York indicated that pavements with plastic-coated dowels had not developed faulting or joint cracking after more than 10 years of service (Vyce 1987). On an Ohio project, plastic-coated dowel bars were found to exhibit less faulting than non-coated dowels after 19 years of service (Smith et al. 1997).

Solid Stainless Steel Dowel Bars. Solid stainless steel dowel bars offer strong resistance to corrosion along with high levels of strength and durability. Stainless steels are low carbon steels (less than 1 percent carbon) that contain at least 10.5 percent chromium by weight (FHWA 2001). The chromium content allows an invisible chromium oxide film to form on the bar surface that makes the material passive or corrosion resistant (FHWA 2001). Other alloys, such as molybdenum, nickel, and nitrogen, are often added in the production of stainless steel to obtain special material properties that meet the needs of a specific application (corrosion conditions, temperature ranges, strength requirements, and so on).

There are more than 60 grades of stainless steel, divided into the following five classes named for the alloy metallurgical structure (FHWA 2001):

- Austenitic
- Duplex (ferritic-austenitic).
- Ferritic.

- Martensitic.
- Precipitation hardening.

Austenitic stainless steels are most commonly used for rebar applications. These have the highest corrosion resistance, and contain nickel (between 8 to 25 percent) and increased chromium contents (between 17 and 25 percent); molybdenum can also be added (up to 7 percent) for increased corrosion resistance (FHWA 2001).

Austenitic stainless steels are not magnetic and have exceptional resistance to high and low temperatures. Some common types of austenitic stainless steel are (FHWA 2001):

- Type 304 (most commonly used for reinforcement in structures).
- Type 304L (same as 304 but with lower carbon content).
- Type 310 (used for high temperatures).
- Type 316 (increased corrosion resistance).
- Type 316L (same as 316 but with lower carbon content).
- Type 316LN (same as 316 but with a lower carbon content and nitrogen added).
- Type 317 (highest corrosion resistance).

These bars are available in grades 40, 60, and 75 (corresponding to minimum yield strengths of 300 MPa [40,000 lbf/in^2], 420 MPa [60,000 lbf/in^2], and 520 MPa [75,000 lbf/in^2], respectively), although other strength levels may be requested from manufacturers (FHWA 2001). Stainless steel reinforcing bars are governed by ASTM A955M, *Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement*. Detailed alloy specifications are provided in ASTM A276, *Standard Specification for Stainless Steel Bars and Shapes*.

Most PCC pavement projects featuring solid stainless steel dowel bars have used Type 316 or 316L stainless steel, which is the type recommended by FHWA. In addition to its primary advantage of being highly resistant to corrosion, it is also very strong and durable (although not as strong as conventional carbon steel bars). The initial costs of stainless steel bars are higher (about five times the costs of conventional epoxy-coated bars), but overall life-cycle costs are expected to be lower because of the longer service lives of stainless steel bars.

A laboratory study of different types of reinforcing bars for bridge deck structures found that Type 316 solid stainless steel dowel bars performed very well (FHWA 2000). Type 304, on the other hand, exhibited some moderate degree of corrosion.

Stainless Steel Clad Dowel Bars. Stainless steel clad bars use a grade of stainless steel that is metallurgically bonded to a carbon steel core. The resulting composite material possesses both the corrosion resistance of solid stainless steel dowel bars and the mechanical properties of the carbon steel core at a cost much lower than solid stainless steel bars.

Commonly Type 316 (or one of its derivatives) conforming to ASTM A276 is used as the cladding material. The thickness of the cladding depends on the diameter of the bar, but for most highway pavement dowel bars (32 and 38 mm [1.25 and 1.5 in] diameter) the cladding ranges from about 1.8 to 2.3 mm (0.07 to 0.09 in) thick (compared to a typical epoxy coating thickness of between 0.2 to 0.3 mm [0.008 to 0.012 in]). The strength of the bonding between the stainless steel cladding and the carbon steel core, coupled with the thickness of the cladding itself, make these dowel bars very durable and not susceptible to damage from construction handling.

The exposed carbon steel ends of the clad bars are susceptible to corrosion, although this may not be a concern for dowel bars since the ends are embedded in the PCC slab. However, if it is determined that the exposed ends should be sealed to prevent corrosion, it can be done by using stainless steel welding, compatible stainless steel end caps, or an epoxy sealant.

There has been a problem getting an adequate supply of quality stainless steel clad dowels in the U.S. Before specifying stainless steel clad dowels for a large project, their availability should be investigated.

Stainless Steel Tubes. This is an alternative dowel bar that makes use of the corrosion resistance of stainless steel but in a tubular form to reduce costs. As with the FRP composite tubes, the stainless steel tube (commonly Type 316L) is filled with a high-strength cement grout to provide stiffness and resistance to crushing. However, as also with FRP tubes, there have been reports of difficulty in getting grout filled tubes from suppliers. The primary advantages of these types of load transfer devices are their corrosion resistance (same as solid stainless steel bars) and their reduced costs.

The idea of using stainless steel tubes for load transfer is not new. Research conducted by FHWA in the late 1980s evaluated the load-carrying capacity of various dowel bars (solid stainless steel, stainless steel tubes, and cement grout-filled stainless steel tubes) under a cyclic 106.8 kN (24,000 lbf) loading in the laboratory. Findings from the investigation include (Black et al. 1988):

- The hollow stainless steel tubes failed immediately under initial loading.
- The cement grout-filled stainless steel tubes (42-mm [1.66-in] outside diameter with 1.65-mm [0.065-in] wall thickness and 42-mm [1.66-in] outside diameter with 2.77-mm [0.109-in] wall thickness) deflected less than the 32-mm (1.25-in) diameter solid stainless steel bars.
- The cement grout-filled stainless steel tube with the greater wall thickness deflected about half that of the cement grout filled stainless steel tube with the smaller wall thickness.

Additional tests are being conducted on Schedule 40 (0.14 wall thickness) unfilled stainless steel structural pipe as a possible option. Accelerated testing is underway using the Minne-ALF at the University of Minnesota to evaluate the performance.

Other Materials. Other materials that are being tested for corrosion resistant steel in bridge decks, such as MMFX-2 "microcomposite" steel and a new "lean" duplex stainless steel called 2101 LDX, might also be considered for corrosion-resistant dowels (Clemena 2003). In addition, a newer zinc clad steel dowel has been proposed. Further evaluation of these materials including their corrosion resistance and cost effectiveness is needed.

TE-30 FIELD INSTALLATIONS OF ALTERNATIVE DOWEL BARS

As previously mentioned, the alternative dowel bars described above have been installed on several experimental PCC pavement projects constructed under FHWA's TE-30 program (Smith 2002a; Smith 2002b; QES 2004). Fifteen HPCP or related projects, located in Illinois, Iowa, Kansas, Michigan, Minnesota, Ohio, West Virginia, and Wisconsin, are currently evaluating the use of alternative dowel bar materials for providing load transfer across transverse joints. The purpose of these studies is to assess the effectiveness of these devices in actual field installations. One related additional project is evaluating the MIT Scan device to help verify the accuracy of dowel (or tie bar) placement. Table 2 summarizes the TE-30 projects evaluating alternative dowel bar materials (the number after the state refers to the TE-30 project designation). A brief description of some of those field installations, and any preliminary performance findings, are described in the following sections.

Illinois. Illinois has four TE-30 or related projects, all of which are evaluating the use of alternative dowel bars (some in conjunction with sealed or unsealed joints). The oldest was built in 1996 on a weigh station ramp on I-55 near Williamsville; it was soon followed by a project on Route 59 near Naperville in 1997 and a project on U.S. 67 near Jacksonville in 1999 (Gawedzinski 1997). The most recent project was constructed in 2000 on Route 2 in Dixon. Dowel bar types evaluated in the various projects include FRP composite dowels, cement grout-filled FRP tubes, type 316L stainless steel clad dowels, type 316 stainless steel tubes filled with cement grout, and conventional epoxy-coated dowel bars. Consideration is being given to include elliptical steel and FRP dowels in a future project.

The Illinois DOT has been monitoring the performance of these sections, including regular measurements of load transfer efficiency. After up to 4 years of service, all of these sections are performing well (Gawedzinski 2000). LTE data collected on the one of the projects (IL 2) is shown in figure 1. This figure shows the LTE for the sections containing FRP dowels is lower and more variable than that for the section containing conventional epoxy-coated steel dowel bars. More deflection testing and evaluation is planned (Gawedzinski 2004).

One construction issue that arose on at least one of the Illinois projects involved the method used to secure the FRP composite bars to the dowel basket. During the construction of IL 2, it was noted that the fiber composite bars were loose and only partially attached to the upper support wire of the basket (Gawedzinski 1997). A special metal spring clip had to be devised to secure the dowel bars to the basket so they did not move when the PCC was placed.

Iowa. Iowa has a TE-30 project that is studying the performance of PCC pavement joints containing FRP composite dowel bars, solid Type 316L stainless steel dowel bars, and conventional epoxy-coated steel dowel bars under the same design criteria and field conditions (Cable and McDaniel 1998). Located on U.S. 65 near Des Moines, the project features two configurations for the alternative dowels bars: a conventional 305-mm (12-in) center-to-center spacing across the transverse joints, and a shorter 203-mm (8-in) center-to-center spacing across the transverse joints.

During the construction of the project, several items were noted to be of importance to future installations of alternative dowel bars in PCC pavements (Cable and McDaniel 1998):

- The original method of securing the fiber composite and stainless steel dowel bars to the basket was inadequate. To address this, plastic zip ties were fastened around each basket brace loop and end of dowel to hold them in place. Any excess tie length was cut or turned down to prevent surface finishing problems.
- The placement of the stainless steel dowels required three to five people to handle the baskets. Future use of stainless steel dowels may require "x" braces welded to the basket to prevent side sway and collapse during handling.
- Nails were attached to the bottom of the fiber composite tie bars to facilitate their location using both cover meters and ground penetrating radar (GPR).
- Fiber composite tie bars, placed on some of the sections using an inserter on the paver, were susceptible to "floating" to the surface. After several bars surfaced in succession, epoxy-coated steel tie bars were used on the remainder of the project.

After 5 years of service, a follow-up evaluation was conducted and resulted in the following findings (Cable and Porter 2003):

- All dowel materials tested are performing equally in terms of load transfer, joint movement, and faulting over the 5-year period.
- Stainless steel dowels do provide load transfer performance equal to or greater than epoxy-coated steel dowels in this study on the average over 5 years.
- FRP dowels of the sizes tested in this research should be spaced no greater than 203 mm (8 in) apart to gain load transfer performance the same as epoxy-coated steel dowels at 305-mm (12-in) spacing.
- No deterioration due to road deicers was found on any of the dowel materials retrieved in the 2002 coring operation (FRP and epoxy coated dowels only). Note: A horizontal delamination was noted in the core adjacent to one of the FRP dowels.

It was concluded that the evaluation period would need to be extended to 10 to 20 years to adequately evaluate the performance. It was also concluded that the cost of solid FRP and stainless steel dowels would have to be reduced to make them cost competitive with epoxy coated dowels (Cable and Porter 2003). Additional work was performed on elliptical steel and FRP dowels installed on experimental projects in 2003 (Cable et al. 2003; QES 2004).

Kansas. Kansas has constructed one experimental project under the TE-30 program, which was built in 1997 and incorporates a wide variety of experimental features, from alternative dowel bars to alternative sawing practices to different PCC mix designs. One of the test section contains 51-mm (2-in) diameter FRP composite tubes that are filled with a high-strength cement grout. The cost of these alternative dowels was $28.87/m ($8.80/ft) as compared to $8.00/m ($2.44/ft) for the conventional epoxy-coated steel dowels (Wojakowski 1998). This test section is performing well after a few years of service (Smith 2002a; Smith 2002b; QES 2004). One concern is that some of the sections with epoxy-coated dowels have LTEs of 70 percent or less. Additional evaluation of the cause of the low LTEs obtained is needed.

Michigan. In 1993, Michigan constructed two pavements on I-75 in downtown Detroit to compare a European jointed plain concrete pavement (JPCP) design (featuring a thick aggregate foundation, a notched lean concrete base, widened slabs, and two-course construction) with Michigan's then-standard jointed reinforced concrete pavement (JRCP) design (Weinfurter et al. 1994). The European design employs dowel bars that are variably spaced (clustered in the wheelpaths), 32 mm (1.25 in) in diameter, and plastic (polyethylene) coated. The dowel bars for the JRCP design are 32-mm (1.25-in) epoxy-coated bars spaced at 305-mm (12-in) intervals.

After 5 years of service, both of these sections are reportedly performing well (Buch et al. 2000). Although little faulting exists, the deflection load transfer efficiencies for both sections are noted to be somewhat low (60 to 70 percent), which may be due to warping of the slabs at the time of the deflection testing (Buch et al. 2000). It appears additional evaluations to determine the cause of the low LTEs is needed.

Minnesota. Minnesota has constructed two projects under the TE-30 program, both of which feature the use of alternative dowel bars (Smith 2002a; Smith 2002b; QES 2004). The first project, located on I-35W in Richfield, a suburb of Minneapolis, is evaluating the performance of epoxy-coated steel dowel bars, type 316L stainless steel clad dowel bars, and type 316 solid stainless steel dowel bars as part of a study investigating long-life PCC pavements. The second project is located on the low volume road (LVR) test loop at the Minnesota Road Research Project (Mn/Road) located near Albertville. One of the new test sections on the LVR test loop is evaluating the performance of conventional epoxy-coated steel bars and FRP composite bars.

Both of these projects were constructed in the summer of 2000 and are performing well. However, there were some problems with obtaining the required number of stainless steel clad dowel bars for the I-35W project, and consequently solid stainless steel bars were substituted for sections that otherwise would have used the stainless steel clad bars. Also, because of the unavailability of stainless steel clad dowel bars, plastic-coated dowel bars were used in the transverse joints of the PCC shoulders being used as a bus lane. An adjacent section of I-35W constructed with epoxy coated dowels is being used as the control section. Additional details on Minnesota's 60 year pavement design are available (Turgeon 2003).

Ohio. In 1998, the Ohio Department of Transportation completed the construction of three TE-30 pavement projects, all located on U.S. 50 near Athens. One of the projects is evaluating the use of conventional epoxy-coated dowel bars, type 304 stainless steel tubes filled with cement grout, and FRP composite dowel bars; several of these dowel bars were instrumented to allow investigation of dowel response under a variety of loading and environmental conditions and to compare the measured responses of different types of dowel bars (Sargand 2001).

The instrumented dowels were monitored under both environmental and dynamic loading for the first few months after paving. An analysis of the strains in the FRP composite and conventional epoxy-coated steel bars revealed the following (Sargand 2001):

- Environmental forces (caused by thermal curling and/or moisture warping) produced greater bending moments in both the steel and FRP composite dowel bars than dynamic loading forces. The dynamic bending stresses induced by a 56.9 kN (12,800 lb) load were considerably less than the environmental bending stresses induced by a 3 ^{o}C (5.4 ^{o}F) temperature gradient.
- Steel dowel bars induced greater environmental bending moments than FRP composite bars.
- Significant stresses were induced by the steel dowel bars early in the life of this pavement as it cured late in the construction season under minimal temperature and thermal gradients in the slab. PCC pavements paved in the summer under more severe conditions may reveal even larger environmental stresses.
- Both types of dowel bars induced a permanent bending moment in the PCC slabs during curing, the magnitude of which is a function of bar stiffness.
- Curling and warping during the first few days after PCC placement can result in large bearing stresses being applied to the PCC around the dowels. This stress may exceed the strength of the concrete at that early age and result in some permanent loss of contact around the bars.
- Steel dowel bars transferred greater dynamic bending moments and vertical shear stresses across transverse joints than FRP composite bars of the same size.

Again, these results are for the steel and FRP composite dowels only. The stainless steel tubes were not instrumented because the thin tube thickness did not permit the machining of a flat surface for the attachment of the lead wires (Sargand 2001).

Additional FWD testing and coring was performed on this project in 2004 (Green 2004). FWD testing in 2001 and 2004 were taken during relatively high temperatures which significantly affects the conclusions that can be made from the data. The 100-mm (4-in) diameter cores taken of the epoxy-coated dowels and the concrete filled Type 304 stainless steel showed delamination of the concrete at the dowel bar level. As corrosion of the stainless steel dowel at this age is unlikely, the cause of the cracking is most likely due to the high early environmental stresses noted during construction and/or the poor support provided by the New Jersey unstabilized permeable base. Further evaluation of this issue, including additional FWD testing at lower temperatures and additional 150-mm (6-in) diameter cores, is planned in 2005.

Wisconsin. The Wisconsin DOT constructed three experimental PCC projects under the TE-30 program, two in the summer of 1997 and one in the summer of 2002. The older projects (both located on Highway 29, one between Owen and Abbotsford and one between Hatley and Wittenberg) were constructed to evaluate the use of alternative dowel bars, alternative dowel bar spacings, and variable pavement cross sections (Crovetti 1999). The dowel bars included in the study are standard epoxy-coated steel dowel bars, type 304L solid stainless steel dowel bars, FRP composite dowel bars, and type 304L stainless steel tubes filled with cement grout. All were placed in standard dowel configurations with 305-mm (12-in) spacings with the exception of some of the solid stainless steel dowel bars, which were placed in configurations clustering three and four dowel bars in the wheelpath of the outer lane (Crovetti 1999).

These sections are performing well after only a few years of service. FWD testing of transverse joint load transfer has been conducted on the projects, with the results for the outer lane wheelpaths of WI 2 and WI 3 shown in figures 2 and 3. Generally speaking, the late season tests (October 1997 and November 1998) indicate significantly reduced LTE for the FRP composite dowels, although the LTE measurements in the summer do not indicate any significant differences within the test sections, probably because of the increased aggregate interlock brought about by the closing of the joints due to the warmer temperatures (Crovetti 1999; Smith 2002b). Additional field testing was conducted in 2004 and the summary of performance is expected to be available in mid-2005.

The more recent HPCP project was constructed by the Wisconsin DOT in September 2002 with a design life of 50-years (QES 2004). Dowel bars were Type 316L solid stainless steel. One problem was the flexibility of the baskets made with 3 mm (0.125-in) diameter wire; 5 mm (0.19 in) minimum diameter wire will be specified on future projects. The project is too new to have any significant findings.

SUMMARY

Load transfer is the mechanism through which wheel loads are transferred at a joint from one slab to the next and is an important factor influencing the performance of PCC pavements. Presently, all agencies are requiring the use of dowel bars for most medium- and high-traffic facilities because of their proven ability to prevent or reduce transverse joint faulting.

Unfortunately, steel dowel bars are susceptible to corrosion, which can limit their long-term effectiveness and may even contribute to the development of other distresses. Consequently, over the years highway agencies have experimented with a variety of dowel bar coatings to prevent or reduce the rate of corrosion development, and the use of epoxy-coated steel dowel bars has become the industry standard. However, even epoxy-coated steel dowel bars have been shown to be susceptible to corrosion under some circumstances, and because of those corrosion concerns there has been a strong interest in the use of alternative dowel bars for transverse joint load transfer in PCC pavements. These all have the primary advantage of having a greater resistance to corrosion, but also have the disadvantage of being more expensive than conventional epoxy-coated dowel bars. Among some of these materials currently being investigated are:

- Fiber reinforced polymer (FRP) composite dowel bars. These have shown good performance to date, but similar size bars show lower LTE than conventional epoxy-coated steel bars. In addition, because of their low specific gravity, they may have a tendency to "float" to the surface if placed using a dowel bar inserter.
- FRP composite tubes filled with cement grout. These show similar behavior as solid FRP bars with the cement grout filler providing resistance to deformation (i.e. crushing under heavy wheel loads).
- Plastic-coated dowel bars. These bars are slightly more expensive than conventional epoxy-coated bars but show good resistance to corrosion. However, after 30 years a Michigan investigation revealed potential problems and now only allows the use of epoxy-coated dowels.
- Solid stainless steel dowel bars. These bars are expensive but are showing good performance and have the greatest potential for providing long service lives (50 to 75 years). Type 316 gives superior corrosion resistance than type 304.
- Stainless steel clad dowel bars. Characterized by a stainless steel cladding bonded to a carbon steel core, these bars offer a high level of corrosion resistance at a lower cost. Supply of sufficient numbers of quality bars has been a problem.
- Stainless steel tubes filled with cement grout. Laboratory testing of these materials suggests that they can provide effective load transfer at a reduced cost. Limited field performance data are promising. However, like the FRP composite tubes, there has been some difficulty getting the tubes filled properly with quality grout.

Under the FHWA's TE-30 program, these alternative dowel bars have been installed in some experimental pavement projects. Preliminary findings or recommendations from projects in Illinois, Iowa, Kansas, Michigan, Minnesota, Ohio, and Wisconsin are described. Although these projects are not very old, the preliminary performance is promising. However, continued monitoring of these projects is needed for an extended period (up to 20 years or more) so that the long-term effectiveness of the alternative dowel bars can be established in terms of their load transfer longevity, their long-term resistance to corrosion, and their long-term contribution to the overall performance of the pavement. Due to their higher cost, cost effectiveness is also an issue particularly for long-life pavements.

Other dowel bar related research projects recently completed or underway in California, Manitoba, and West Virginia should provide valuable information to develop interim guidance. Nevertheless, it will take 10 to 20 years of performance evaluation and/or additional accelerated testing research to resolve some of the critical issues identified so the cost effectiveness of the various corrosion resistant dowel bar materials can be predicted.

Based on some of the data collected thus far, it appears that additional guidelines for conducting FWD testing and analysis are warranted. For example, available information suggests that if the pavement temperature is greater than about 21 ^{o}C (70 ^{o}F), the results are unlikely to be of much value for evaluating alternate dowel materials, sizes, and/or spacings. Doweled joints with LTEs 85 percent or less and/or a differential deflection greater than 0.13 mm (5 mils) (with the load on each side of the joint) in 5 years or less are unlikely to provide satisfactory long term performance. The maximum differential deflection criteria of 0.13 mm (5 mils) may help evaluate dowel looseness or the possibility of delaminations in the concrete at the dowel bar level. Furthermore, a maximum deflection criteria would help evaluate the quality of the base/subbase/subgrade support which is critical and has been identified as the cause of low LTEs on some of the projects. Finally, FWD testing using the FHWA LTPP test protocol, including the complete load-deflection time histories (60 m-sec) on the last drop from each drop height, would be desirable to help evaluate the various experimental sections. Animating the load-deflection time history data would help evaluate the quality of load transfer at the joint and would help determine whether looseness or delamination in the adjacent concrete was the probable cause of the low LTEs on some joints. The large number of joints with low LTEs of FRP dowels in less than 5 years is a serious concern. However, there are also a number of HPCP projects with LTEs of epoxy-coated dowels of 70 percent or less in 5 years. Additional testing and evaluation appear to be required to determine the cause of these results and to evaluate the effect on future performance.

Another important gap is the lack of standardized testing procedures for alternate dowel bar materials. Also, improved analysis models are needed to predict the long-term pavement performance to help optimize the joint design.

ACKNOWLEDGMENTS

This paper was based on research sponsored by the Federal Highway Administration (FHWA) under contract number DTFH61-01-P-00290, *Technical Reports on Pavement Technology*, and by research sponsored by an agreement with the American Society of Civil Engineers (ASCE) Highway Innovative Technology Evaluation Center (HITEC). The assistance and support provided by Mr. Mark Swanlund, FHWA, and Mr. David Reynaud, HITEC, are gratefully acknowledged. Special thanks are given to the numerous State DOT and university researchers who provided information on the sections constructed under the HPCP program, including Mr. Mark Gawedzinski, Illinois DOT; Dr. James Cable, Iowa State University; Mr. Mark Dunn, Iowa DOT; Mr. John Wojakowski, Kansas DOT; Mr. David Smiley, Michigan DOT (now retired); Mr. Tom Burnham, Minnesota DOT; Mr. Roger Green, Ohio DOT; Dr. Shad Sargand, Ohio University; Ms. Debbie Bischoff, Wisconsin DOT; and Dr. James Crovetti, Marquette University. Draft work plans for the CALTRANS research, draft final reports for the West Virginia University research, and final reports for the University of Manitoba research were also made available by the researchers or FHWA program managers.

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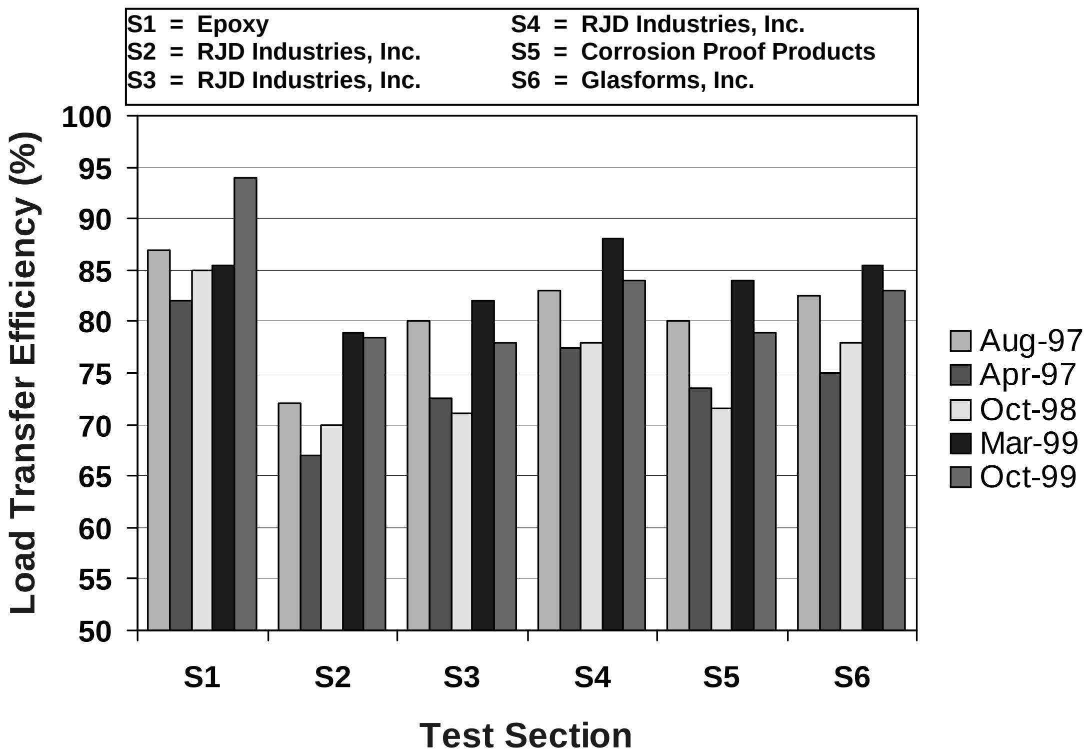

Figure 1. LTE measurements on IL 2 project (Gawedzinski 2000).

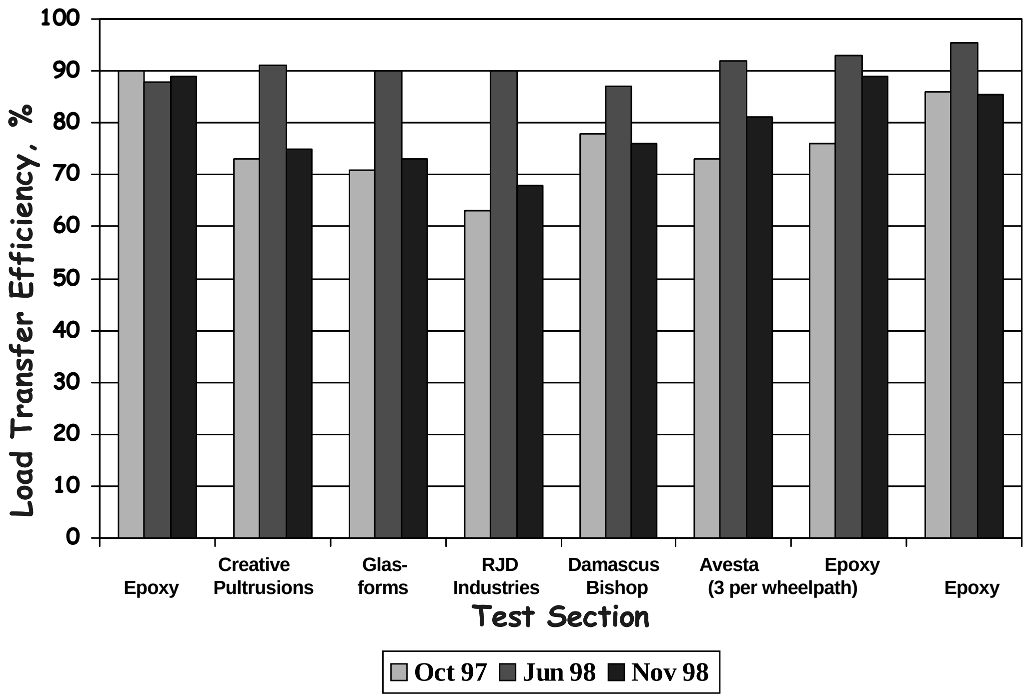

Figure 2. LTE measurements for WI 2 project (Smith 2002b).

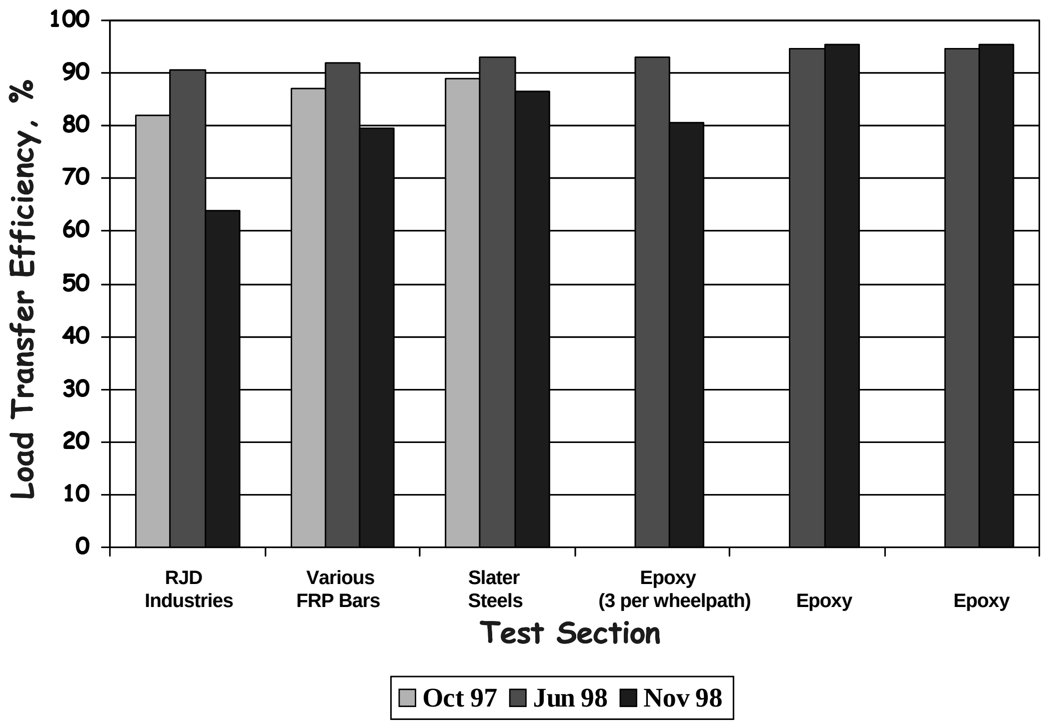

Figure 3. LTE measurements for WI 3 project (Smith 2002b).

Table 1. Summary of alternative dowel bar materials (Smith 2002a).

Material Type	Description	Advantages	Disadvantages	Nominal Cost
FRP Composite Bars	A solid bar made up of a composite material consisting of a matrix binder (such as polyester, vinyl ester, or epoxy), a reinforcing element (such as fiberglass or carbon fiber), and fillers	• Not susceptible to corrosion • Durable • High tensile strength • Light weight /easy to handle • Closer in relative stiffness to PCC than steel bars, which reduces damage at dowel interface	• More expensive than epoxy-coated steel bars • Lower modulus of elasticity and shear strength than epoxy-coated steel bars • Low specific gravity (bar may float to surface during vibration if not secured)	• $6.61 to $8.81 per kg ($3 to $4 per lb) • $4 to $9 per dowel (depends on diameter)
FRP Composite Tubes Filled with Cement Grout	An FRP composite tube filled with a high-strength cement grout for strength and deformation resistance	• Not susceptible to corrosion • Durable • Less expensive than solid FRP composite bar • Closer in relative stiffness to PCC than steel bars, which may reduce damage at dowel interface	• More expensive than epoxy-coated steel bars • Lower modulus of elasticity and shear strength than epoxy-coated steel bars	• $4 to $9 per dowel (depends on diameter)
Plastic-Coated Dowel Bars	A carbon steel bar containing a thin layer (about 0.5 mm [0.020 in]) of plastic coating, such as polyethylene.	• Corrosion resistance • Relatively moderate cost • Does not bond to PCC (may not require bond breaker coating) • Maintains low pull-out resistance	• Potential for damage during construction handling • Greater relative stiffness of bar compared to PCC may cause damage at dowel interface	• $3 to $6 per dowel (depends on diameter)
Solid Stainless Steel Bars	Low carbon steels (less than 1 percent) that contain at least 10.5 percent chromium by weight for corrosion resistance. Type 316 is commonly used for dowel bars.	• Strong corrosion resistance • Durable • High tensile strength • Long service lives (50–75 years) • No special handling requirements	• More expensive than epoxy-coated steel bars • More difficult to handle than FRP bars • Higher relative stiffness than FRP bars	• $4.40 to $5.28 per kg ($2 to $2.40 per lb) • $18 to $20 per dowel *(depends on diameter)*
Stainless Steel Clad Bars	Stainless steel cladding (commonly Type 316 and between about 1.8 to 2.3 mm [0.07 to 0.09 in] thick) metallurgically bonded to a conventional carbon steel core.	• Strong corrosion resistance • Durable • High tensile strength • Long service lives (50–75 years) • Cheaper than either FRP or solid stainless steel bars • No special handling requirements	• More expensive than epoxy-coated steel bars (but not as expensive as solid stainless steel bars) • More difficult to handle than FRP bars • Higher relative stiffness than FRP bars	• $1.10 to $1.65 per kg ($0.50 to $0.75 per lb) • $6 to $11 per dowel (depends on diameter)
Stainless Steel Tubes Filled with Cement Grout	A stainless steel tube filled with a high-strength cement grout for strength and deformation resistance	• Strong corrosion resistance • Durable • High tensile strength • Long service lives (50–75 years) • Cheaper than either FRP or solid stainless steel bars • No special handling requirements	• More expensive than epoxy-coated steel bars (but not as expensive as solid stainless steel bars) • More difficult to handle than FRP bars • Higher relative stiffness than FRP bars	• $5 to $10 per dowel (depends on diameter)
Epoxy-Coated Steel Bars	A carbon steel bar containing a fusion-bonded epoxy coating (commonly between 0.2 to 0.3 mm [0.008 to 0.012 in] thick) which acts as a barrier system against moisture and chlorides.	• Resistance to corrosion • High tensile strength • Cheapest of all corrosion-resistant bars	• Long-term effectiveness of corrosion protection may be an issue • Coating can easily be nicked or scratched during construction handling • Greater relative stiffness of bar compared to PCC may cause damage at dowel interface	• $0.66 to 0.77 per kg ($0.30 to $0.35 per lb) • $2.50 to $5.00 per dowel *(depends on diameter)*

Table 2. FHWA HPCP projects evaluating alternative dowel bar materials (Smith 2002a).

Project/ Location	Date Built	Type of Load Transfer Devices	Dowel Diameter
Illinois 1 I-55 SB, Williamsville	1996	Epoxy-coated dowels	38 mm (1.5 in)
		FRP composite dowels (*RJD Industries, Inc.*)	38 mm (1.5 in)
Illinois 2 Route 59, Naperville	1997	Epoxy-coated dowels	38 mm (1.5 in)
		FRP composite dowels (*RJD Industries, Inc.*)	38 mm (1.5 in) 44 mm (1.75 in)
		FRP composite dowels (Corrosion Proof Products, Inc.)	38 mm (1.5 in)
		FRP composite dowels (*Glasforms, Inc.*)	38 mm (1.5 in)
Illinois 3 U.S. 67 WB, Jacksonville	1999	Epoxy-coated dowels	38 mm (1.5 in)
		FRP composite dowels (*RJD Industries, Inc.*)	38 mm (1.5 in)
		FRP composite dowels (*Strongwell Corporation*)	38 mm (1.5 in)
		FRP composite dowels (Creative Pultrusions, Inc.)	38 mm (1.5 in)
		FRP composite tubes filled with cement grout (*Concrete Systems, Inc.*)	51 mm (2 in)
		Type 316L stainless steel clad dowels (*Stelax Industries, Inc.*)	38 mm (1.5 in)
Illinois 4 Route 2 NB, Dixon	2000	FRP composite tubes filled with cement grout (*Concrete Systems, Inc.*)	51 mm (2 in)
		Type 316L stainless steel tubes filled with cement grout	38 mm (1.5 in) 44 mm (1.75 in)
		Type 316L stainless steel clad dowels (*Stelax Industries, Inc.*)	38 mm (1.5 in) 44 mm (1.75 in)
Iowa 2 U.S. Route 65, Des Moines	1997	Epoxy-coated dowels	38 mm (1.5 in)
		FRP composite dowels (*Hughes Brothers, Inc.*) (203- and 305-mm [8- and 12-in] spacings)	48 mm (1.88 in)
		FRP composite dowels (*RJD Industries, Inc.*) (203- and 305-mm [8- and 12-in] spacings)	38 mm (1.5 in)
		Type 316L Solid stainless steel dowels (203- and 305-mm [8- and 12-in] spacings)	38 mm (1.5 in)
Kansas 1 K-96, Haven	1997	Epoxy-coated dowels	32 mm (1.25 in)
		FRP composite tubes filled with cement grout (*Concrete Systems, Inc.*)	51 mm (2 in)
		X-Flex™ Device (Kansas State University)	—
Michigan 1 I-75, Detroit	1993	Plastic-coated dowels	32 mm (1.25 in)
		Epoxy-coated dowels	32 mm (1.25 in)
Minnesota 1 I-35W, Richfield	2000	Epoxy-coated dowels	38 mm (1.5 in)
		Type 316L stainless steel clad dowels (*Stelax Industries, Inc.*)	38 mm (1.5 in) 44 mm (1.75 in)
		Type 316 solid stainless steel dowels (various manufacturers)	38 mm (1.5 in)
		Plastic-coated dowels (PCC shoulders only)	38 mm (1.5 in)
Minnesota 2 Mn/Road Low Volume Road Facility, Albertville	2000	Epoxy-coated dowels	25 mm (1.0 in) 32 mm (1.25 in)
		FRP composite dowels	32 mm (1.25 in) 38 mm (1.5 in)
Ohio 2 U.S. Route 50, Athens	1997/1998	Epoxy-coated dowels	38 mm (1.5 in)
		FRP composite dowels (*RJD Industries, Inc.*)	38 mm (1.5 in)
		Stainless steel (type 304) tubes filled with cement grout	38 mm (1.5 in)
Wisconsin 2 WI 29, Owen	1997	Epoxy-coated dowels (5 layout configurations)	38 mm (1.5 in)
		FRP composite dowels (*RJD Industries, Inc.*)	38 mm (1.5 in)
		FRP composite dowels (Creative Pultrusions, Inc.)	38 mm (1.5 in)
		FRP composite dowels (*Glasforms, Inc.*)	38 mm (1.5 in)
		Type 304L solid stainless steel dowels (*Avesta Sheffield, Inc.*) (2 layout configurations)	38 mm (1.5 in)
		Type 304L stainless steel tubes filled with cement grout (*Damascus Bishop Tube Company*)	38 mm (1.5 in)
Wisconsin 3 WI 29, Hatley	1997	Epoxy-coated dowels (2 configurations)	38 mm (1.5 in)
		FRP composite dowels (*Strongwell Corporation*)	38 mm (1.5 in)
		FRP composite dowels (*Glasforms, Inc.*)	38 mm (1.5 in)
		FRP composite dowels (Creative Pultrusions, Inc.)	38 mm (1.5 in)
		FRP composite dowels (*RJD Industries, Inc.*)	38 mm (1.5 in)
		Type 304L solid stainless steel dowels (*Slater Steels, Inc.*)	38 mm (1.5 in)