2004-17B

Final Report

PERFORMANCE TESTING OF EXPERIMENTAL DOWEL BAR RETROFIT DESIGNS PART 2 – REPEATABILITY AND MODIFIED DESIGNS

MINNESOTA DEPARTMENT OF TRANSPORTATION

Research

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.
MN-RC 2004-17B		

4. Title and Subtitle	5. Report Date
Performance Testing of Experimental Dowel Bar Retrofit Designs: Part 2 – Repeatability and Modified Designs	December 2003
	6.
7. Author(s) Nicholas A. Popehn Arturo E. Schultz Mark B. Snyder	8. Performing Organization Report No.
9. Performing Organization Name and Address University of Minnesota Department of Civil Engineering 500 Pillsbury Dr., S.E. Minneapolis, MN 55455-0116	10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (c) 74708 (wo) 131
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

www.lrrb.org/PDF/200417B.pdf

This is part 2 in this series. Report 2004-17A is part 1 and is available at www.lrrb.org/PDF/200417A.pdf

16. Abstract (Limit: 200 words)

Effective load transfer across Portland cement concrete pavement joints significantly decreases pavement deterioration. Dowel bars placed transversely across a joint or crack provide a mechanism for effective load transfer to take place. Dowel bars are used in new construction as well as retrofitted into existing pavements for restoration of load transfer. Areas of concern with using dowel bars include high costs, due to the labor-intensive procedure of retrofitting, and corrosion associated with standard mild steel epoxy-coated dowels. This research addresses these problems by evaluating four dowel bar details tested in an accelerated manner. Retrofit testing was performed using mild-steel epoxy coated dowels and fiber reinforced polymer (FRP) dowels. The details tested provide comparisons among dowel bar materials, depth of placement, number of dowels used, and dowel diameter. Verification testing of previously tested details is also presented.

17. Document Analysis/Descriptors		18. Availability Statement
accelerated load testing	concrete pavements	No restrictions. Document available from:
deflections	dowel bars	National Technical Information Services,
fiber reinforced polymer	load transfer	Springfield, Virginia 22161
repeated loads	retrofit designs	

19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	108	

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Final Report

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December 2003

Published by:

Minnesota Department of Transportation
Research Services Section
Transportation Building
395 John Ireland Boulevard
St. Paul, Minnesota 55155-1899

Acknowledgements

This research would not have been possible without the generous support of the Minnesota Department of Transportation (Mn/DOT) and the Department of Civil Engineering of the University of Minnesota. In particular, the authors would like to thank Rebecca Embacher – Mn/DOT Materials Laboratory, and Ann McClellan – Mn/DOT Office of Research and Strategic Services.

Table of Contents

List of Figures

List of Tables

Executive Summary

Portland cement concrete (PCC) pavements feature joints that are formed as part of the construction process, and they develop cracks from exposure to vehicular loads and the environment. The management of PCC pavements must consider load transfer across joints and cracks. Effective load transfer across concrete pavement joints and cracks significantly decreases pavement deterioration and enhances riding quality.

Dowel bars placed transversely across joints and cracks provide a mechanism for effective transfer of load between the sections of pavement that span the joints and cracks. Dowel bars are used in new pavement construction, as well as retrofitted into existing pavements for restoration of load transfer. Current practice for the rehabilitation of PCC pavements is to place steel dowel bars at mid-depth of the pavement across the joint or crack (1). The two most important considerations regarding the use of retrofit dowels are the high expense associated with the retrofitting operation and the corrosion that has been associated with the use of steel dowels.

This research addresses the problems of dowel bar retrofit cost and dowel bar corrosion by evaluating innovative dowel bar retrofit designs. Accelerated load testing of retrofit dowel bar details was performed using mild-steel, epoxy coated dowels and fiber reinforced polymer (FRP) dowels. The designs tested include a replicate of a design tested by Odden [14] in the first part of this study, as well as two new designs that featured variations of the current standard dowel bar retrofit design in terms of dowel bar

material, depth of placement, number of dowels used, and dowel diameter. Verification testing of previously tested details is also presented.

The performance of the innovative dowel bar designs (Slabs 7, 9 and 10) is evaluated in comparison with that for Slab 8, which featured 1.5-in. diameter epoxy-coated mild steel dowels with a 15-in. length, 2-in. clear cover and 12-in. spacing. Slab 8, which represents the standard dowel bar retrofit design except for a reduced clear cover (2 inches instead of 3 inches), is also a replicate of Slab 5-6 in Phase 2A [14]. Slab 8 demonstrated excellent performance in terms of large LTEs (in excess of 90%) and small differential deflections (less than 3 mils) over the 6.7-million cycle duration of the test. Slab 8 also exhibited very similar performance to Slab 5-6 in Phase 2A, indicating that the Minne-ALF test stand is capable of producing repeatable measurements. The results of these two slabs also demonstrate that a reduction in clear cover from the 3 inches to 2 inches does not affect adversely the load transfer at the joint.

Test Slabs 7 and 9 were nominally identical to each other, and they were similar to Slab 8, except that they featured only two dowels each instead of the standard three dowels used in Slab 8. Slabs 7 and 9, which generated very similar performance results, exhibited the poorest performance in terms of larger differential deflections. At the end of these tests (6 million cycles), the measured values for LTE were slightly larger than 90%, which is well above the acceptable limit of 70%. However, differential deflections by the end of the tests for both of these slabs were approximately twice as large as the acceptable limit of 5 mils.

Test Slab 10 utilized fiber-reinforced polymer (FRP) dowels of a larger diameter (1.75 inches) than is used for the standard dowel bar retrofit design (1.5 inches). The increase in dowel diameter was intended to improve the measured performance of Slab 2 in Phase 2A, which had the smallest LTEs and largest differential deflections of all test slabs in that series of tests. The increased diameter enabled Slab 10 to perform as well as Slab 8 in Phase 2B. Measured LTEs were larger than 90% and measured differential deflections were less than 3 mils for the 6.7-million cycle duration of the test of this slab. These results, taken in conjunction with those documented by Odden in Phase 2A [14], strongly suggest that a retrofit design featuring three 2-inch diameter FRP dowels with at least 2 in. of clear cover should match the performance of the standard design (Slab 1 in Phase 2A). Testing of that configuration is strongly recommended.

1. INTRODUCTION

1.1 Problem Statement

The need for long lasting, reliable, and economical transportation systems is a critical component for the continuous movement of goods and services. In particular, extensive research on highway pavements is needed to address current problems as well as develop new designs and techniques for future pavement applications.

Research into more effective load transfer devices in Portland cement concrete (PCC) pavements is one way to reduce pavement problems. The ability to transfer vehicle loads across a crack or joint is accomplished by using mechanical devices such as dowel bars, tie bars, and studded plates. These devices, placed perpendicular to a pavement joint, provide a reduction in slab stresses and deflections by efficiently transferring the vertical shear from one side of the joint to the other. It is also important that the ability of a joint to expand and contract be maintained when mechanical load transfer devices are used. Where this is the case, tie bars and studded plates present some problems. Tie bars do not allow for expansion and contraction of a joint but do transfer shear effectively. Conversely, studded plates allow for joint expansion and contraction but reductions in shear transfer are produced over time as the aggregate interlock effect is diminished.

Due to the disadvantages associated with studded plates and tie bars when used in contraction and expansion joints, steel dowels are the current design standard. Dowels have the ability to transfer vertical shear forces while allowing for expansion and contraction of the joint.

Two important issues associated with retrofit steel dowels are the high installation costs and corrosion of the bars over time. Retrofit expenses are costly due to the labor-intensive procedure needed to place dowels in an existing slab. Improper installation often results in premature corrosion of the bars leading to "locking" of the joint. When a dowel bar corrodes, the volume increases, leading to large slab stresses. The joint is then prohibited from moving when normal temperature and moisture gradients occur in the slab. Ultimately, this "locking" of the joint can cause spalling and cracking of the slab.

1.2 Project Goals

The focus of this project was to determine in an accelerated fashion the best performing dowel bar details and material types for effective load transfer in PCC pavements. It was important to study different types of dowels to find which ones proved most cost effective, had properties to resist corrosion, and transferred loads most effectively. Different configurations were needed to give insight into the proper placement and correct numbers of dowels to use. The ability to test in an accelerated manner was of paramount importance since collecting sufficient and reliable field data can take several years. Also, expedited testing would allow for specimens to be repeated and validated quickly, prior to any implementation, ensuring the results were in fact reliable.

1.3 Implementation of Research

In order to achieve the previously stated project goals, the following guidelines were used to formulate the basis for the laboratory tests. First, it was necessary to confirm that the chosen dowel bar retrofit details ensured both cost effective and corrosion resistant designs. Next, criteria were established to provide uniformity in comparisons between potential new dowel bar designs and to the current standard design. These aspects of the investigation are discussed in relation to the literature review in Chapter 2. The actual testing was then performed using the Minnesota Accelerated Load Facility (Minne-ALF) test program. The Minne-ALF facility is described in Chapter 3, and the research program is documented in Chapter 4. After testing was completed, using the comparison criteria, the performance of each detail was evaluated (Chapter 5). Finally, conclusions and recommendations were made based on the compared results (Chapter 6). Any significant features resulting from a completed test and comparison were then reviewed. Potential retrofit details were reevaluated to reflect newly collected data.

1.4 Scope

The scope of this phase (Phase 2B) of the Minne-ALF project encompasses the testing of four dowel bar retrofit details. Two of the retrofit details were replicate tests; one being a replicate of a detail from a previous series of tests (Phase 2A), and the other being a replicate of the first detail tested in Phase 2B. The remaining two tests were dowel bar retrofit details that had not been tested before. The analysis of data and comparison of test results, however, included all data from all tests performed in Phase 2A and Phase 2B of the Minne-ALF program. Phase 2 included eight tests over a period of two and one-half years. Figure 1-1 summarizes all the details tested in Phase 2 using the Minne-ALF facility. Preliminary testing (Phase 1) is discussed in Section 3.4 and is summarized in Table 3-2. In Figure 1-1, Phase 2A consists of previously performed tests by Trevor Odden [14], and Phase 2B encompasses tests that are the focus of this report. It should also be noted that Slab 3-4 in Phase 2A was tested until 13.5 million cycles, and Slab 5-6 in Phase 2A was tested until 12.7 million cycles. Testing these two details to roughly twice the standard number of cycles was done as per Mn/DOT's request [14].

Table 1-1: Summary of Minne-ALF Phase 2 Details

Phase 2	**Phase 2A** *(Trevor Odden ,[14])*	**Slab 1** Three, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 3 inches clear cover	**Slab 2** Three, 1.5 inch diameter, 15 inch long, fiber reinforced polymer dowels, mid-depth placement	**Slab 3-4** Three, 1.66 inch diameter, 15 inch long, grout filled stainless steel tube dowels, mid-depth placement	**Slab 5-6** Three, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover
	Phase 2B	**Slab 7** Two, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover	**Slab 8** Three, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover	**Slab 9** Two, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover	**Slab 10** Three, 1.75 inch diameter, 15 inch long, fiber reinforced polymer dowels, mid-depth placement

2. LOAD TRANSFER LITERATURE REVIEW

2.1 Introduction to Load Transfer Problem

Effectively transferring vehicle axle loads across a joint or crack in a concrete pavement significantly extends the life of the roadway. Without proper transmission of slab loads, detrimental effects to the pavement, such as cracking, spalling, pumping, and faulting, may occur. Load transfer, in general, is the transfer of slab stresses or loads from one slab to an adjoining slab [1]. Load transfer, by means of transmitting vertical shear forces from one slab to another, is accomplished through aggregate interlock or by introducing mechanical load transfer devices [1].

2.1.1 Cracking and Spalling

Cracking and spalling of concrete pavements result in increased repair and maintenance costs, as well as undo hazards for motorists. Cracking and subsequent spalling of pavements are most commonly due to stress concentrations from vehicle loads initiating at slab edges. Stress concentrations are higher at slab edges and corners due to less concrete resisting the vehicle loads [2].

As a crack propagates through a pavement, uneven loading of the slab on either side of the crack further exacerbates the problem. The uneven pavement surface that is created can give rise to spalling of the concrete on both the pavements surface as well as the bottom of the slab at a joint or crack. A vehicle traveling across a joint or crack, that does not contain a load transfer mechanism, encounters a "lip" as it approaches the adjacent slab. Spalling commonly occurs where large differential vertical movements of the slab take place.

2.1.2 Pumping and Faulting

A common mechanism leading to slab failure is known as pumping. Pumping occurs when large vertical deflections of adjacent slabs are present [1]. In the presence of free water and transportable foundation materials, as a vehicle load is transmitted across a joint or crack having deficient load transfer capabilities, the foundation support material can be shifted. Material once providing support for the slab can be forced up through a joint, crack, or slab edge, and subsequently create uneven support conditions for the pavement [1]. Faulting and cracking can then form due to the non-uniform slab support while loaded.

2.1.3 Concrete Pavement Joints

Joints placed in concrete pavements are designed to relieve thermal gradient stresses and control crack formation [3,4]. Concrete pavement joints are positioned in both the longitudinal and transverse directions of the pavement. Typical joints include construction joints, contraction joints, isolation or expansion joints, and longitudinal joints [1].

2.1.3.1 Construction Joints

Construction joints are needed when paving is halted for an extended period of time. These joints are created to transfer adjoining slab loads rather than control crack locations [1,5]. Construction joints are generally a smooth formed joint created by placing a form at the point where paving was stopped. When paving is continued, the new casting can then be butted up to the previously formed joint. It is then necessary to provide load transfer devices, usually in the form of dowels or shear keys, to transfer loads across the joint. The most desirable location for a construction joint is where a contraction joint is to be placed [6]. This maintains the predetermined joint spacing in the pavement.

2.1.3.2 Contraction Joints

Contraction joints are intended to control the position of cracking due to thermal gradients in the concrete [1,5]. Created by means of a saw cut or groove formation, slab stresses are reduced through cracking at that location. A saw cut creates a discontinuity one-third the depth of the slab [2]. Across these types of joints, mechanical load transfer devices are introduced to provide proper load transfer.

2.1.3.3 Isolation and Expansion Joints

Isolation and expansion joints are formed to separate one structure from another [2]. When a pavement meets a structure such as a building, manhole conduit, or traffic median barrier, it is necessary to introduce some separation. Large compressive stresses formed in the concrete may damage adjacent structures if a separation was not introduced [2]. These isolation joints allow for the pavement and structure to move independently from one another both vertically and horizontally.

2.1.3.4 Longitudinal Joints

Longitudinal joints, unlike construction and contraction joints, are created parallel to traffic flow. They provide stress relief thereby controlling the formation of longitudinal pavement cracks [2]. Longitudinal joints require mechanical load transfer devices such as smooth or deformed reinforcing bars, a pavement key system, or a combination of reinforcement.

2.2 Transferring Slab Loads

Load transfer through aggregate interlock and mechanical devices provide varying degrees of effectiveness. The ultimate goal for all load transfer devices is to fully transfer vertical shear forces across pavement discontinuities [7].

2.2.1 Load Transfer Through Aggregate Interlock

Transferring slab loads through aggregate interlock is accomplished by friction and bearing of aggregate particles on each other as shear forces are applied across adjacent joint or crack faces. The more rough or angular the aggregate, the higher the friction coefficient and the more effective the load transfer mechanism. Conversely, smooth or less coarse aggregates result in reduced coefficients of friction and poorer load transfer.

Aggregate interlock, however, becomes less reliable as a load transfer mechanism if the gap between adjacent joint faces is increased [5]. As the space increases, fewer aggregate particles are in contact with each other, resulting in increasingly more deficient load transfer. Thermal variations in a pavement can result in such a situation. As expansion of a joint occurs due to temperature fluctuations, the aggregate interlock mechanism becomes less effective. Construction joints, in particular, cannot rely on aggregate interlock due to the lack of contact between adjacent joint faces.

2.2.2 Load Transfer Through Mechanical Devices

Mechanical load transfer devices are mechanisms that are placed within a joint or crack to physically bridge the gap between two slab faces. Mechanical load transfer devices include dowel bars, tie bars, double-vee shear devices, and studded plates, among others [1]. By providing a mechanism to span a given pavement discontinuity, shear forces can be transferred from one slab to another. Uniform loading is then created at joint or crack interface as a load transmitted to the pavement nears the discontinuity. Deflections on either side of a joint are also more uniform as a load nears joint interfaces. Slab stresses in the loaded side of a joint are subsequently reduced due to the larger area resisting the vertically applied load.

2.3 Load Transfer Using Dowel Bars

2.3.1 Dowel Bar Description

Dowel bars are the most widely used load transfer devices for transferring vertical shear forces across PCC pavement joints [1,8]. Typically, dowels are round, having a diameter 1/8 the thickness of the slab depth, and they are between 14 and 18 inches long. Aside from the standard mild steel epoxy-coated dowel bars, other types of dowel materials include fiber reinforced polymer (FRP), solid stainless steel dowels, grouted stainless steel dowels, stainless steel clad dowels, and stainless steel pipe dowels [1]. The FRP and various types of stainless steel dowels are still considered experimental and are not as extensively used as mild steel dowels. FRP and stainless steel dowels have the added advantage of being more corrosion resistant than mild steel dowels coated with epoxy.

Other dowel cross-sections include I-beam shapes, oval dowels, and various flat plate configurations. The aim of these dowel shapes is to increase bearing area while still keeping the mass equal to traditional mild steel dowels. Dowels with a larger bearing area result in decreased bearing stresses in the concrete when vehicle loads are applied.

2.3.2 Applications and Configurations of Dowel Bars

Dowel bars are used extensively in new PCC pavements and can also be used to retrofit existing pavements [7]. Dowel bars do not restrict thermal expansion and contraction of the pavement but still resist vertical shear forces. The spacing between transverse joints where dowels are placed varies from 10 to 20 feet in most PCC pavements [5]. Dowels are typically placed at mid-depth in the pavement and are positioned perpendicularly to the transverse joint [9]. Spacing between dowels themselves is generally 12 inches center to center [9].

2.3.2.1 New Construction

In new construction, dowel bars are either set into the concrete automatically as the paver moves forward, or the dowels are pre-positioned by tack welding them into steel wire "baskets" [2]. In either case, great care must be taken to ensure proper alignment of the dowels across the joint. Initial problems with horizontal and vertical placement of the dowels will result in less effective load transfer and possible binding of the dowels. If the concrete is not allowed to move longitudinally relative to the dowels, thermal and moisture gradients in the slab may produce high tensile stresses. Ultimately, spalling and cracking of the pavement can result. Prior to the dowels being paved over, they are, in most cases, coated with a concrete debonding agent. If proper alignment is achieved, the use of a debonding agent will allow the joint to expand and contract without binding on the dowels.

After the dowels have been placed in the pavement or paved over, the concrete is allowed to cure before the joint is sawn. The transverse joint is usually formed by saw cutting partially through the pavement directly over the center of the dowel bars [2,3]. The joint is typically cut through 1/3 of the total depth of the slab. Once the joint is completed, the pavement now has a discontinuity where cracks due to thermal variations in the concrete can propagate and eventually form a full-depth discontinuity. The dowel bars, along with some aggregate interlock, then become the mechanisms that transfer shear forces across the joint.

2.3.2.2 Existing Pavements

By retrofitting dowel bars into existing pavements, issues such as load transfer across transverse cracks, dowel bar failures, and joints that have never been doweled, can be addressed. Large cracks that form in pavements over time can be retrofitted with dowel bars to prevent further deterioration of the concrete. Pavements containing dowels that have failed due to corrosion, improper placement, or other reasons, can be replaced through a retrofitting process to restore load transfer [1,5,6,7].

The retrofitting process is very labor intensive and can be costly depending on the size of the rehabilitation project. Due to these facts, retrofit dowel bar details usually do not call for dowels being spaced evenly across the entire joint or crack [7,8]. Typical designs generally use two to three dowels in the outside wheel path, closest to the shoulder, and two dowel bars near the centerline separating lanes [5]. Dowel bars are typically placed at mid-depth and spaced 12 inches transversely from one another. They are centered longitudinally over existing cracks or re-doweled joints.

Slots must be cut, material removed, dowels properly positioned, and the slots backfilled. To create a slot for the dowel bar, two parallel saw cuts are made about 3 inches apart and each having a length of roughly 2.5 feet [5]. The depth of the cut must be calculated to allow for mid-depth placement of the dowels. This includes taking into consideration the clearance needed below the dowels to allow for proper backfill consolidation. After the initial parallel saw cuts are made, the remaining material within the slot can be removed. This is primarily accomplished by means of a chipping hammer. Once the bulk of the material is removed, the slots must be thoroughly cleaned to allow for proper bond between the slot surfaces and the backfill material. Also, to ensure strong bond, a bonding agent, in the form of mortar or other epoxy-based materials, is applied to all slot surfaces immediately before placement of dowels and backfilling of the slots. After application of the bonding agent, the dowels are coated with a concrete debonding material and positioned in the slots, centered over the joint or crack. The dowels are placed in the slots sitting on chairs for clearance requirements and use end caps to reduce bearing stresses in the concrete at the ends of the dowels. A piece of foam or plywood is also placed in the slot at the joint location to ensure a continuous joint after backfilling.

In many retrofit projects backfilling the newly cut slots must be done in a timely manner with quick set backfill material to reduce the time the roadway needs to be closed [3]. After the dowels are properly positioned, backfilling can commence. It is imperative to provide good consolidation of the backfill material. Poor consolidation will result in low load transfer efficiencies and larger differential deflections. After the backfill material has cured, the roadway can be reopened for traffic.

2.4 Defining Load Transfer

2.4.1 Load Transfer Efficiency

Load transfer efficiency (LTE) is defined as "the ability of a joint or crack to transfer load from one side of the joint or crack to the other." [1]. Load transfer efficiency can be quantified in several ways. The three most extensively used equations for calculating LTE are [1]:

$$LTE = \frac{\Delta_{UL}}{\Delta_L} \times 100 \qquad \text{Eqn. (2-1)}$$

$$LTE = \frac{2\Delta_{UL}}{\Delta_L + \Delta_{UL}} \times 100 \qquad \text{Eqn. (2-2)}$$

$$LTE = \frac{\sigma_{UL}}{\sigma_L} \times 100 \qquad \text{Eqn. (2-3)}$$

Defining:

Δ_{UL} = *deflection of the unloaded slab*
Δ_L = *deflection of the loaded slab*
σ_{UL} = *stress in unloaded slab*
σ_L = *stress in loaded slab*

Equation 2-1 is the most widely accepted equation for determining LTE, and therefore it was used for LTE calculations in this research. Figure 2-1 pictorially describes the measurement and calculation of LTE for the extreme cases of zero load transfer efficiency and 100 percent LTE. If there is no load transfer device present at a joint or crack, as a wheel load approaches the discontinuity, deflections in the loaded slab are high while the adjacent slab exhibits no deflection. Based on Equations 2-1 and 2-2, this is zero percent load transfer efficiency. Conversely, if a load transfer device such as a dowel bar is bridging the gap between adjacent slabs, deflections on either side of the joint will ideally be equal as the wheel load approaches the joint. This is 100 percent load transfer efficiency from Equation 2-1 and 2-2. Equation 2-3 defines LTE similarly but uses slab stresses in the computation.

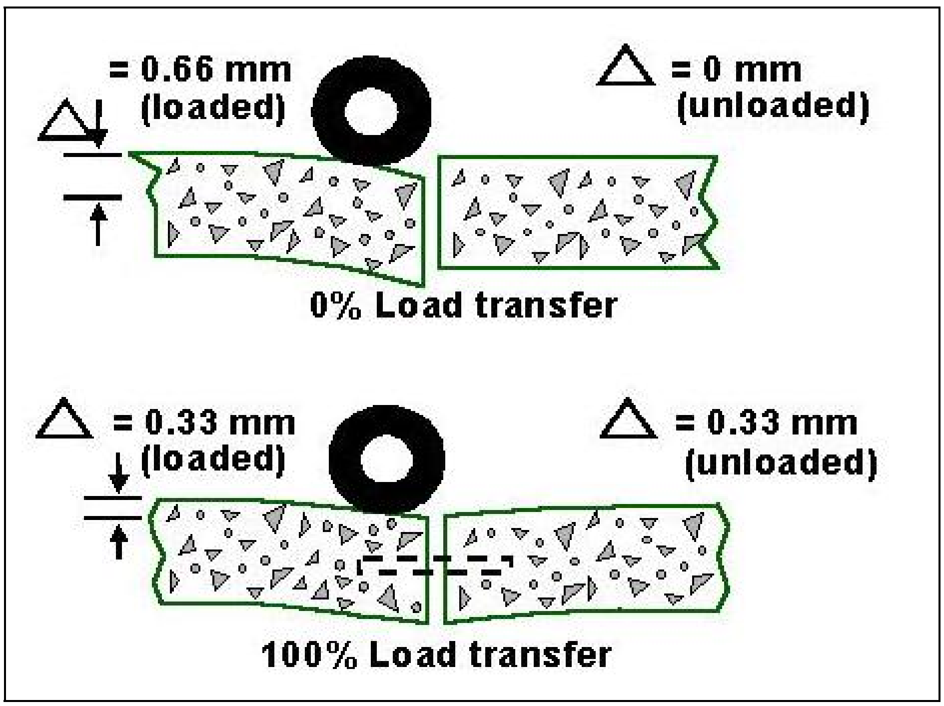

FIGURE 2-1: PICTORIAL REPRESENTATION OF ZERO AND 100 PERCENT LOAD TRANSFER EFFICIENCY

Load transfer efficiencies between 70 and 100 percent are considered as good load transfer [2]. However, in rehabilitation projects, LTE values between 90 and 100 percent should be expected if retrofit procedures are carefully followed [10]. LTE values below

50 percent often result in pavement problems similar to those found in joints or cracks containing no load transfer devices.

Determining LTE on a typical pavement is most often measured using a falling weight deflectometer (FWD). FWD devices simulate impulse wheel loads and measure pavement response through sensors located at specified distances from a joint or crack. Based on the measurements, deflections and load transfer efficiencies can be computed.

2.4.2 Differential Deflection

Measuring differential deflection between adjacent slabs provides further information about the load transfer efficiency of a pavement joint or crack. Differential deflection is the difference in vertical movement between the loaded and unloaded portions of a pavement at a discontinuity [1]. Differential deflection is computed using equation 2-4.

$$DD = \Delta_L - \Delta_{UL} \qquad \text{Eqn. (2-4)}$$

Defining:

Δ_L = *deflection of the loaded slab*
Δ_{UL} = *deflection of the unloaded slab*

Measuring differential deflection is necessary to better understand the effectiveness of load transfer efficiency, since LTE does not take into account the magnitudes of deflections. Different magnitudes of differential deflections can result in the same LTE value since LTE is simply a ratio of deflections taken on the loaded and unloaded sides of a joint. Therefore, it is important to look at the differential deflections of adjacent slabs, in conjunction with LTE values, to determine the effectiveness of a joints ability to transfer vertical shear forces.

2.4.3 Interaction Between LTE and Differential Deflection

Figures 2-2 through 2-5 below describe pictorially the interaction between LTE and differential deflection (DD). Four possible example combinations of high and low LTE and differential deflection are shown. The wheel load in each of the figures is moving from left to right across adjacent pavement slabs separated by a full depth joint (loaded slab is on the left, unloaded slab is on the right). Figure 2-2 illustrates low LTE and low differential deflection as the wheel load travels across the pavement joint. By using Equation 2-1, LTE in Figure 2-2 is zero. From Equation 2-4, differential deflection is 0.001 in. In Figure 2-3, LTE is still zero, but differential deflection is now comparatively much larger at 0.1 in. (vs. 0.001 in. in Figure 2-2). The comparison between Figures 2-2 and 2-3 show the need for differential deflection to quantify the calculation of LTE. As illustrated in Figure 2-1, Figure 2-4 represents large LTE and low differential deflection. This situation would occur if a dowel bar placed across the joint performs ideally. In Figure 2-4, LTE is 100% and differential deflection is zero. Much larger overall deflections are shown in Figure 2-5. However, as illustrated in the drawing, LTE is still high at 90%. Differential deflections are also high at 0.1 in., in comparison to the other figures. Deflection magnitudes must be considered when evaluating the performance of a particular doweled pavement. As illustrated in Figures 2-4 and 2-5, both have high LTEs but the differential deflections are two orders of magnitude apart.

A pavement retrofitted with dowel bars across joints or cracks is considered flexible when large differential deflections are present (i.e., in Figures 2-3 and 2-5). A pavement can be flexible regardless of the performance evaluated by LTE. Additionally, a joint can be considered incompatible when there is a low LTE, even if differential deflection is small (i.e. Figures 2-2 and 2-3 represent incompatible joints). Figure 2-3 illustrates a flexible and incompatible joint.

Pumping and subsequent faulting as discussed in Section 2.1.2 are often associated with flexible pavement joints since large vertical deflections are present. Pavement joints categorized as incompatible often eventually suffer from spalling and cracking (as discussed in Section 2.1.1).

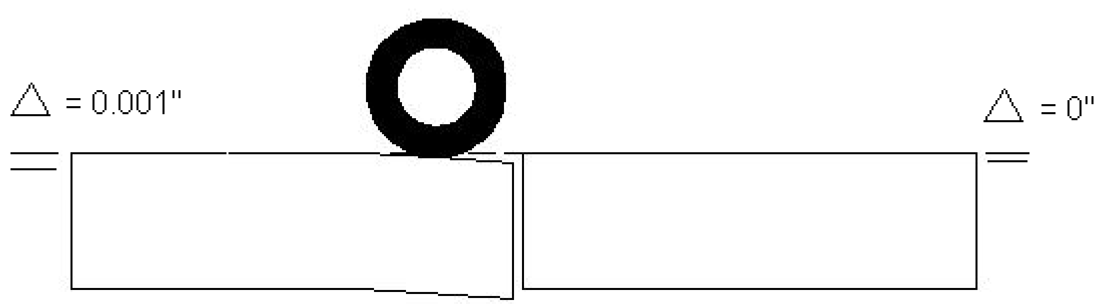

FIGURE 2-2: LOW LTE AND LOW DIFFERENTIAL DEFLECTION

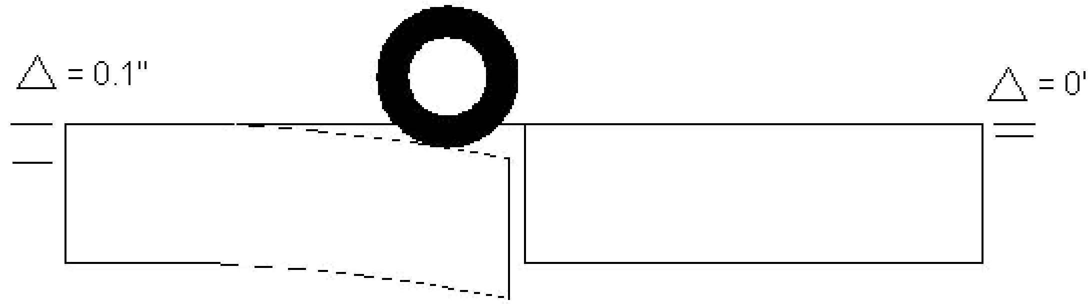

FIGURE 2-3: LOW LTE AND LARGE DIFFERENTIAL DEFLECTION

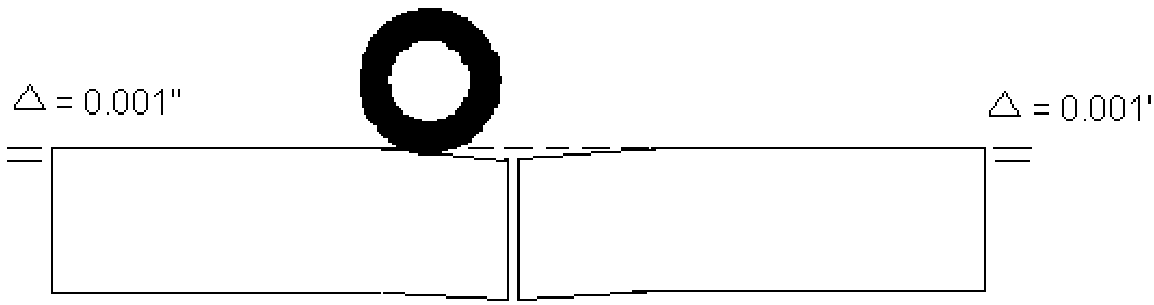

FIGURE 2-4: LARGE LTE AND LOW DIFFERENTIAL DEFLECTION

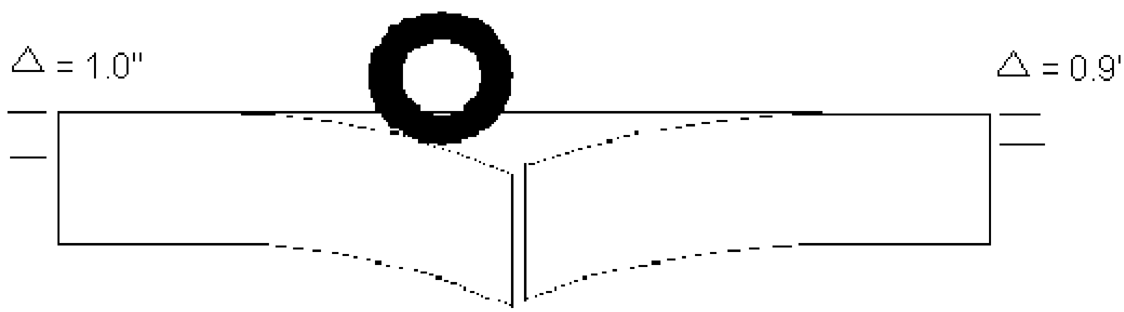

FIGURE 2-5: LARGE LTE AND LARGE DIFFERENTIAL DEFLECTION

3. BACKGROUND OF MINNE-ALF TEST FACILITY

A description of the current Minne-ALF test stand, along with how the facility was developed and its performance capabilities are presented in this chapter [11,12].

3.1 Description of Current Minne-ALF Test Stand

The current Minne-ALF test stand is housed in the Civil Engineering building at the University of Minnesota. General illustrations of the Minne-ALF facility can be found in Appendix A. Refer to "Development of an Accelerated Loading Test Platform for Pavements" by Michael G. Beer [17], and "Design and Development of Modifications for an Accelerated Pavement Testing Facility" by Josh A. Mauritz [12] for detailed design drawings and specifications.

The entire structure creates a roughly square footprint covering an area of about 400 square feet. Creating the foundation of the structure, are nine W27 x 84 transverse beams connected to two W27 x 84 longitudinal beams. At the center of the two W27 x 84 longitudinal beams, two HP 12 x 74 columns are attached to each one and extend upward to support a W 27 x 114 beam to which the vertical actuator is attached. At the East end of the two W27 x 84 longitudinal beams, two more HP 12 x 74 columns are attached and provide support for a W 12 x 72 beam, upon which the horizontal actuator is mounted.

A ¼ inch layer of neoprene sits on top of the eleven W27 x 84 beams and a 3/8 inch steel plate sits on top of the neoprene. The neoprene is used to provide some vibration reduction while the testing is being performed. On top of the aforementioned steel plate, the specimen itself is enclosed by four, fifteen-inch steel channels. This creates a roughly 8 x 16 foot enclosure where the roadway bed is formed. The foundation of this bed consists of a ¼ inch layer of neoprene, on top of which is a nine-inch layer of clay loam and finally, a 3 inch layer of Mn/DOT class 5 material. Each specimen is then cast on top of this pavement foundation. This foundation is a scaled approximation of the foundation found in test section 6 at Mn/ROAD [11], which features 5 inches of class 4 material.

Once the specimen is cast and allowed to cure, the remaining portion of the test facility can be assembled. To create the simulated traffic flow and loading of the pavement, a rocker beam connected to two independently controlled actuators is placed longitudinally over the joint. The rocker beam is a nine-foot long, W10 x 68 steel beam. A curved aluminum arc is attached to the bottom of the beam to help facilitate the rocking motion. At the beams' center, a W10 x 60 steel stub column is perpendicularly attached and subsequently connected to the actuators. In order for the rocker beam to maintain its position while in operation, three additional guidance fixtures are attached. At one end of the rocker beam, a roller bearing system is used, and at the opposite end a U-shaped guide is mounted. In the center of the rocker beam, a lateral guidance wheel is positioned to aid in uniformity of movement.

3.2 Development of Minne-ALF

The current Minne-ALF test facility as described in Section 3.1, is the result of 8 years of cooperation between the Minnesota Department of Transportation and the University of Minnesota as briefly outlined in this section.

The need for a facility that could efficiently and accurately evaluate the long term performance of new and experimental highway pavement designs was realized in 1994 when the Minnesota Department of Transportation commissioned the University of Minnesota to develop such a program.

Traditional field testing of structural pavement designs requires long time commitments, which results in high costs, and can be very detrimental to the data acquisition systems and field sensors in a given environment. The Mn/ROAD research facility, aside from yielding many opportunities and breakthroughs in how structural pavement designs are used, has experienced many of these problems.

The Minne-ALF project was an effective way to deal with the previously stated concerns. In a laboratory setting, cost issues and sensor problems could be easily dealt with. The major unknown in the project was the reliability and accuracy of predicting long term performance of the tested details since the usual years of load repetitions in the field were now being performed in the laboratory in a matter of months.

To try to minimize the effects of some of the unknowns involved with such a facility, a large amount of research was conducted to formulate design concepts and criteria in order to create the best possible design. By researching twenty-two existing accelerated load facilities, the most critical design requirements were decided upon and incorporated into the Minne-ALF project. Some of the key categories considered in the design requirements include: Field to Laboratory Replication, Pavement Types, Traffic Load Simulation, Pavement Foundations, and Environmental effects. The capabilities or features deemed most necessary are summarized in Table 3-1.

Table 3-1: Necessary Design Requirements for Minne-ALF Facility

Capability / Feature	*Laboratory / Field*	*Pavement Types*	*Traffic Load Simulation*	*Pavement Base / Foundation*
Necessary Requirement	Laboratory pavement testing	Test rigid pavement	Apply 125,000 loads/day	Use natural pavement foundation
	Easily upgradable	Evaluate design methodologies	Apply legal limit wheel loads	use artificial pavement material
	Low initial cost	Evaluate rehabilitation techniques	Evaluate half-axle loading	
		Evaluate load transfer devices	Evaluate full scale paved sections	

Based on the above criteria, three load application designs were formulated. These three loading designs all incorporated a linear loading technique due to its cost effectiveness and required application. The designs included a rocker beam controlled by two vertical actuators, multiple vertical actuators aligned in series, and a long-stroke actuator connected to a load cart.

Initially, a rocker beam controlled by two vertical actuators was chosen as the final design. Unfortunately, soon after the load apparatus was assembled and initial testing began, it was found that the control system was not able to apply a constant nine kip single wheel load and still maintain the appropriate simulated vehicle speeds [12]. Due to the action/reaction response of the actuators, when one actuator applied a load the other one had to compensate from the reaction it felt (i.e., cross-coupling). At relatively slow speeds the control system was able to perform this adjustment sufficiently, but when speeds increased, the applied load fluctuated enough giving inconsistent results. This resulted in modifications to the load application system and subsequently gave way to the current Minne-ALF set up.

This final design still incorporated a rocker beam but with the actuators now attached to a stub column in the center of the rocker beam. One actuator could now be used to apply the load, more easily maintaining a 9 kip uniform load, while the other actuator controlled the horizontal displacement or stroke. Other changes to the apparatus included a faster control system, modifications of the hydraulic supply system, and frame stiffening components in the form of cross bracing.

3.3 Minne-ALF Testing Capabilities

The current Minne-ALF test facility provides a means to quickly and accurately test new and experimental structural pavement designs. Once a design is decided upon, implementation and testing of that design can begin within one week and be completed on a timeline nearing two months.

3.3.1 Description of Loading

Vehicle loads traveling across pavement joints at highway speeds can be simulated by means of two hydraulic actuators acting on a steel rocker beam moving transversely over the concrete pavement joint. The movement of the rocker beam is set at 1.5 hertz or 1.5 cycles per second. This loading frequency is able to produce 129,600 load cycles per day. The simulated vehicle speed as the rocker beam moves across the joint is roughly 30 mph over a total load path of nine feet (the effective length of the rocker beam from one end to the other).

The actual simulated vehicle load acting on the pavement specimen is a unidirectional nine-kip load with a return load of two kips. The 9-kip load is used because the allowable maximum single axle load in Minnesota is 18,000 lbs and the size of the test specimen is one half the size of a standard lane. The test specimens are six feet wide, allowing for testing of one half of one axle, compared with a standard lane width of twelve feet. The 2 kip return load ensures the rocker beam will be in constant contact with the pavement surface, which negates the possibility of any impact loading on the specimen. Also, the 9-kip load acts only in one direction because it is the most common load type on highway pavements.

3.3.2 Description of Hydraulic System

The hydraulic system used on the Minne-ALF powers two actuators. A central pump powers all the hydraulic systems in the Department of Civil Engineering at the University of Minnesota. The Minne-ALF hydraulic system hoses are connected to this central pump by means of a hydraulic service manifold (HSM). The HSM provides a regulatory function and is necessary to keep other laboratory tests from being affected by the hydraulic flow demands of the Minne-ALF system. Each actuator is connected to two, one-inch diameter hydraulic hoses, that are in turn connected to the HSM, and finally to the central pump. At full capacity, the system is able to operate at a pressure of 3,000 psi and supply 150 gpm.

3.3.3 Description of Control System

Control of the hydraulic system is provided by an MTS TestStar system [13]. The MTS TestStar system is connected to the actuators by two 15 gpm electronic servo-valves that regulate the inward and outward flow of the hydraulic fluid.

The MTS TestStar system components include a computer with a Windows NT operating system and a TestStar controller. The cables controlling the actuators are connected directly to the TestStar controller and the controller is connected to the personal computer in a freestanding cabinet near the Minne-ALF. In order to create the proper movement of the rocker beam, command signals are first sent to the actuators from a text file. The text file contains the desired waveform described by a 1,024-point sequence. A square waveform is used to generate the movement of the load-producing actuator (vertical actuator), and a sinusoidal waveform is used for the stroke-producing actuator (horizontal actuator). The square waveform required for the load-producing actuator varies from nine kips to two kips and the sinusoidal waveform controlling the movement of the horizontal actuator produces the required stroke of 0.75 inches in both the positive and negative directions. Figure 3-1 shows the ideal command waveforms.

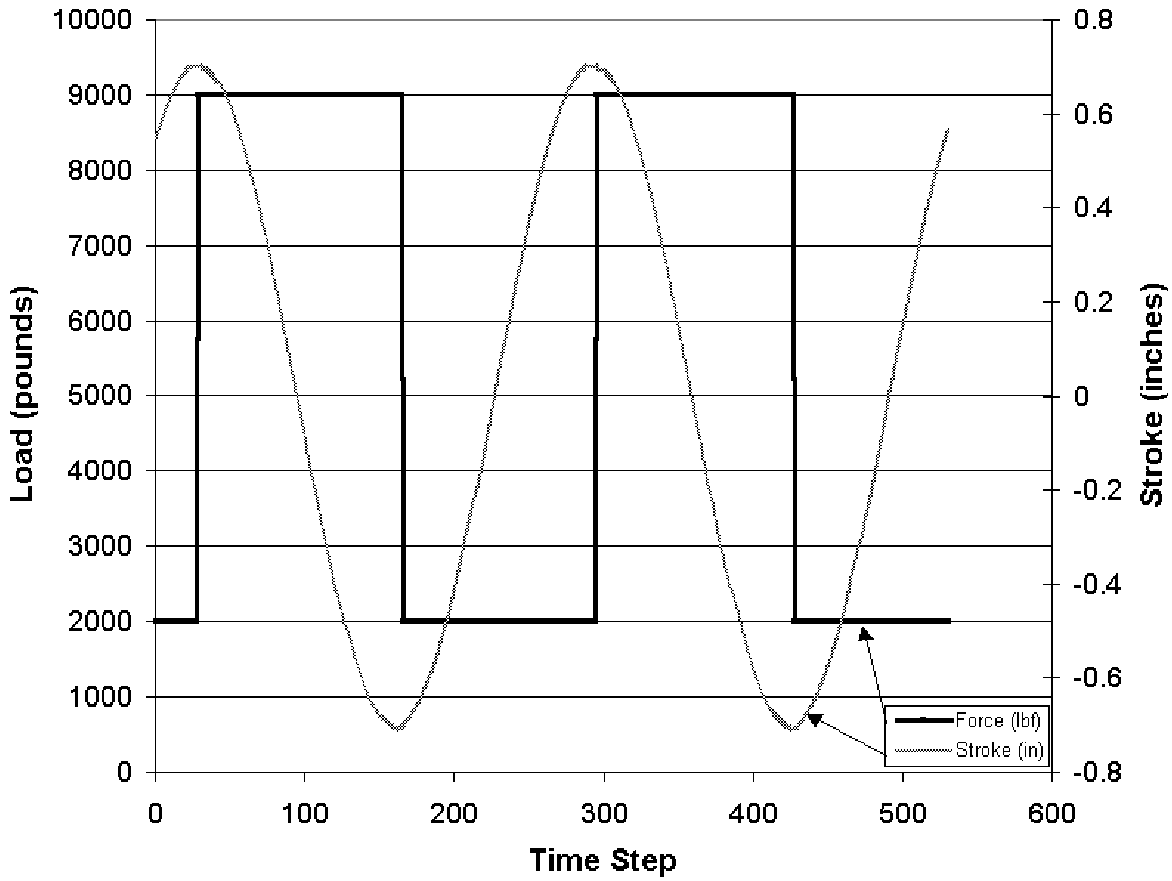

FIGURE 3-1: PLOT OF IDEAL COMMAND WAVEFORMS FOR LOAD AND STROKE

Before testing of a new specimen is initiated, a procedure called a "shakedown" is performed. This process creates rapid, incremental movements of both actuators by sending a high frequency signal through the system. Measured response from this "noise" is used to formulate correction factors needed to generate the correct command signals. During the shakedown procedure, the "noise" sent through the system lasts roughly 39 seconds. Feedback responses from the linear variable displacement transducers (LVDT's) in the actuators are recorded and used to correct the outgoing command signals thereby decreasing the error between the feedback and command signals. Once the signals are corrected sufficiently so that the actual load profile matches the desired load profile of a square waveform, the information is saved. This saved file, called the "drive file" is then played repeatedly to continuously generate the proper commands to produce the required load profile.

3.3.4 Description of Data Acquisition System

Collecting data once the system is running is accomplished by the system's TestWare software. The software collects data automatically at predetermined specified points as well as when the collection system is triggered manually. When the system is prompted to take a data point, it does so for two seconds at a rate of 400 hertz, thus collecting 800 lines of data that is saved to a Microsoft Excel spreadsheet. Viewing the data is easily done by accessing the appropriate saved data file from the computer.

The actual sensors used to measure the deflection of the pavement consist of two external measuring devices. The two external sensors are connected to the system through a conditioner box and then to the computer. The conditioner box provides the displacement readings on the external LVDT's and is read when manual data points are taken. Internal load cells within each actuator measure the applied load and the horizontal position of the rocker beam.

3.4 Preliminary Testing of Minne-ALF (Phase 1)

In order to determine the effectiveness of the Minne-ALF facility, six pavement specimens were tested in Phase 1 by Snyder, Embacher, and Mauritz [11,12.]. The goal of this testing was to ensure that consistent results could be obtained and to work out any problems with the control systems. More precisely, the preliminary testing of Phase 1 was performed to evaluate the following goals [11]:

- Determine the effects of selected design and construction variables on retrofit dowel load transfer system performance,
- Determine the variability of Minne-ALF test results,
- Demonstrate the general usefulness of the Minne-ALF,
- Identify the need for any additional test modifications.

Achieving these goals required casting the slabs and test cylinders, retrofitting the dowel bars, loading the slab specimens, collecting the load and displacement data, and analyzing the results. A typical Minnesota PCC paving mix 3A41, with a ¾-in. maximum aggregate size and a target air content of 5.5 %, was used. The specimens were 15 feet in length, 6 feet wide, and 7.5 inches deep and the retrofitted dowel bars were located at slab mid-depth. Table 3-2 summarizes the dowel type, backfill type, and crack type for the six trial specimens in Phase 1 [11, 12]. The stainless steel dowels in Slab 6 were purchased in a metric size and had a diameter that was slightly smaller than 1.5 inches.

Table 3-2: Phase 1 Detail Summary for Minne-ALF Trial Specimens [11, 12]

Slab #	Dowel Type	Backfill Type	Crack Type
1	1.5" diameter, 18" long, epoxy coated steel	Mn/DOT 3U18 patch mix	Fatigue induced (aggregate interlock)
2	1.5" diameter, 18" long, epoxy coated steel	Mn/DOT 3U18 patch mix	Smooth, formed during casting (no aggregate interlock)
3	1.5" diameter, 18" long, epoxy coated steel	Mn/DOT 3U18 patch mix	Smooth, formed
4	1.5" diameter, 18" long, epoxy coated steel	Tamms Speedcrete 2028	Smooth, formed
5	1.5" diameter, 15" long, epoxy coated steel	Tamms Speedcrete 2028	Smooth, formed
6	1.44" diameter, 15" long, stainless clad steel dowels	Tamms Speedcrete 2028	Smooth, formed

3.4.1 Preliminary Test Specimen Descriptions

The first specimen in Table 3-2 was a precast slab transported to the test facility and loaded by means of a modified load plate attached to the vertical actuator in order to initiate a full-depth transverse crack at slab mid-length. Three 18-inch long, 1.5-in. diameter, epoxy-coated mild steel dowels were retrofitted across the crack according to the current design standard configuration (6 in. from the edge with the remaining two at 12 in. on center).

The second and third specimens in Table 3-2 also contained three 18-inch long, 1.5-in. diameter, epoxy-coated mild steel dowels. These specimens, along with the remaining specimens, were all cast in place to eliminate the leveling problems associated with the first precast specimen. Also, to eliminate the effects of aggregate interlock on load transfer across the joint, the remaining specimens were cast with a full depth ¼ inch thick plywood joint at mid-length of the slab. This ensured that the load transfer, after retrofit, would depend solely on the dowel bars used.

The fourth specimen in Table 3-2 used the same dowel bars and configuration as specimens two and three, but used Speed Crete 2028 instead of the Mn/DOT 3U18 backfill material. Speed Crete 2028 is a commercially available material. The fifth specimen was identical in configuration and backfill to specimen four, but used dowels of 15 inches in length instead of 18 inch long dowels. The final specimen also used shorter dowels and was identical to the fifth specimen but the dowel bar material was changed. The sixth specimen utilized stainless steel clad dowels in place of the previously used epoxy-coated, mild steel dowels.

3.4.2 Testing Procedure for Phase 1 Preliminary Specimens

After curing for six days, the specimens were retrofitted and tested. The first specimen, however, was not retrofitted nor tested until one year after slab placement, which allowed time for test stand modifications to be completed. Testing of the specimens commenced 24 hours after retrofit to simulate actual highway retrofit specifications that allow traffic to resume on the retrofitted section as soon as possible. The 9 kip unidirectional load, with the 2 kip return load, was applied at a rate of 2 hertz.

Data was collected automatically at load cycles of 50, 100, 1,000, 2,000, 5,000, 10,000, 20,000, 50,000, 100,000, 300,000, 600,000, and at every 600,000 cycles thereafter. The data included vertical actuator load, horizontal actuator stroke, slab displacement, and time. Slab displacements were measured by two external LVDT's placed near the pavement joint.

3.4.3 Phase 1 Test Specimen Results

Snyder et al. [11, 12, 17] analyzed the collected data and computed differential deflection and Load Transfer Efficiency (LTE) of the pavement system. Observations and conclusions were made on the basis of comparisons between dowel bar types, dowel bar lengths, backfill material, and joint face texture of the specimens tested [11].

A summary of conclusions and recommendations based on the testing of the six specimens featuring the preliminary designs tested in Phase 1 is presented by Trevor Odden in "Performance Testing of Experimental Dowel Bar Retrofit Designs" [14].

4. CURRENT RESEARCH PROGRAM DESCRIPTION – PHASE 2B

4.1 Introduction

This chapter provides detailed information explaining the most current research (Phase 2B) conducted with the Minne-ALF facility. Explanations of the design variables, performance criteria, test specimens, dowel bar designs, data acquisition, and test procedures are detailed in this chapter.

4.2 Design Variables

This research studied the load transfer effectiveness and differential deflection of PCC pavements with respect to four test variables. These variables were dowel bar material, dowel bar size, dowel bar configuration, and number of dowels. The repeatability of test details was also evaluated. Three of the test specimens used the same dowel bar material but varied with respect to the amount of cover or the number of bars used. One specimen was retrofitted with a different dowel bar material and used larger diameter dowels than the other three.

The main issues of cost effectiveness and corrosion resistance were addressed by varying the above design variables. By varying the dowel bar material, it is possible to find the most effective material while still maintaining performance. Also, different materials provide different levels of corrosion protection. Using different dowel bar diameters also addresses the issues of cost and performance. Larger diameter bars of one material may provide better load transfer performance and corrosion resistance and still be more cost effective than smaller bars of another material. Varying the number of bars provides insight into costs associated with large retrofit projects. If fewer bars can be used while still maintaining performance, then some of the expense involved with retrofitting can be reduced. High retrofit costs as well as other problems with retrofitting thin pavements are addressed by varying the geometric configuration of dowel bar details.

4.3 Performance Criteria

The performance of the dowel bar details was measured through load transfer efficiency, differential deflection, and daily visual inspections. By analyzing these performance measures, conclusions were made as to the effectiveness of a particular detail.

4.3.1 Load Transfer Efficiency

Load transfer efficiency is defined as "the ability of a joint or crack to transfer load from one side of the joint or crack to the other" [1]. There are different techniques and equations used to measure and compute LTE. The computation of LTE in this research was based on Equation 2-1. Two external LVDT's attached to the pavement specimen near the joint, provided the slab displacement data used to compute the LTE.

4.3.2 Differential Deflection

Measuring differential deflection between the slabs on either side of the joint was also accomplished by the two external LVDT's. Differential deflection is "the relative displacement between the loaded and unloaded sides of the joint or crack" [1]. Increasing differential deflection measurements may indicate crushing of concrete near the joint, deterioration of the dowels, and other general performance trends of the retrofitted dowels. Equation 2-4 was used for computation of differential deflection.

4.3.3 Visual Inspections

Observing the pavement specimen on a daily basis was also used as a performance measure. These daily inspections included visual inspection of the pavement surface, joint, and retrofitted dowel slots. Any signs of cracking, deterioration, or other changes to the pavement system were noted. After the specimen testing was complete, the dowels were carefully removed and inspected for damage. The backfill concrete used in each dowel slot was also examined for distress and for proper consolidation of the concrete.

4.4 Current Test Specimen Descriptions – Phase 2B

4.4.1 General Description of Test Slabs

All the pavement specimens were made from a typical Minnesota PCC pavement mix and were of the same dimensions. The concrete was a Mn/DOT 3A41 mix and was supplied from an outside vendor. The test slabs were cast in place on top of the pavement foundation material. The dimensions of all specimens were 15 feet in length, 6 feet wide, and 7.5 inches deep. The slabs were cast without dowel bars since the focus of this project is to determine the effects of retrofitting dowels in existing pavements. Figure 4-1 shows the Minne-ALF test facility with a test specimen immediately after casting.

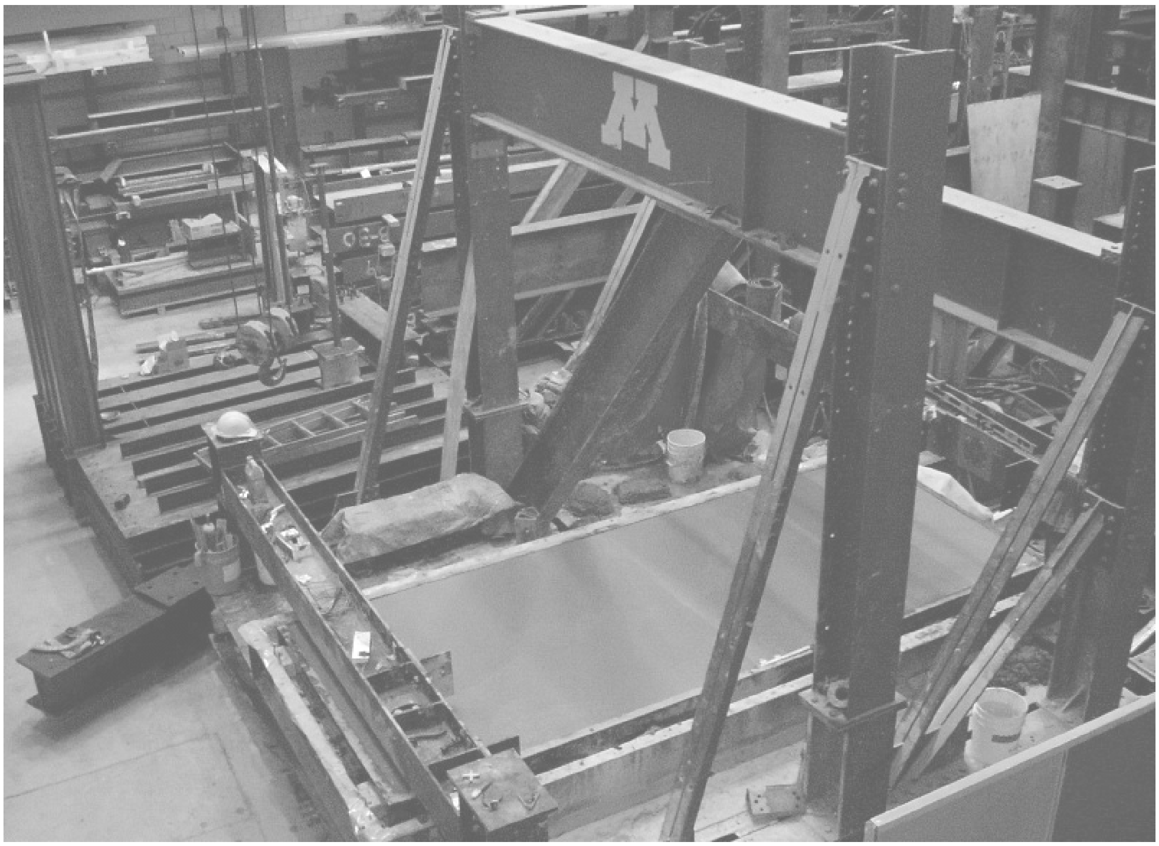

FIGURE 4-1: MINNE-ALF TEST FRAME WITH SPECIMEN

4.4.2 Joint Description

At the time of casting a joint was formed at the center of the specimens length. The joint was made from a ¼-inch thick piece of plywood, 7.375 inches in height, and 6 feet wide.

The joint ran the total width of the specimen, forming a smooth, full-depth, transverse joint. This ensured that all load transfer would depend only on the retrofitted dowel bars.

4.4.3 Test Cylinder Descriptions

At the time each test specimen was cast, twenty 6-inch diameter, 12-inch long test cylinders were made. The cylinders were used for material property evaluation, based on ASTM C192. Compressive strength, split tensile, and static modulus of elasticity tests were performed at 1 day, 3 days, 7 days, and 28 days to comply with ASTM C193 and ASTM C469 standards. Table 4-1 summarizes slab specimen compressive strengths.

Table 4-1: Cylinder Compressive Strengths for Slab Specimens in Phase 2B

Slab Specimen Compressive Strengths (psi)								
Moist Curing Time (Days)	Slab 7				Slab 8			
	Cylinder Number			Average Strength	Cylinder Number			Average Strength
	1	2	3		1	2	3	
1	2039	1961	1967	1989	1991	1820	1985	1932
3	3050	3129	3178	3119	2810	2954	2928	2897
7	3798	3839	3808	3815	3802	3995	3893	3897
28	4828	4936	4879	4881	4650	4867	4962	4826
Moist Curing Time (Days)	Slab 9				Slab 10			
	Cylinder Number			Average Strength	Cylinder Number			Average Strength
	1	2	3		1	2	3	
1	1893	2022	2105	2007	1735	1905	1577	1739
3	3220	3241	3286	3249	3399	3004	2998	3134
7	4039	4100	4155	4098	3500	3926	3881	3769
28	5620	5490	5483	5531	5601	5443	5156	5400

4.4.4 Backfill Material Description and Properties

In all four test specimens in Phase 2B, Speed Crete 2028 was used for backfilling the dowel bar slots. Two 50-pound bags of commercially available Speed Crete were combined with 100 pounds of Mn/DOT CA8 gradation aggregate and 11.1 pounds of water to create the mix for the backfill material. Once mixed, the backfill material is able to achieve strength of 5,000 psi in three hours. It has a granular consistency after mixing and has zero slump. The backfill material was mixed on-site and placed in the dowel bar slots by hand. During the backfilling process, six, eight-inch long, four-inch diameter test cylinders were cast as per ASTM C192 specification. The cylinders provided compressive strength information after one day of moist curing. Table 4-2 lists the compressive strength values of the backfill for each of the four specimens in Phase 2B.

Table 4-2: Backfill Material Compressive Strengths – Phase 2B

Backfill Material Compressive Strengths (psi)				
Specimen Number	***Slab 7***	***Slab 8***	***Slab 9***	***Slab 10***
1	4377*	4800*	4526*	4910*
2	5011	5100	6102	4880
3	5028	5052	5283	5428
4	4987	5021	5200	5377
5	4999	4990	5461	5935
6	5010	5029	5506	5088
Average Strength	5007	5038	5510	5342

* Indicates specimens tested between 14 and 16 hours

4.5 Current Dowel Bar Designs Tested – Phase 2B

The scope of this research includes testing four dowel bar retrofit details using the Minne-ALF facility. Table 1-1, Phase 2B summarizes these four details. This section describes each of those details, including the type of dowel used, the number of dowels, and the configuration of the dowels. As a reference, the standard dowel bar retrofit detail, for one-half axle loads, consists of three dowel bars spaced 12 inches on center, with the first dowel placed six inches from the edge of the pavement and with three inches of clear cover above the dowel. All the dowels were placed parallel to one another and centered longitudinally over the smooth formed joint.

4.5.1 Phase 2B Detail One (Slab 7):

The first detail tested in Phase 2B, Table 1-1 Slab 7, used a retrofit pattern consisting of two dowel bars instead of three that had been tested in all previous specimens. The dowel bars were 1.5 inches in diameter, 15 inches long, and made of epoxy coated mild steel. Varying the number of bars from three to two was done in order to determine the effects on LTE and differential deflection. The dowels in this specimen were also placed higher in the slab than previous designs. Only two inches of clear cover was provided as opposed to the standard three inches. The first bar was placed six inches from the longitudinal edge of the slab and the second bar was placed transversely, 12 inches on center from the first.

4.5.2 Phase 2B Detail Two (Slab 8):

The second retrofit detail tested, Table 1-1 Slab 8, was a replicate of Slab 5-6 in Table 1-1. This was done to show that the previous test detail results were accurate and could be repeated. This detail also used mild steel epoxy coated dowels, 1.5 inches in diameter, and 15 inches long. The three dowels were placed in the current Minnesota retrofit spacing detail of 12 inches on center and starting six inches from the pavement edge. Two inches of clear cover, instead of the standard three inches, was also used for this specimen.

4.5.3 Phase 2B Detail Three (Slab 9):

The third dowel bar design, Table 1-1 Slab 9, was also a replicate detail. It was a replicate of Detail One (Slab 7) in Phase 2B (Refer to Section 5.4.1).

4.5.4 Phase 2B Detail Four (Slab 10):

The final retrofit detail in the scope of this research (Phase 2B), Table 1-1 Slab 10, used fiber reinforced polymer (FRP) dowels. This detail contained the same retrofit configuration and same length dowel bars as Slab 2, Phase 2A in Table 1-1, but used larger diameter dowels. This detail used three 15-inch long FRP dowels, the composition of which (i.e., fiberglass strands with polymer resin) makes them more corrosion resistant than standard mild steel dowels. The dowels were placed in the standard retrofit pattern of 12 inches on center, starting six inches from the longitudinal edge of the slab. The dowels were 1.75 inches in diameter whereas the previously tested FRP design (Slab 2, Phase 2A in Table 1-1) used 1.5-inch diameter dowels. The dowels were placed at mid-depth of the slabs, with a resulting clear cover of 2.875 inches, instead of the current standard of 3 inches, or the reduced cover of 2 inches used in the other Phase 2B slabs.

4.6 Data Acquisition System Description

The systems TestWare software accomplishes collecting data, once the system is in operation. The software collects data automatically at predetermined specified points as well as when the collection system is triggered manually. Automatic data collection occurs at 50, 100, 1,000, 2,000, 5,000, 10,000, 20,000, 50,000, 100,000, 300,000, and 600,000 load cycles, as well as every 600,000 load cycles from then on. Manual data points were taken roughly four times per week, coinciding with regular roller bearing maintenance. When the system is prompted to take a data point, it does so at a rate of 400 hertz, in turn, collecting 800 lines of data that is saved to a Microsoft Excel spreadsheet. Viewing the data is easily done by simply downloading the file from the computer.

The actual sensors used to take the data consisted of internal and external measuring devices. Information provided by these sensors included applied load, horizontal actuator displacement, and slab displacement. The actuator load cells and internal LVDT's were calibrated to correspond to the two external LVDT's for measuring the load and displacement acting on the pavement specimen. The two external LVDT's were Lucas model #GCA-121-125. They operated between a range of plus or minus 0.25 inches and have a level of accuracy of 0.00004 inches. These external sensors were connected to the system through a conditioner box and then to the computer. The conditioner box provided the displacement readings on the external LVDT's and was read when manual data points were taken.

4.7 Test Procedures

4.7.1 Preparation of Foundation

Prior to casting the pavement slab, the test foundation was prepared. The top layer of the foundation was a Mn/DOT Class 5 material. After removal of the previous slab, the foundation surface was often no longer completely level. The uneven surface was therefore leveled by moving a four-foot level over the top layer both transversely and longitudinally. Then, a plastic barrier, two mils thick, was placed on top of the foundation to separate the concrete from the foundation material.

4.7.2 Form Installation

On top of the plastic, steel forms were placed and properly positioned. The steel forms consisted of two 6 foot and two 12 foot, eight-inch deep steel channels. The channels were connected by steel brackets in the corners using four bolts. Spaced evenly along the longitudinal length of the forms were two ¼-inch diameter steel rods spanning transversely. These rods eliminated spreading of the forms while the concrete was being placed. Once the steel rods were in place, a final check of the form placement was made and the forms were then clamped and blocked in place to prevent movement during casting. Finally, the forms were coated with a release agent to prevent the concrete from bonding to the steel. At this time, roughly 20, 6-inch diameter by 12-inch long steel and plastic molds were also prepared and coated with the concrete release agent.

4.7.3 Joint Installation

Once the forms were securely positioned, the transverse joint was cut and secured in place. Figure 4-2 shows the smooth formed joint spanning transversely between the longitudinal forms at the mid-point of the specimen.

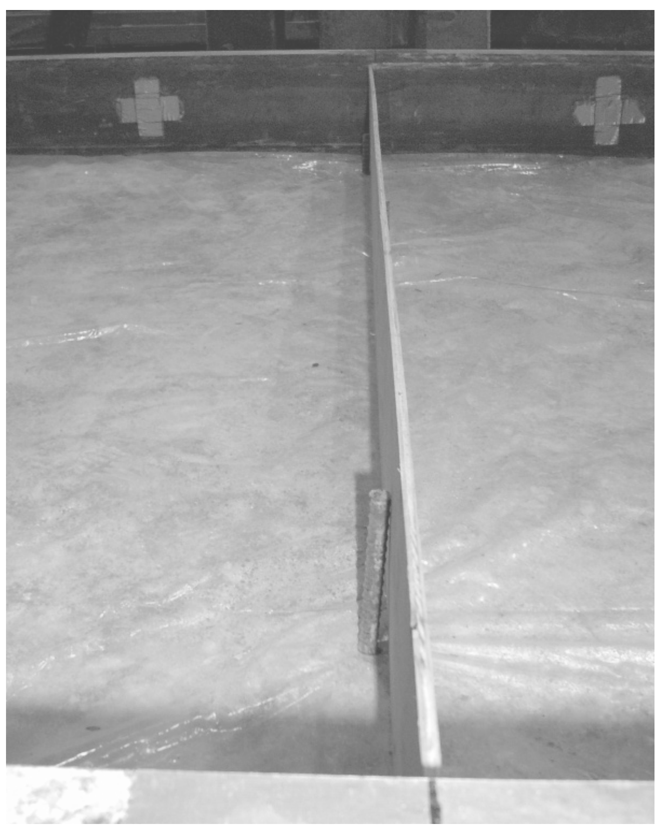

FIGURE 4-2: CLOSE-UP OF SMOOTH FORMED JOINT

The joint was cut to dimensions of 7.375 inches in height and 6 feet long from a ¼-inch thick piece of plywood. Small length adjustments were made to the plywood to ensure it would fit snugly between the steel forms without any bowing. To prevent the joint from moving and to keep it upright during casting, three to four 10-inch long number 4 reinforcing bars were hammered into the foundation material alongside the joint. Care was taken to prevent the bars from interfering with the dowel bar slots to be cut later.

4.7.4 Casting of Slab Specimen

After the forms were in place and the joint was set, the concrete was delivered via a local ready mix supplier. Once the truck arrived, measurements of concrete slump and air content were taken. The mix was tempered by the addition of water if the concrete slump was too low. If the mix did need to be adjusted, new measurements were taken and recorded. The requested slump was 4 inches and the target value for the water-to-cement ratio was 0.48. Table 4-3 shows the final measured values of slump and air content for the four specimens in Phase 2B.

Table 4-3: Measured Slump and Air Content for Slabs 7 Through 10 in Phase 2B

	Slab 7	*Slab 8*	*Slab 9*	*Slab 10*
Slump (inches)	4.75	5.75	6.5	5
Air Content (%)	5	4	4.5	5.5

After the mix was confirmed to have acceptable slump and air content, the concrete was loaded into a crane operated dump bucket. The bucket was then maneuvered over the foundation and placed within the forms. As soon as the concrete was shoveled into place, a pencil vibrator was used for consolidation. This process was repeated until the required amount of concrete was placed. Roughly 1.5 cubic yards of concrete was craned in at a time, making about three loads necessary. After consolidation, a leveling screed was drawn back-and-forth across the surface to strike off any excess concrete. Next, a bullfloat, and later hand floats and trowels were used to achieve a smooth, finished surface. Figure 4-3 is a close up of a test specimen immediately after casting.

FIGURE 4-3: TEST SPECIMEN IMMEDIATELY AFTER CASTING

Immediately after the surface was finished, two one-inch square metal plates were set into the concrete near the joint. Figure 4-4 shows the metal LVDT contact plates positioned near the joint along the edge of the slab. These plates were positioned approximately 1 inch and 5 inches away from the joint. They provided a hard surface for the two external LVDT points to ride on. When the concrete had cured to the point where it did not leave marks when touched, wet burlap was placed on the surface and covered with tarps. The slab was moist cured in this manner for seven days. The test cylinders were also moist cured in the same way as the slab.

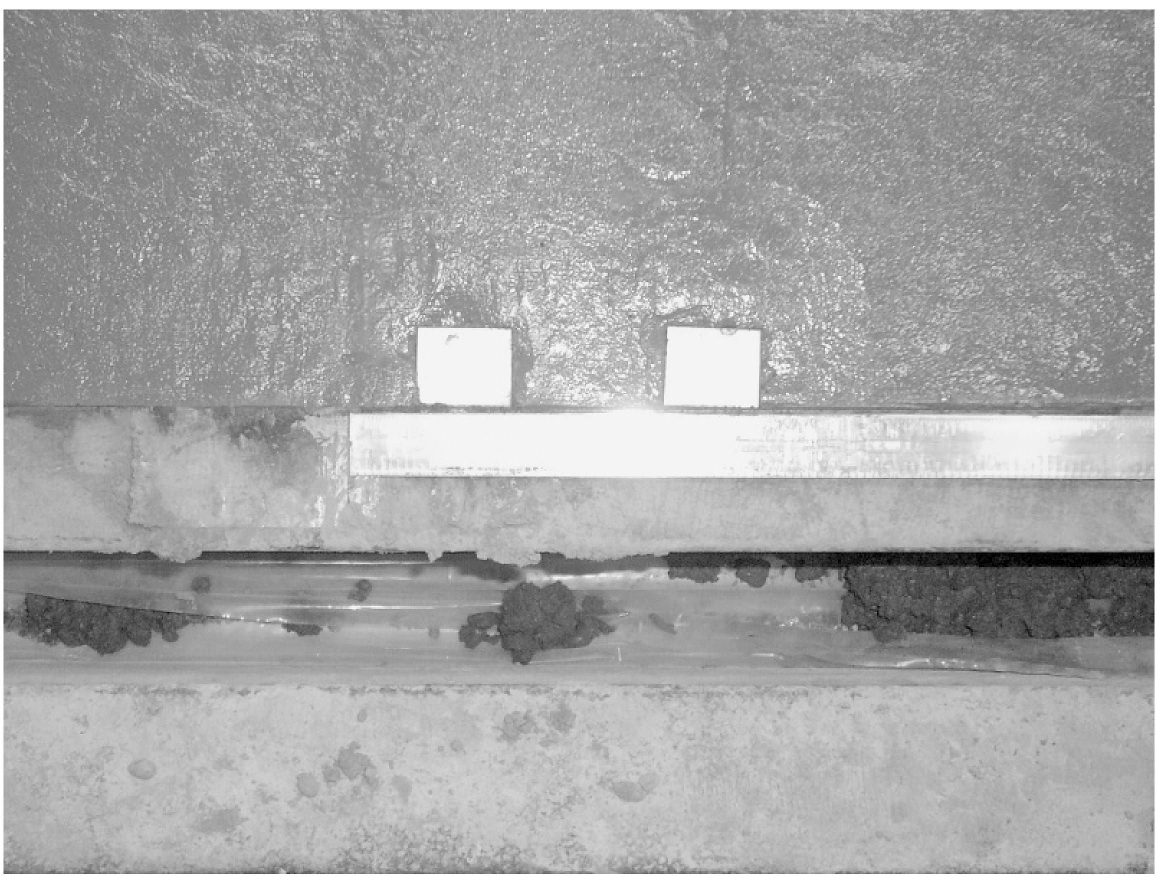

FIGURE 4-4: LVDT CONTACT PLATES

4.7.5 Cutting and Preparation of Dowel Bar Slots

Once a slab had cured for about four days, the retrofit slots were cut. The number of slots cut and the depth of the slots was dependent upon the individual detail to be tested, as discussed in Section 4.5 of this report. In all the specimens, the layout of the slot material to be removed was first drawn on the slab surface for reference when cutting. The slots measured 30 inches in length, evenly positioned longitudinally across the joint. The width of each slot was between 2.75 and 3 inches and the depth varied from 4 to 5 inches, depending on the amount of cover required.

To cut each slot, a hand held, wet run concrete saw fitted with a diamond tipped blade was used. This saw cut the two parallel 30-inch long vertical cuts on each side of each slot. The ends of each slot were curved upward to match the radius of the saw blade. Levels fitted to the saw were used as guides to cut the slot sides as vertically as possible. The depth of the cut was determined by marks set on the blade. After the longitudinal cuts were made, the remaining concrete was removed using a 20-pound air driven chipping hammer. The hammer was fitted with a 1-inch wide chisel. This was a careful process to ensure that the proper amount of material was removed and that the bottom surface of the slot was level and smooth. Figure 4-5 shows partial completion of the slot material being removed with the air chipping hammer.

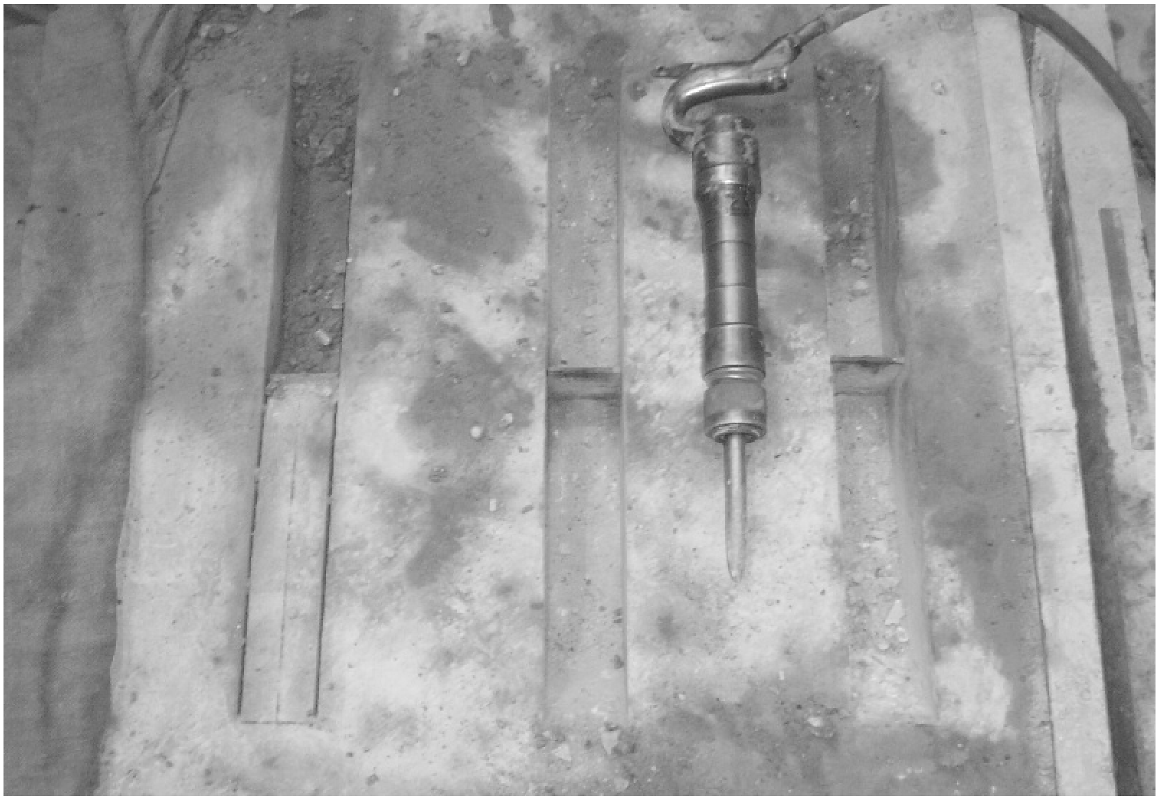

FIGURE 4-5: PARTIAL REMOVAL OF SLOT MATERIAL WITH CHIPPING HAMMER

When all the material had been removed, the slots were thoroughly cleaned. The slots were cleaned with water, compressed air, and brushes. Careful cleaning had to be performed so proper bonding of the concrete to the backfill material could be achieved. Figure 4-6 shows three slots with the plywood joint in the center after removal of all material and cleaning. The rectangular piece of wood that was removed from the joint when the slots were cut now needed to be replaced. Each slot was fitted with a custom cut, ¼-inch thick piece of plywood to match the existing joint. The fitted plywood pieces each contained an appropriately positioned hole to allow for the dowel to snugly pass through. Prior to the backfilling of the slots, the dowels were placed in the slots and checked for proper alignment.

FIGURE 4-6: FINAL SLOTS AFTER REMOVAL OF DEBRIS AND CLEANING

4.7.6 Backfilling the Dowel Bar Slots

After the slab had cured for four days, slots were cut, dowel bar positioning checked, and the dowels were retrofitted. Final preparations were made to the slots by coating them with a bonding agent. The bonding agent was a mixture of sand, cement, and water. Next, the dowel bars were coated with a concrete release agent that would allow them to move longitudinally within the slots after backfilling. Dowel bar chairs and end caps were attached and the dowels were positioned in the slots.

The backfill material consisted of two 50-pound sacks of Speed Crete 2028, 100 pounds of CA-8 washed pea gravel, and 11.1 pounds of water. An electric mixer was used to combine the components until the proper consistency was achieved. The backfill material was then placed in each slot using three lifts. After each lift, the material was compacted through tamping and by means of a pencil vibrator. Special care was used when compacting to make certain the dowels maintained their positions and that proper compaction was achieved. To create the finished surface for each slot, floats and trowels were used.

Concurrently while retrofitting the slots, 4-inch diameter by 8-inch long test cylinders were cast. These cylinders were tested within one day after retrofit to ensure the proper strength was achieved. The entire backfill process was completed within 20 to 30 minutes after mixing, due to the quick set time of the mix.

4.7.7 Assembly of Loading Components

In order to cast each specimen, the rocker beam and associated guidance and bracing fixtures were removed. Once the specimen was in place and the backfilling of the slots complete, the assembly of the loading and bracing components could commence. First, four holes were drilled in the slab surface, and anchor hooks inserted, to attach the mat that the rocker beam rides on. Two holes were also drilled in the longitudinal side of the slab, near the joint, to allow for the attachment of one LVDT stand. Two bolts were grouted into the holes and allowed to set for 24 hours.

The rocker beam was then craned into place and centered over the critical dowel (the dowel nearest the slab edge). Since the backfilled slots were still covered with wet burlap and tarps, the rocker beam was later lifted to install the riding mat. Next, the lateral guidance fixtures were installed. One fixture was affixed at either end of the rocker beam and one fixture was positioned to provide lateral support at the midpoint of the rocker beams stub column. All these guidance components were bolted into place and secured using an impact wrench. Four roller bearings were then bolted into place and greased. These bearings attached the rocker beam, at one end, to one of the guide fixtures.

Once the rocker beam was in position, the two actuators were lifted and bolted into place. Care was taken in aligning each actuator so that a smooth rocking motion would result. Each end of each actuator was secured using four bolts. The bolts were tightened to 150 ft-lbs using a torque wrench. Once the actuators were in position, the hydraulic hoses were secured and checked for areas of wear and padded if necessary. Longitudinal bracing, in the form of double angles, was bolted into place on both sides of the rocker beam. Next, the actuator cables were connected and the hydraulic power was turned on.

After the system had been reassembled, the backfill material test cylinders were tested for the proper compressive strength. Mn/DOT specifications require the backfill material to have at least 5,000 psi compressive strength within 24 hours. This specification was met for all test specimens. With confirmation of the compressive strength, the rocker beam was raised to remove the burlap and tarps used for moist curing of the backfill material. The pad that the rocker beam rides on was then placed under the beam and secured to the slab. The mat was made of a urethane material and was 5/8 inches thick, 12 inches wide, and roughly 12 feet long. To complete the assembly of the test system, the LVDT stands were bolted in place and the LVDT's themselves attached after first being calibrated. Finally, a comprehensive check of all the components was performed to ensure that the system was ready for testing.

4.7.8 Test System Calibration

Calibration of the system included calibrating the two external LVDT's, calibrating the TestStar controller, and adjusting the rocker beam to create the proper rocking motion. The LVDT's were calibrated along with the conditioner box to an accuracy of plus or minus 0.0001 inches. An MTS calibration wheel was used to perform the procedure. Next, the controller was calibrated so that the LVDT readings matched the measurements the TestStar system was recording. This procedure converted voltage readings to measurements of force and length, allowing the TestStar system to correspond to the LVDT readings. Each LVDT was calibrated to the TestStar system separately, to achieve an output of plus or minus 10 volts. After the LVDT's and the TestStar controller were calibrated, the LVDT's were secured in their stands. They were adjusted in their stands to within plus or minus 0.0003 inches of their mechanical zeroes.

Adjusting the rocker beam to produce the required rocking motion was achieved through a procedure called a "shakedown". Before this process was started, the rocker beam was manually leveled by placing a 4 foot level on the beam and adjusting the load and stroke of the actuators. A "zero" reading was then achieved, meaning the beam was level and no load was applied over the joint. The process of a "shakedown" creates the drive file that tells the system how the loading is to be applied. This process creates rapid, incremental movements of both actuators by sending a high frequency signal through the system. Measured response from this "noise" was used to formulate correction factors needed to generate the correct command signals. During the shakedown procedure, the "noise" sent through the system lasted roughly 39 seconds. Feedback responses from the linear variable displacement transducers (LVDT's) in the actuators were recorded and used to correct the outgoing command signals thereby decreasing the error between the feedback and command signals. Once the signals were corrected sufficiently so that the actual load profile matches the desired load profile of a square waveform, the information was saved. This saved file, called the "drive file" was then played repeatedly to continuously generate the proper commands to produce the required load profile. Now that the rocking motion of the beam was established, LVDT readings were taken when the beam was in its zeroed position. These readings were later used to compute the differential deflection and LTE at a particular point in time.

5. TEST RESULTS – PHASE 2

5.1 Experimental Program

This research studied the load transfer effectiveness and differential deflection on PCC pavements with respect to four test variables. These variables were dowel bar material, dowel bar size, dowel bar configuration, and number of dowels. Repeatability of test details was also analyzed. Although the scope of this research included only four specimens (Table 1-1, Phase 2B), the analysis of data and comparison of test results will include all data from the tests performed in Phase 2 of the Minne-ALF program. Phase 2 included eight tests over a period of two and one-half years as summarized in Table 1-1. The data from the first four tests of Phase 2, i.e., Phase 2A, are results obtained from analysis and testing performed by Trevor Odden [14].

5.2 Data Analysis Procedure

The data collected for each dowel bar detail was summarized in a graphical format expressing both differential deflection and LTE with respect to the number of applied cycles. Automatic data points, as well as data points taken manually, used in the Phase 2A tests and explained in Section 3.3, were used in the analysis of the Phase 2B tests as well. Each data point consists of a set of 800 lines of data. For every 800-line set of data, four graphs depicting approach LTE, leave LTE, differential deflection, and the load profile were produced. These graphs were used to verify that the collected data was correct. The ‘approach’ and ‘leave’ sides of the slab correspond to the slab portions on either side of the joint in relation to the moving direction of 9-kip unidirectional load. With the 9-kip load being applied to the slab from West to East, the approach side of the slab is the West side and the leave side is the East side.

From each 800-line data set, the recorded data showed the 9-kip unidirectional load crossing the joint three times. At each of these three times, two lines of data were used corresponding to two values of load, differential deflection, and LTE. The values from each line were computed and averaged using Equations 2-1 and 2-4. The lines of data were chosen to correspond to the instant in time when the 9-kip load was 6 inches away from the joint on the approach side. This was done in order to be consistent with the positioning of the load plate when field testing using a Falling Weight Deflectometer (FWD). Using the averaged values of load, differential deflection, and LTE from each of the three times the 9-kip load acted on the joint within a data set, the final averaged values were plotted as one point for LTE and one point for differential deflection. This process was continued for each 800-line data set until a representative number of data points was achieved. The computed averaged points were plotted on two semi-log graphs; one for differential deflection vs. number of applied load cycles, and another for LTE vs. number of applied load cycles. Table 5-1 provides a summary of test results for the slabs tested within the scope of this research (Phase 2B). Table B-1 located in Appendix B summarizes data included in the analysis but represents dowel bar details tested in the first portion of this project by Trevor Odden [14].

Table 5-1: Summary of Differential Deflection and Load Transfer Efficiency for Slabs 7 Through 10 (Phase 2B)

	Slab 7 Two, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover		**Slab 8** Three, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover		**Slab 9** Two, 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, 2 inches clear cover		**Slab 10** Three, 1.75 inch diameter, 15 inch long, fiber reinforced polymer dowels, mid-depth placement	
Applied Cycles (Millions)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)
0.00005			1.2	94			1	95
0.0001	2.7	95	1.5	93	2.1	96		
0.001	2.6	96	1.4	95	2.2	95	1.1	95
0.002	2.7	96	1.8	95	2.2	96		
0.005	3.1	96	2.1	92	2.6	95		
0.01	3.2	96			2.6	91		
0.02	3.7	93	1.9	92	2.6	95	1.17	95
0.05	3.3	95	1.9	92	3.1	93	1.2	95
0.1	4.7	95	2.1	93	2.9	96	1.2	95
0.3	5.2	95	2.5	94	3.4	96	1.46	93
0.4								
0.5			1.9	91				
0.6	5.5	94	1.8	92	4.4	95	1.9	91
0.7								
0.8			2	93				
1.2	5.8	94			4.4	94	2.1	92
1.5			2.6	94				
1.8	6.5	97			5.1	95	2	92
2			2.3	94				
2.4	8.5	97	2.5	93	5.9	94		
2.9								
3		92	1.9	93		94	2.2	92
3.3							2.4	93
3.6		93	2.4	92		92	2.3	92
4.2	10.3	92	3	91	8.1	91	2.5	89
4.8	11.0	94	3	92	8.9	91	2.5	90
5.4	11.1	94			9.2	92	2.7	90
6	11.1	94			9.5	91	2.5	89
6.2								
6.4			2	93				
6.6							2.8	90
6.7			2.8	92			2.9	90

Experimental observations and test data for each of the four slab specimens tested in Phase 2B are reported in this chapter. This information is presented in a discussion of the principal experimental variables in this study. For each experimental variable, the discussion compares and contrasts the performance of two or more slabs that either (1) differ only in the choice of the variable being studied (e.g., dowel bar type or material), or (2) are replicate specimens. The discussion also includes any pertinent observations that were drawn from the visual inspection of the specimens.

5.3 Effects of Changing Dowel Bar Configuration

Elements of the dowel bar configuration which were varied included the amount of clear cover and the number of dowels in a given slab specimen. Each of these variables was analyzed separately. The dowel bar details designated with (2B) were tested within the scope of this research, while the remaining data, denoted (2A), is previously performed research conducted by Odden [14]. The performance of each dowel bar connection detail was evaluated based on LTE, differential deflection, and visual observations.

5.3.1 Changing Clear Cover

The effects of changing the amount of clear cover for dowel bars placed in a 7.5-inch thick PCC pavement was determined from the performance of three dowel bar details. Two of the details, Slab 1 and Slab 5-6, were tested by Odden [14] and the third detail, Slab 8, was tested as part of the present research. Slab 8 in Phase 2B was a replicate of Slab 5-6 in Phase 2A. Two of the details, Slab 5-6 and Slab 8, had clear cover of 2 inches, while the remaining detail, Slab 1, had 3 inches of clear cover. All three details contained three, 15 inch long, 1.5 inch diameter, epoxy-coated mild steel dowels.

5.3.1.1 Load Transfer Efficiency

Figure 5-1 represents graphically the LTE obtained from the tests of the three dowel bar details, Slab 1, Slab 5-6, and Slab 8, with respect to applied load cycles. From Figure 5-1, it can be concluded that there is not a significant effect on load transfer efficiency when comparing mid-depth placement of dowels (3 inches clear cover) to a shallower placement (2 inches clear cover). The dowel bar detail (Slab 1) with 3 inches of clear cover did, however, perform slightly better than the details placed with 2 inches of cover.

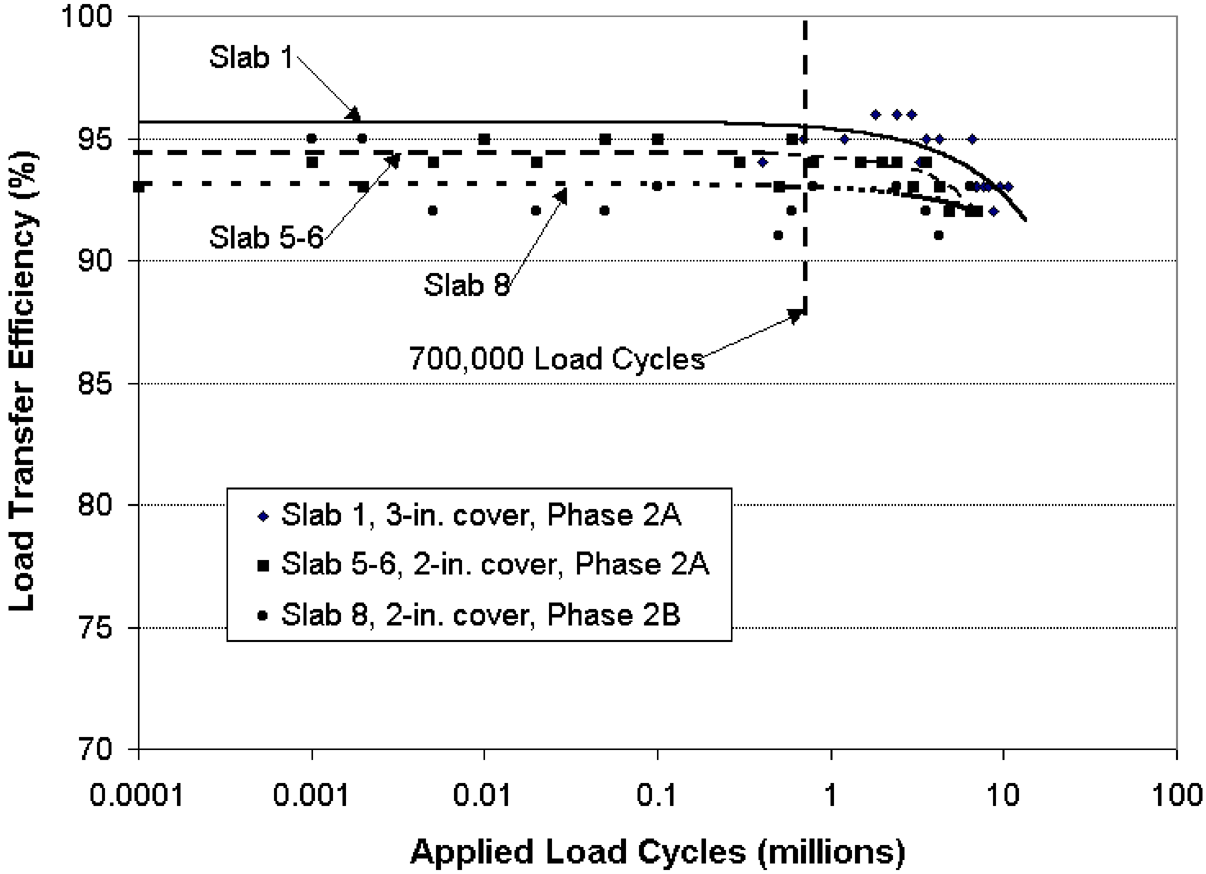

FIGURE 5-1: LTE EFFECTS OF CHANGING AMOUNT OF CLEAR COVER

Decreases in LTE were noted for all three details beginning at approximately 700,000 cycles. Regardless of the amount of clear cover over the dowel bars, the decline in LTE was observed at nearly the same number of applied load cycles. This observation suggests that changing the depth of placement of the dowels, from 2 to 3 inches, is not a factor in determining when the load transfer efficiency starts to drop significantly. Therefore, the mechanism causing a reduction in LTE can be attributed to either a deterioration of the dowel bars after a given number of load cycles, or, more likely, crushing and deterioration of the concrete around the dowel bars, or a combination of the two. Stresses in the cover concrete away from the concrete-dowel interface do not appear to affect LTE.

From inspections of the dowel bars and dowel bar slots after testing was complete, no apparent deterioration of the epoxy-coated mild steel dowel bars was found. Based on core samples taken of the dowel bars and slots, the backfill material in all three test specimens was found to be well consolidated. Determinations regarding crushing of the backfill concrete material at the smooth formed joint were found to be inconclusive. The coring and inspection process proved to be difficult and thus yielded no useful information concerning crushing of concrete as an explanation for declining LTE.

Testing of Slab 1 (Figure 5-1) was continued past the standard test duration of 6.7 million cycles, as per request of MnDOT. This explains the seemingly more pronounced drop in LTE for that specimen. The continued decline in LTE after 700,000 cycles is relatively minor when considering the partial failure criteria for the dowel bar is defined as LTE dropping below 70 percent. Overall, the specimens exhibited similar rates of decline with regard to LTE. After 6.7 million cycles all three specimens continued to perform with load transfer efficiencies above 91 percent.

5.3.1.2 Differential Deflection

The differential deflection performance of the dowel bar details mentioned above (Slabs 1, 5-6 and 8), relative to changing clear cover, are presented here. Figure 5-2 represents graphically the results obtained for the three dowel bar details in terms of differential deflection vs. applied load cycles.

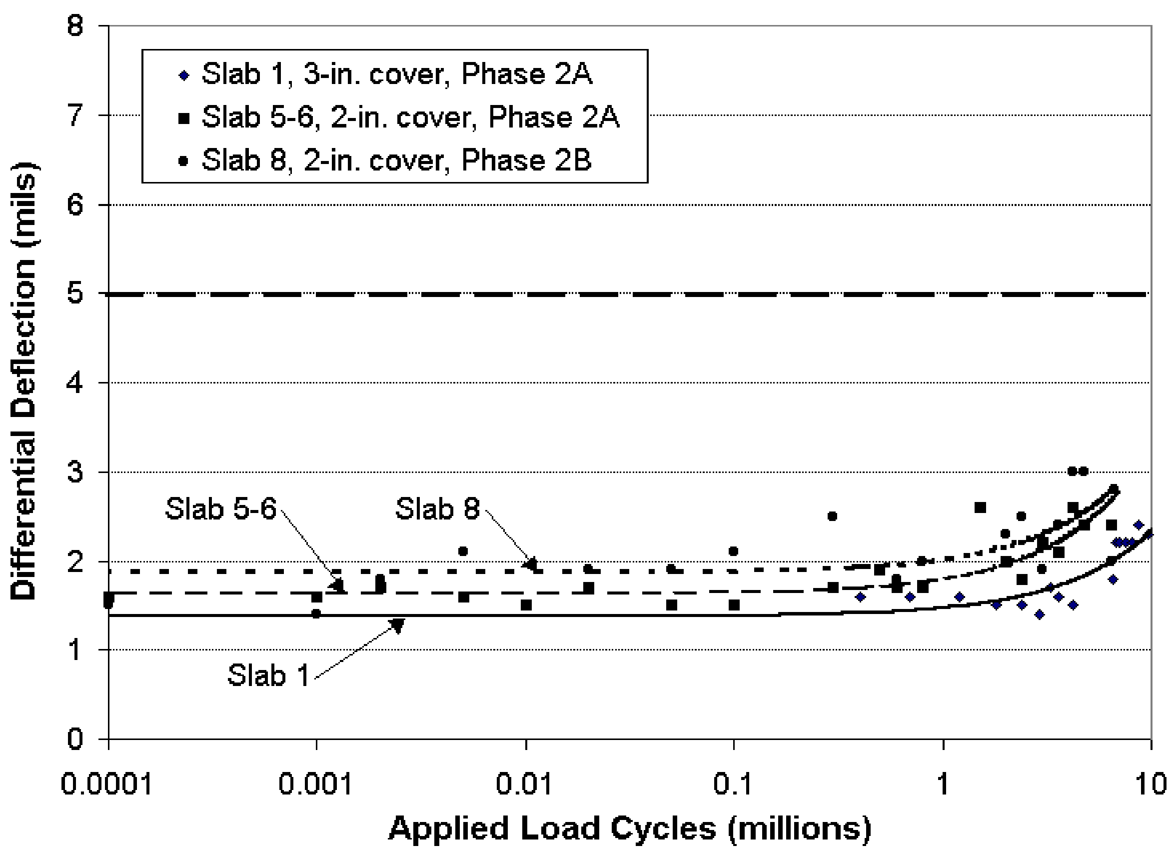

FIGURE 5-2: DIFFERENTIAL DEFLECTION EFFECTS OF CHANGING AMOUNT OF CLEAR COVER

The performance trends for differential deflection vs. applied load cycles were qualitatively similar to those found for LTE. The dowel bar details tested with two inches of clear cover resulted in slightly higher differential deflections than the detail tested with three inches of cover. From Figure 5-2, all three specimens exhibited differential deflections ranging from 1.4 mils to 3 mils throughout the duration of the 6.7 million applied load cycles. The three specimens in Figure 5-2 were well below the partial failure criteria of developing more than 5 mils of differential deflection. Slab 1 Phase 2A, with a dowel bar configuration placed with 3 inches of clear cover resulted in the lowest differential deflections. Slab 5-6 Phase 2A and slab 8 Phase 2B, which both used 2 inches of clear cover over the dowels, had increasingly larger overall differential deflections. Similar to the LTE results, after approximately 700,000 load cycles, more differential deflection was observed for all slab specimens.

There is a quantitative difference in the differential deflection performance of Slabs 1, 5 and 8 relative to LTE performance. This difference has to do with the magnitude of change in these parameters relative to the corresponding acceptable ranges for LTE and differential deflection. Whereas Slabs 1, 5 and 8 had exhausted only 30% of their useful LTE capacity by the end of the tests (i.e., the LTE's were never less than 91% relative to the LTE failure threshold of 70%, or (100 – 91) / (100 – 70) = 0.30 = 30%), all three specimens lost at least 50% of the useful range of differential deflection (i.e., differential deflection increased to at least 2.5 mm relative to the failure threshold of 5 mm, or (5 – 2.5) / (5 – 0) = 0.5 = 50%). This difference does not signify different deterioration modes for these two parameters, but rather different rates in their evolution.

As discussed more thoroughly in Section 5.3.1.1, the possible causes for the increases in differential deflections are dowel bar deterioration, crushing of the concrete near the joint and around the dowels, or both. Since the different dowel bar configurations, regardless of the amount of clear cover, exhibited very similar rates of increasing differential deflection after roughly the same number of applied load cycles, the amount of cover is, therefore, not considered a factor in the observed increasing differential deflections.

It can be concluded that dowels placed at mid-depth (i.e., 3 inches of clear cover) do not outperform, in terms of smaller differential deflections, dowels placed in a shallower configuration (e.g., 2 inches of cover) in a 7.5-in. thick PCC pavement over a 6.7-million cycle lifespan. Based on the observed LTE's and differential deflections, dowel bars placed with 2 inches of clear cover can be an effective means to reduce retrofit costs. Less material is removed, thus saving time and disposal costs. Retrofit projects will also require smaller amounts of backfill material, which is particularly important for large retrofit projects.

5.3.2 Varying Number of Dowels

This section discusses the effects on LTE and differential deflection of reducing the number of dowel bars from 2 bars to 3. In the 2-dowel configuration, the bar furthest from the critical dowel is eliminated. Four specimens were tested which are used for study of the effect of number of dowel bars as described in Table 1-1; Slab 5-6 from

Phase 2A, and Slabs 7, 8, and 9 from Phase 2B. The dowels were 15-in. long, 1.5-in. diameter, epoxy-coated mild steel dowels, and all four dowel bar details used 2 inches of clear cover. Two specimens were replicate details (i.e. Slab 8 was a replicate of Slab 5-6, and Slab 9 was a replicate of Slab 7) that were included to verify the consistency of the test results. Three of the dowel bar details were tested within the scope of the present investigation (Phase 2B), while the fourth was tested as part of the previous phase of the research, i.e. Phase 2A conducted by Odden [14].

5.3.2.1 Load Transfer Efficiency

The performance of the four dowel bar details, as indicated by measured LTE, did not vary significantly as the number of dowel bars were reduced from 3 to 2 as indicated in Figure 5-3. At the onset of testing, load transfer efficiencies ranged from 93 percent to 96 percent. The specimens containing 2 dowels (Slabs 7 and 9 from Phase 2B) performed slightly better than the details with 3 dowels (Slabs 5-6 from Phase 2A and 8 from Phase 2B). However, the differences in LTE between the specimens were very small, on the order of 1 to 3 percent. As with other specimens, load transfer efficiencies started to decline for all specimens nearing 1 million applied load cycles. But, this decline was relatively minor as well, with final recorded LTE values ranging from 91 percent to 94 percent. All the details (Slabs 5-6, 7, 8, and 9) were well above the partial failure criterion of 70 percent LTE.

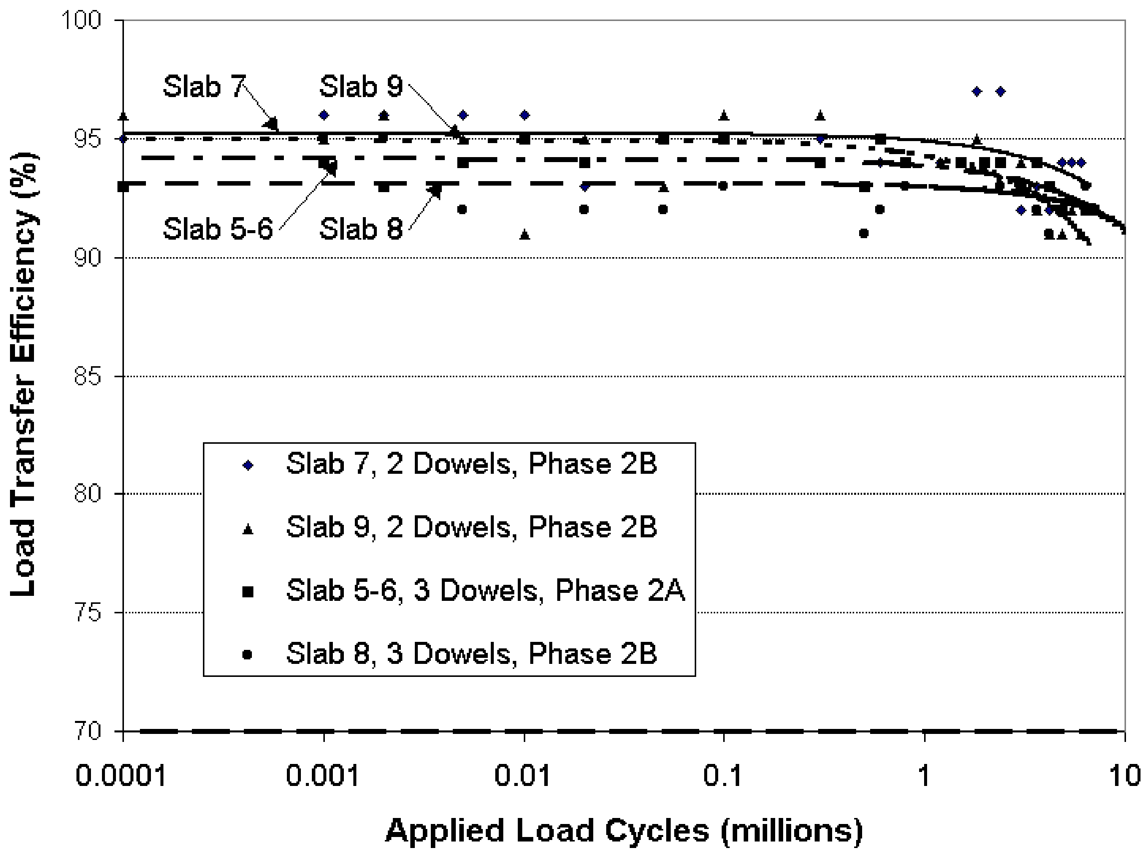

FIGURE 5-3: LTE EFFECTS OF CHANGING THE NUMBER OF DOWEL BARS

The performance of the dowel bar details as measured by load transfer efficiency does not appear to be greatly affected by reducing the number of dowel bars. Since the dowel bar details containing 2 dowels performed as well or better than the details with 3 dowels, with respect to LTE, it is concluded that reducing the number of dowels may be an effective cost saving measure. It is important, however, to consider LTE along with differential deflection (discussed in the following section) in order to make conclusive determinations as to the performance of the specimens.

5.3.2.2 Differential Deflection

The differential deflections of the specimens with varying number of dowel bars are shown in Figure 5-4. While the LTE results remained consistently high for all 4 specimens during the testing (Section 5.3.2.1), the differential deflections showed significant variations. The two details containing 3 bars (Slab 5-6 and Slab 8) exhibited relatively low differential deflections throughout test duration, with slight increases in differential deflections beginning at 700,000 load cycles and continuing thereafter. Moreover, maximum differential deflections for the specimens containing 3 dowels never exceeded 3 mils, which is well below the differential deflection failure criterion (5 mils).

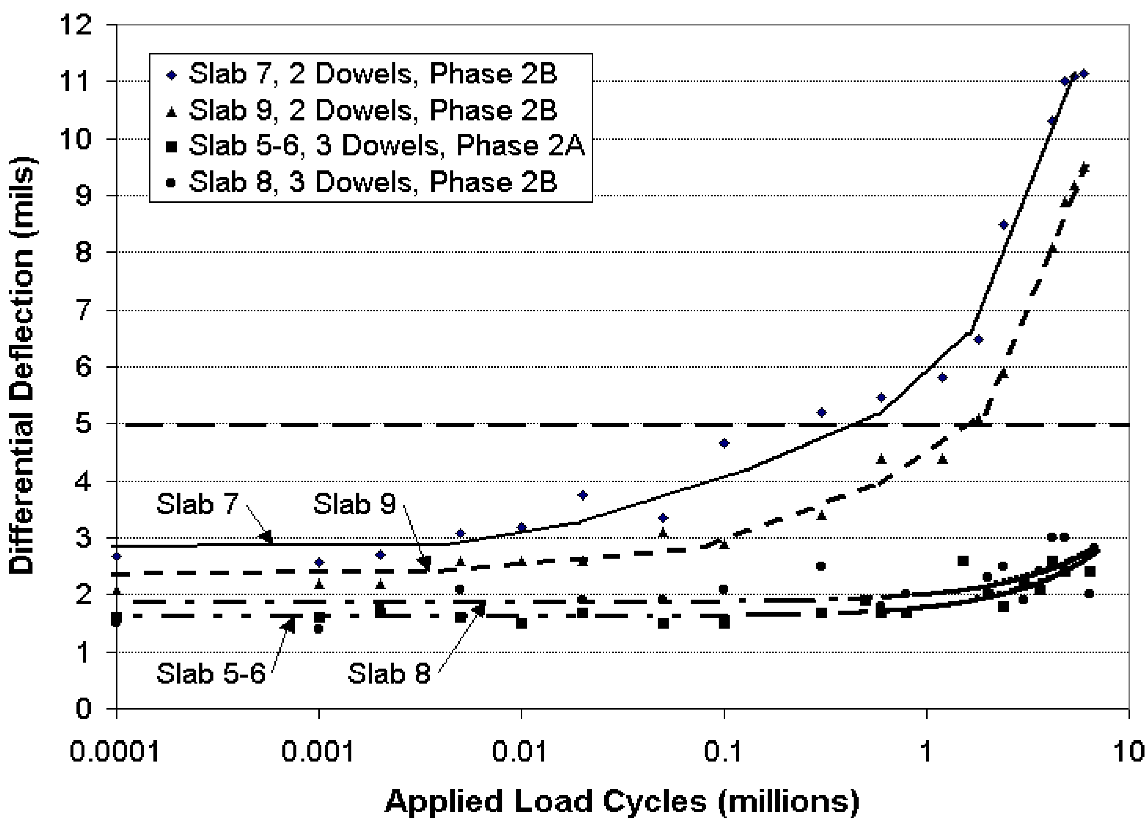

FIGURE 5-4: DIFFERENTIAL DEFLECTION EFFECTS OF CHANGING THE NUMBER OF DOWEL BARS

Conversely, the two slab specimens retrofitted with only 2 dowel bars (Slab 7 and Slab 9) attained much larger differential deflections over the duration of testing. Both specimens exhibited very similar rates of increasing differential deflections. Dowel bar details for Slab 7 and Slab 9 in Figure 5-4 initially produced differential deflections between 2 and 3 mils. Near 5,000 cycles of applied load, both specimens began to show an increasing trend in differential deflection. At roughly 400,000 load cycles, Slab 7 was undergoing differential deflections larger than 5 mils (i.e., the partial failure criterion for differential deflection). Slab 9 crossed the 5 mil differential deflection limit at about 1.5 million load cycles. Both specimens then continued to show rapidly increasing differential deflections throughout the duration of the tests until their conclusion at 6.7 million applied load cycles. Slab 7 dowel bar detail ended with a final differential deflection of 11.1 mils, while Slab 9 finished slightly lower with 9.5 mils differential deflection.

Based on the differential deflection results in Figure 5-4, the use of 2 epoxy-coated mild steel dowel bars resulted in significantly higher differential deflections as more load cycles were applied. In conclusion, specimens containing 2 dowels are more flexible than slabs retrofitted with 3 dowels, whereas the latter demonstrated consistently good LTE and differential deflections throughout the duration of testing.

5.4 Effects of Different Dowel Bar Materials

Different dowel bar materials were tested to determine their performance potential over time. The performance of the different dowel bar materials tested was evaluated through comparisons of differential deflection, LTE, and visual inspections. Data from three of the dowel bar details compared here were reported by Odden [14] in Phase 2A. The remaining dowel bar detail in this material comparison was tested as part of this research.

Three different dowel bar materials in four different retrofit designs were tested. These specimens (Table 1-1) include Slabs 1, 2, and 3-4 from Phase 2A [14], and Slab 10 from Phase 2B. Three dowel bars were retrofitted in each specimen. Slab 2 and Slab 10 contained 15-inch long fiber reinforced polymer (FRP) dowels. The dowels used for Slab 2 had a 1.5-in. diameter, whereas those in Slab 10 were 1.75-in. diameter. Slab 1 contained 15-inch long epoxy coated mild steel dowels with a 1.5 in. diameter, and Slab 3-4 was retrofitted with grouted stainless steel tube dowels. Slab 1 was tested to 10.5 million cycles due to initial problems with the data acquisition system. Testing of Slab 3-4 was continued to 13.5 million cycles at the request of the funding agency (Mn/DOT).

5.4.1 Load Transfer Efficiency

Figure 5-5 shows the performance of the different dowel bar materials with respect to load transfer efficiency. Slab 1, containing epoxy coated mild steel dowels, and Slab 3-4, containing grouted stainless steel tube dowels, demonstrated very similar load transfer efficiencies through about 8 million load cycles. Slab 3-4, however, shows a significant drop in LTE after 8 million load cycles. The grouted stainless steel tube dowel performed as well as the epoxy coated solid steel dowel up to 8 million cycles, but afterwards the performance of the former began to deteriorate faster.

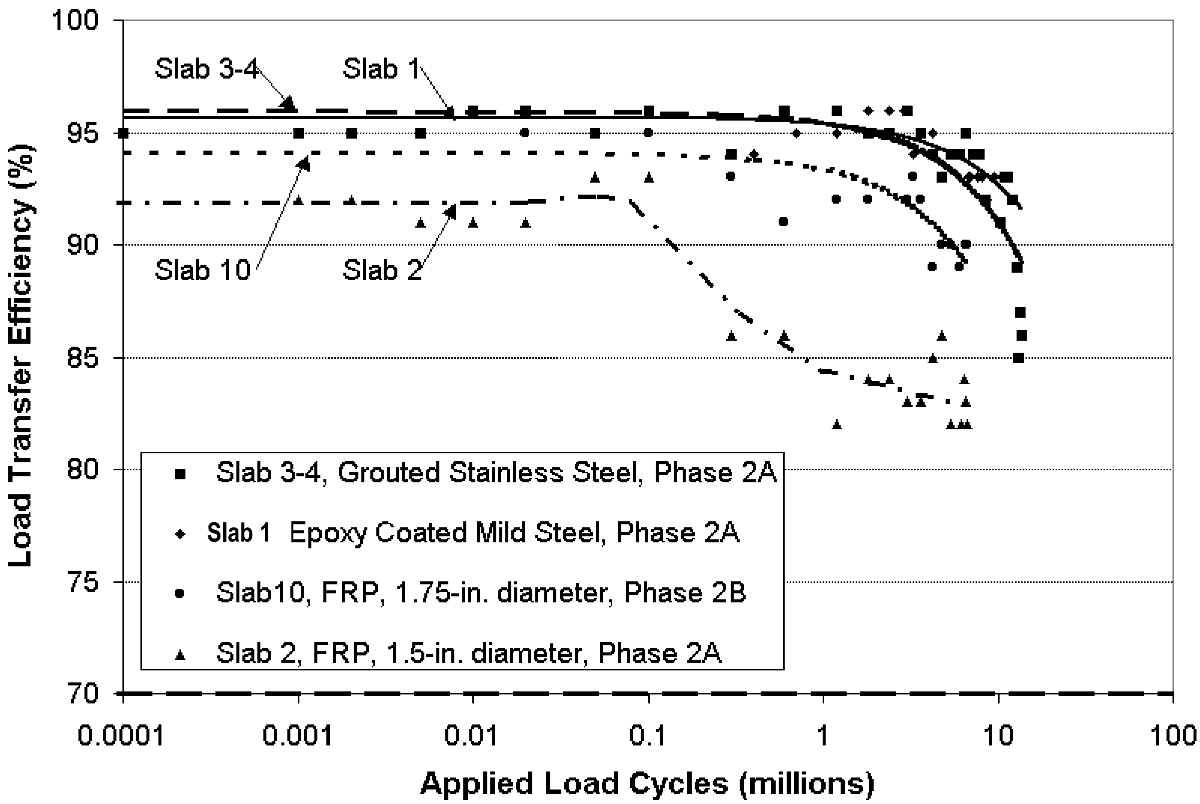

FIGURE 5-5: LTE COMPARISON OF DOWEL BAR MATERIALS AND FRP DIAMETER

The specimens containing FRP dowels (Slab 2 and Slab 10) performed with lower LTEs than Slabs 1 and 3-4. Slab 2, containing FRP dowels with a diameter of 1.5 inches, showed a significant drop in LTE after 100,000 load cycles after starting with a nearly constant LTE of 92 percent. The magnitude of this drop was not seen in any of the other dowel bar materials tested. The performance of the FRP dowels is due to the lower stiffness of the dowels, since the FRP has a lower modulus of elasticity than steel.

The increased diameter of the FRP dowel bars in slab 10, as compared to slab 2, compensates for the decreased stiffness of the FRP material. With larger diameter dowels, Slab 10 shows comparable LTE performance to grouted stainless steel tube dowels in terms of the rate at which LTE deteriorates with increasing cycles of load. However, the consistent difference in the magnitude of LTE between Slab 10 and Slab 3-4 (i.e., about 2%) suggests that the grouted stainless steel is marginally better. The FRP dowels need to have a diameter slightly larger than 1.75 in. if they are to match the performance of the grouted stainless steel tube dowels or the epoxy coated solid steel dowels.. Both FRP specimens, however, were still above the partial failure criterion of 70 percent LTE upon the completion of testing.

Figure 5-5 also can be used to compare the LTE performance of the two specimens containing FRP dowels, Slabs 2 and 10. Slab 2 performed with LTE values at about 92 percent through 100,000 applied load cycles. Between the automatic data points of 100,000 cycles and 300,000 cycles, the LTE of Slab 2 dropped from 93 percent to 86 percent. LTE values continued to decline, but at a slower rate, ending with 82 percent LTE at 6.7 million applied load cycles.

Since FRP dowels have a lower stiffness than standard epoxy-coated mild steel dowels (Modulus, E, for steel is 29,000 ksi, vs. E for FRP of 5,600 ksi), Slab 10 was tested with larger diameter dowels (1.75 inches) to compensate for the effects of reduced stiffness. The larger 1.75 in. diameter dowels were chosen based on final recommendations by Odden in Phase 2A [14]. By applying the theoretical model for determining differential deflection of a doweled PCC joint developed by Timoshenko and Friberg, a slightly larger diameter FRP dowel (larger than 1.75 in.) is necessary in order to match differential deflections produced from 1.5-in. diameter epoxy-coated mild steel dowels.

Combining Timoshenko's deflection equation and Friberg's bending moment equation, results in the theoretical differential deflection equation (Equation 5-1 below) [21, 14]. From Equation 5-1, an FRP dowel with a diameter of about 1.9 inches is needed for the theoretical differential deflections of FRP and epoxy-coated mild steel dowels to be equal. The performance of both slab specimens, Slab 2 (1.5-in. diameter FRP) from Phase 2A and Slab 10 (1.75-in. diameter FRP) from Phase 2B, correlate well with the theoretical differential deflection from Eqn. 5-1 [14].

$$y_0 = \frac{P_t}{4\beta^3 EI}(2 + \beta z) \qquad \text{Eqn. (5-1)}$$

Defining

$y_0 = \textit{Deflection of the dowel at the joint}$
$z = \textit{Width of joint opening}$
$P_t = \textit{Transferred load}$
$E = \textit{Dowel modulus of elasticity}$
$I = \textit{Dowel moment of inertia}$
$\beta = \textit{Relative stiffness of dowel embedded in concrete}$

Where:

$$\beta = \sqrt[4]{\frac{Kb}{4EI}} \qquad \text{Eqn. (5-2)}$$

Defining:

$K = \textit{Modulus of dowel support}$
$b = \textit{Diameter of dowel}$

The ability of the FRP dowel bar to transfer load was increased with an increase in dowel bar diameter. Bearing stresses decrease with an increase in contact area between the dowel and concrete. Slab 10 exhibited load transfer efficiencies near 95 percent through

100,000 cycles. A more gradual decrease in LTE was then observed after 100,000 load cycles, until completion of testing at 6.7 million cycles. The increase in dowel bar diameter, from 1.5 inches to 1.75 inches, resulted in higher LTE values through the duration of the test. The performance of Slab 10, evaluated based on LTE, is comparable to standard epoxy-coated mild steel dowels.

5.4.2 Differential Deflection

Figure 5-6 shows the results of changing dowel bar materials evaluated through differential deflection measurements. Three of the specimens tested (Slabs 1, 3-4, and 10) performed with similar levels of differential deflection through 1 million load cycles. Varying rates of increasing differential deflections were observed after 1 million cycles.

Slab 1, Slab 3-4, and Slab 10, all exhibited differential deflections between 1.1 and 1.5 mils up to 1 million load cycles. Slab 1, containing epoxy-coated mild steel dowels, continued to perform with differential deflections near 1.4 mils until 3.3 million load cycles and ended with maximum differential deflections of 2.4 mils after 10.5 million cycles. Slab 3-4, using grouted stainless steel dowels, and Slab 10, containing 1.75-inch diameter FRP dowels, performed with similar rates of increasing differential deflections after 1 million load cycles. A rapid increase in differential deflections was noted for Slab 3-4 after the standard testing cut-off point of 6.7 million load cycles. Maximum differential deflections of nearly 6 mils were observed upon the completion of testing at 13.5 million cycles for Slab 3-4.

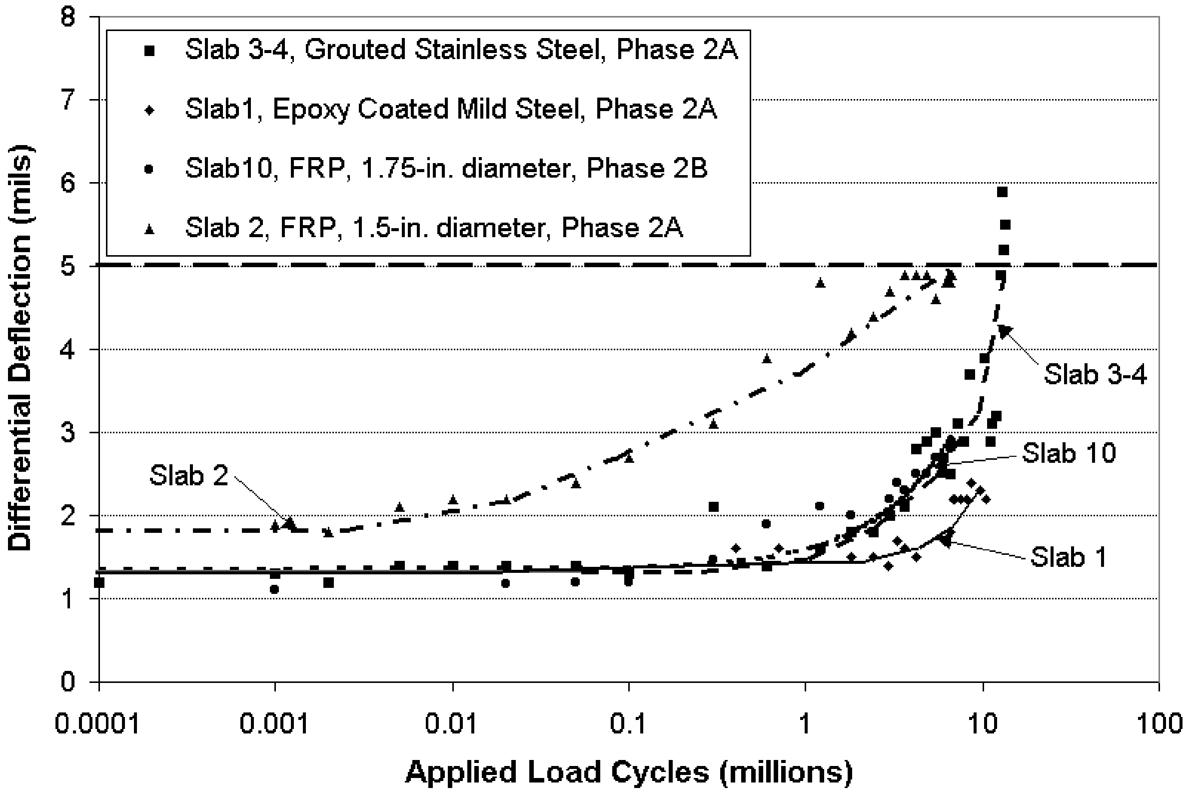

Figure 5-6: Differential Deflection Comparison of Dowel Bar Materials And FRP Diameter

Slab 2, containing 1.5-inch diameter FRP dowels, performed with the highest differential deflections. With initial differential deflections on the order of 2 mils, a nearly linear increase in differential deflections, with respect to the logarithm of the number of cycles, was observed from 1,000 load cycles until completion of testing at 6.7 million load cycles. Keeping all other variables constant, it can be concluded that specimens containing 1.5-inch diameter FRP dowels result in the least desirable differential deflection readings of all the types of dowels tested. However, based on the results of Slab 10, which contained 1.75-inch diameter FRP dowels, by increasing the diameter of the FRP dowels, comparable differential deflection performance to those observed for the other dowel materials were obtained.

Figure 5-6 also compares the performance of the two FRP specimens, Slab 2 and 10, with respect to differential deflection. Similar to the LTE results for Slab 2 and Slab 10, the larger diameter dowels in Slab 10 outperformed the smaller diameter dowels in Slab 2. Upon the completion of testing, differential deflections for Slab 2 approached the partial failure criterion of 5 mils.

The larger diameter dowels in Slab 10 performed with differential deflections less than 1.5 mils through 300,000 cycles. Differential deflection values then gradually increased, with final values less than 3 mils. Based on the performance from both LTE and differential deflection analysis, it is evident that larger diameter FRP dowels (1.75 inch) perform with higher LTEs and lower differential deflections than standard 1.5-inch diameter FRP dowels. An increase in bar diameter is needed for FRP dowels to perform as well as epoxy-coated mild steel dowels and grouted stainless steel tube dowels.

5.5 Comparison of Replicate Specimens

Replicate specimens for two dowel bar configurations were tested to confirm the experimental observations obtained from the original specimens. Replicate specimens were also tested to assess repeatability of previously tested designs. All the specimens used, 15-in. long, 1.5-in. diameter, epoxy-coated mild steel dowels. Two inches of clear cover was also used for each retrofit design. Slab 5-6 was tested in the previous phase of this research program (Phase 2A) by Odden [14] and the remaining three specimens were tested within the scope of this research. Slab 8 was a replicate of Slab 5-6, using three dowel bars in each detail. Slab 9 was a replicate of Slab 7, each containing 2 dowel bars in each specimen. This section compares each replicate specimen to the original dowel bar detail with respect to both load transfer efficiency and differential deflection.

5.5.1 Replicate One

The first replicate detail tested was Slab 8, which was a replicate of Slab 5-6. The specimens used 3 dowel bars with 2 inches of clear cover. The dowel bars were positioned in the standard configuration; the critical dowel placed 6 inches from the edge of the slab, with the next two dowels placed 12 inches on center from the previous one. A comparison of Slab 8 to Slab 5-6 is presented here.

5.5.1.1 Load Transfer Efficiency

Figure 5-8 presents graphically the results for Slabs 8 and 5-6 with respect to LTE. The performance of Slab 8 closely matched the performance of Slab 5-6. Figure 5-8 indicates that only a 1 percent difference in LTE was found throughout the majority of the tests, with Slab 5-6 performing slightly better at 95 percent LTE. After 2.4 million load cycles, Slab 5-6 began to decline in LTE at a faster rate than Slab 8. Upon completion of testing at 6.7 million cycles, both specimens exhibited LTE values near 92 percent. Based on the data shown in Fig. 5-8, the accuracy of the results for Slab 5-6 are confirmed by the close agreement with the data for the repeat test of Slab 8.

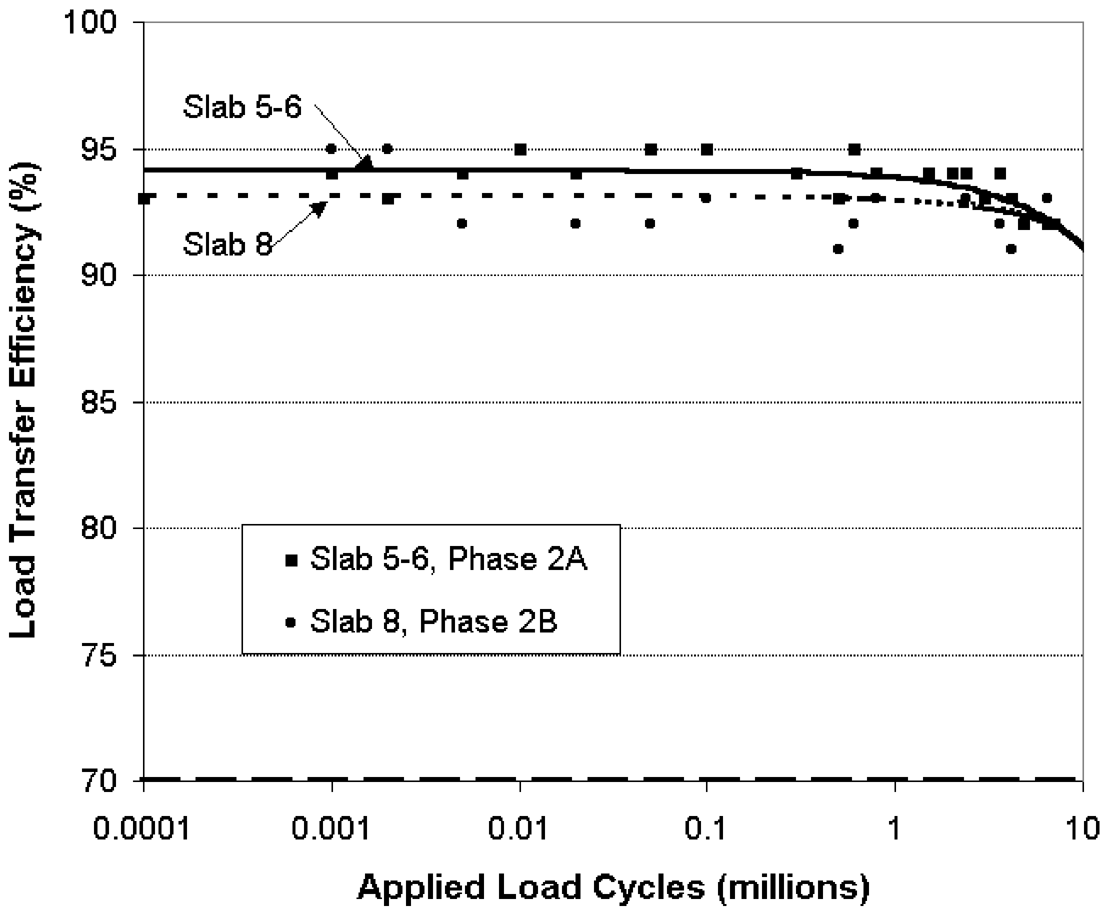

FIGURE 5-8: LTE COMPARISON OF REPLICATE SPECIMENS (3 DOWELS, 2 INCHES COVER)

5.5.1.2 Differential Deflection

Figure 5-9 presents graphically the results for Slabs 8 and 5-6 with respect to differential deflection. The results for differential deflection were similar to those found for load transfer efficiency in the previous section. Slab 8 performed with slightly higher differential deflections than the original specimen, Slab 5-6. Differential deflections for both specimens remained between 1.5 and 2.5 mils through 1 million load cycles. Relatively slow increases in differential deflections were then observed after 1 million load cycles until completion of testing at 6.7 million cycles. The rate of increase for both specimens was nearly identical. Slab 5-6 ended with maximum differential deflections of 2.6 mils, while Slab 8 reached 3 mils. Both specimens were below the partial failure criterion of 5 mils differential deflection at the end of the test.

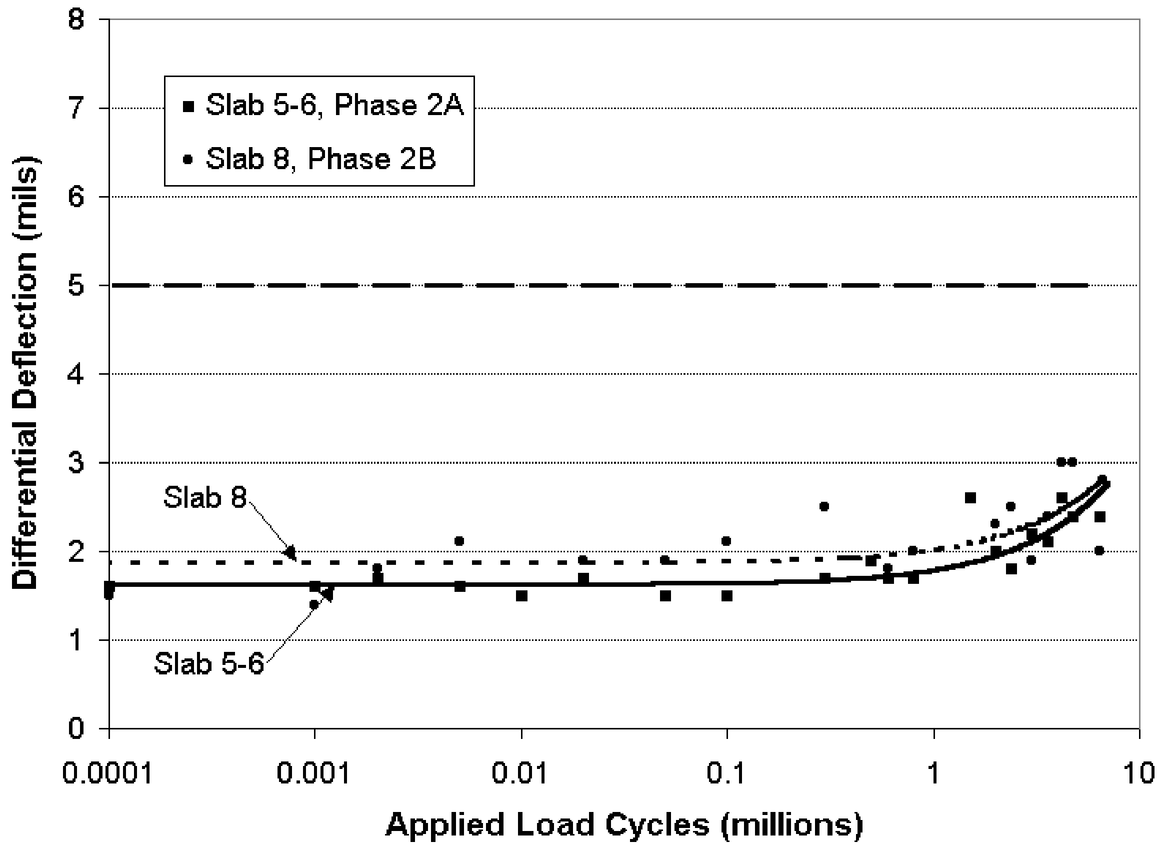

FIGURE 5-9: DIFFERENTIAL DEFLECTION COMPARISON OF REPLICATE SPECIMENS (3 DOWELS, 2 INCH COVER)

The small differences in LTE and differential deflection between the original specimen (Slab 5-6) and the replicate specimen (Slab 8) can most likely be attributed to inherent differences in the retrofit and testing processes. Although all specimens were examined after testing for proper backfill consolidation and found to be well consolidated, small differences in compaction and placement of dowels in the slots may contribute to the slightly less desirable performance of Slab 8. However, the differences are very small, indicating excellent repeatability for these specimens.

5.5.2 Replicate Two

The second replicate detail tested was Slab 9, which was a replicate of Slab 7. The specimens used 2 dowel bars with 2 inches of clear cover. The dowel bars were positioned in the standard configuration using 2 dowels; the critical dowel placed 6 inches from the edge of the slab, with the next dowel placed 12 inches on center from the previous one. A comparison of the performance of Slabs 9 and 7 is presented here.

5.5.2.1 Load Transfer Efficiency

Figure 5-10 presents graphically the results for Slab 7 and Slab 9 with respect to LTE. The performance of Slab 9 was nearly identical to the original specimen, Slab 7. Both specimens performed with load transfer efficiencies near 95 percent through 600,000 applied load cycles. Slab 9 exhibited a faster decline in LTE after 600,000 load cycles. Slab 7 and Slab 9 ended the tests with LTEs of 92 and 91 percent, respectively. The comparable performance with respect to LTE of the replicate specimen (Slab 9) to the original specimen (Slab 7) confirms the accuracy of results for this dowel bar detail.

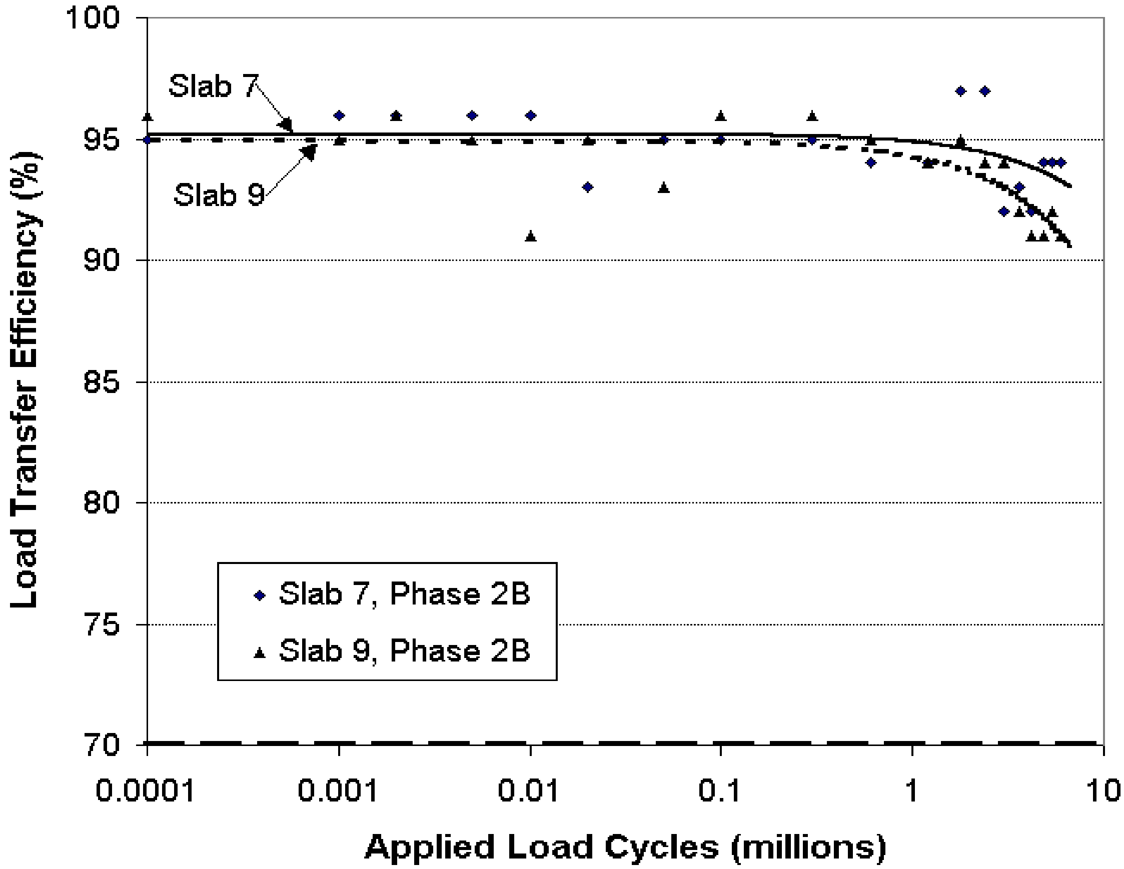

FIGURE 5-10: LTE COMPARISON OF REPLICATE SPECIMENS (2 DOWELS, 2 INCH COVER)

5.5.2.2 Differential Deflection

Figure 5-11 graphically presents the results for Slab 7 and Slab 9 with respect to differential deflection. The replicate specimen, Slab 9, performed at the same rate of increasing differential deflection as the original specimen, Slab 7. Both Slab 7 and Slab 9 began with differential deflections between 2 and 3 mils until 5,000 load cycles. Slab 9 maintained slightly lower differential deflection readings throughout the duration of testing. The 2 inches of clear cover and use of 2 bars resulted in more flexible specimens. Near 1 million load cycles, both specimens exceeded the partial failure criterion of 5 mils differential deflection. The consistency of results between Slab 7 and Slab 9 confirm the accuracy in measured performance of LTE and differential deflection.

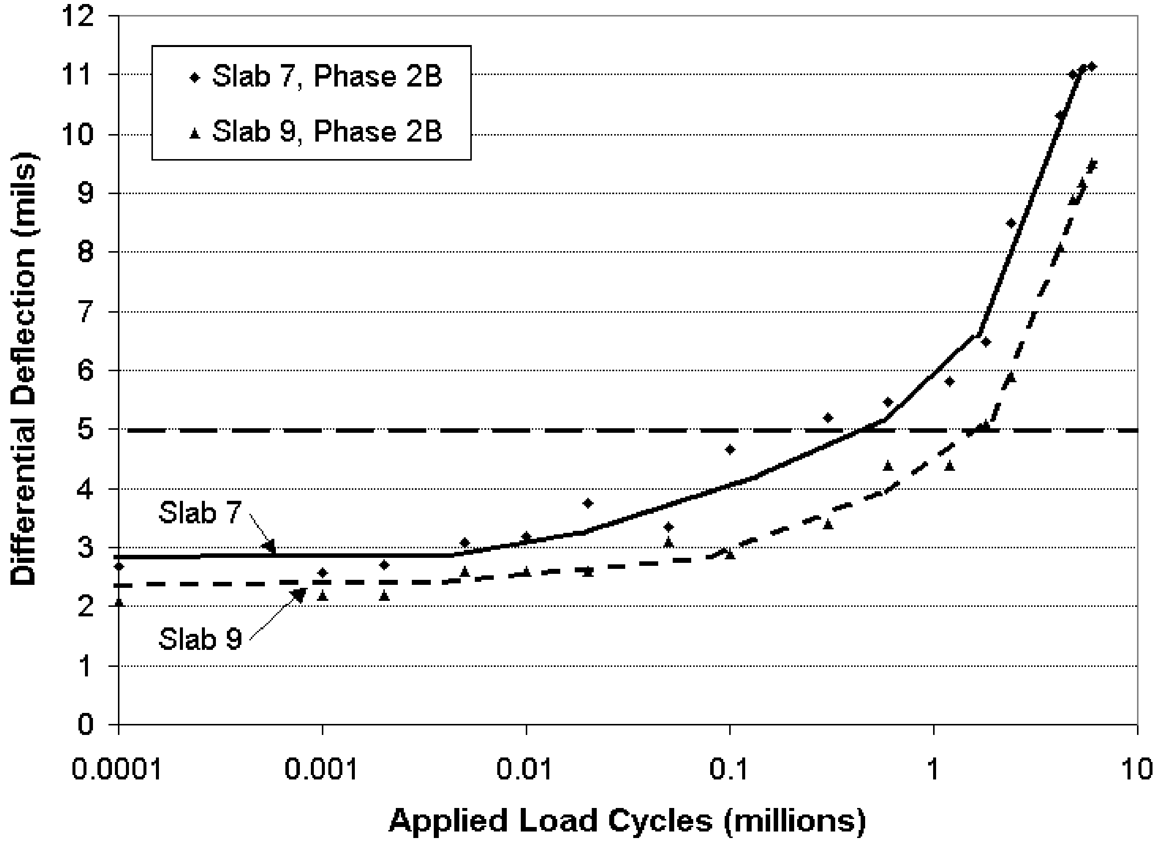

FIGURE 5-11: DIFFERENTIAL DEFLECTION COMPARISON OF REPLICATE SPECIMENS (2 DOWELS, 2 INCH COVER)

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

Phase 2B of the Minne-ALF test program consisted of evaluating four dowel bar retrofit details. The Minne-ALF facility provided the means to evaluate dowel bar details in an accelerated manner to address the issues of high retrofit costs and corrosion susceptibility. The details tested in Phase 2B verified results obtained in Phase 2A and provided additional performance data on mild steel epoxy-coated dowels and FRP dowels. Analysis was conducted based on the performance measures of LTE and differential deflection, in order to further evaluate the effects of dowel bar material, dowel bar size, dowel bar configuration, and number of dowels.

6.2 Conclusions

- Reducing the number of mild steel epoxy-coated dowels from 3 to 2 has a significant effect on PCC pavement response. Larger differential deflections are observed with details containing only 2 dowel bars. This results in a more flexible pavement leading to accelerated pavement deterioration.
- Varying clear cover from 3 to 2 inches has little overall effect on retrofit performance. Comparing results from tested details with varying only the clear cover showed very small overall differences in LTE and differential deflection. Maximum LTE changes were less than 3 percent. Differences in differential deflections were

equally small; less than 1 mil. Similar rates of change for both LTE and differential deflection after 1 million load cycles were also observed.

- Epoxy-coated mild steel, grouted stainless steel tube, and 1.75-inch diameter FRP dowels exhibited comparably high LTE and low differential deflections. The epoxy-coated mild steel dowels performed at the highest level overall.
- Increasing the diameter of FRP dowels from 1.5 inches to 1.75 inches resulted in LTE and differential deflections most closely matching those obtained from grouted stainless steel tube dowels.
- Replicate specimens, Slab 8 and Slab 9, performed consistently with the corresponding original details, Slab 5-6 and Slab 7, respectively. This verification testing shows the repeatability of testing using the Minne-ALF facility.
- All the details tested in Phase 2 resulted in LTE values well above the partial failure criterion of 70% LTE. However, two specimens (Slabs 7 and 9 from Phase 2B) performed with constant increasing differential deflections through 6.7 million cycles. This suggest that problems associated with doweled joints, such as pumping and faulting, may be more commonly associated with excess flexibility rather than incompatibility as discussed in Section 2.4.3.
- After approximately 1 million load cycles, nearly all the tested details began to show signs of decreasing LTE, increasing differential deflections, or both.

6.3 Recommendations

- Replicate testing is recommended to confirm the results of Slab 3-4 from Phase 2A, as it was not included in Phase 2B.
- It is recommended that testing be performed on 2 inch diameter FRP dowels in order to achieve LTE and differential deflections more closely matching the standard 1.5 inch diameter epoxy-coated mild steel dowels.
- It is recommended that the partial failure criterion of 70% LTE be tightened to 85% or less as constituting failure. All specimens tested in Phase 2 exhibited LTE values well above the current failure criterion of 70%. A more stringent standard would allow for more useful comparisons between details.
- Testing beyond the current 6.7 million load cycles standard, as done for Slabs 3-4 and 5-6 in Phase 2A, is also recommended. The longer the testing the more rapid the decrease in LTE and increase in differential deflection.

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Appendix A: Minne-ALF Test Facility Diagrams

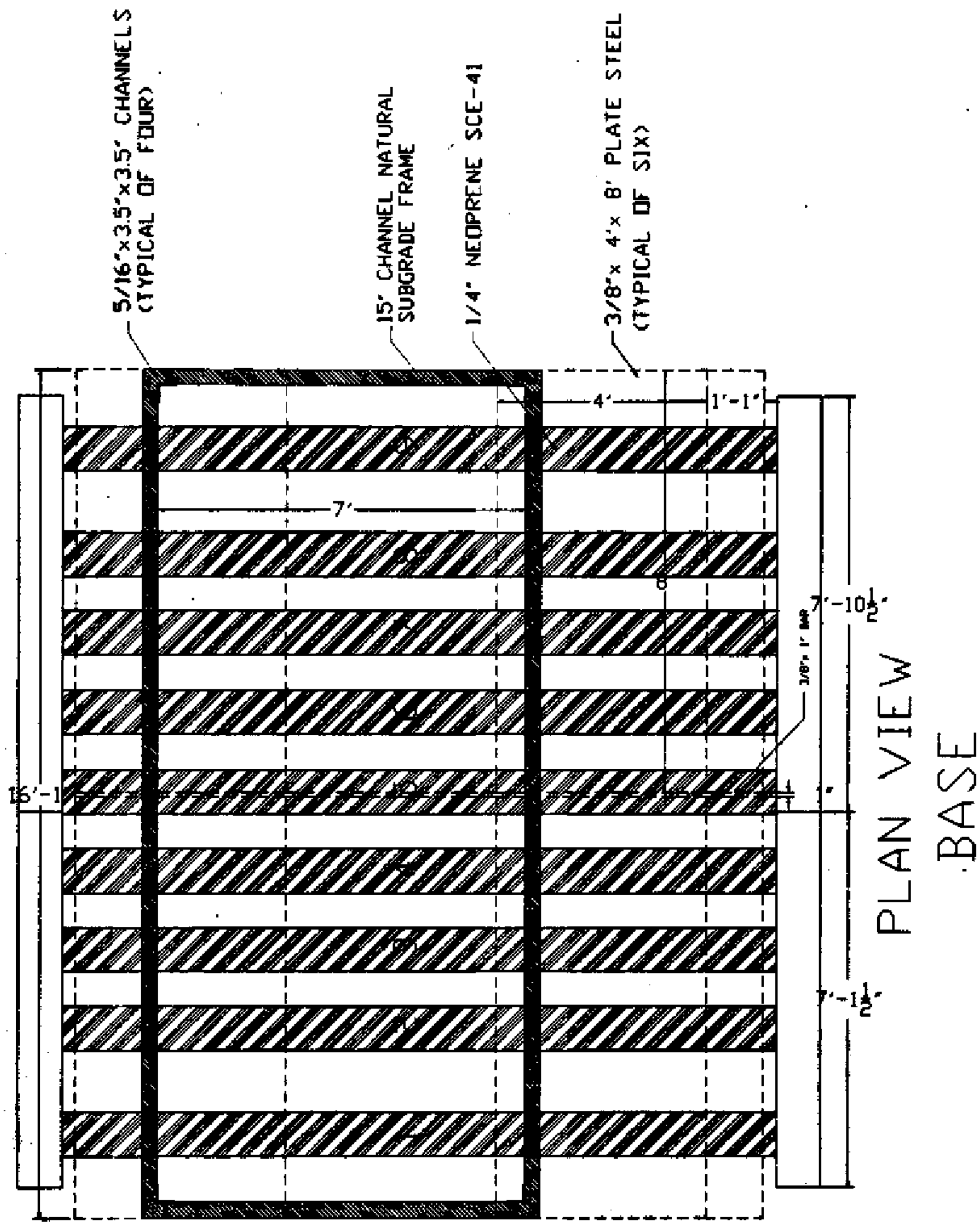

FIGURE A-1: BASE PLAN VIEW OF MINNE-ALF TEST FACILITY [17]

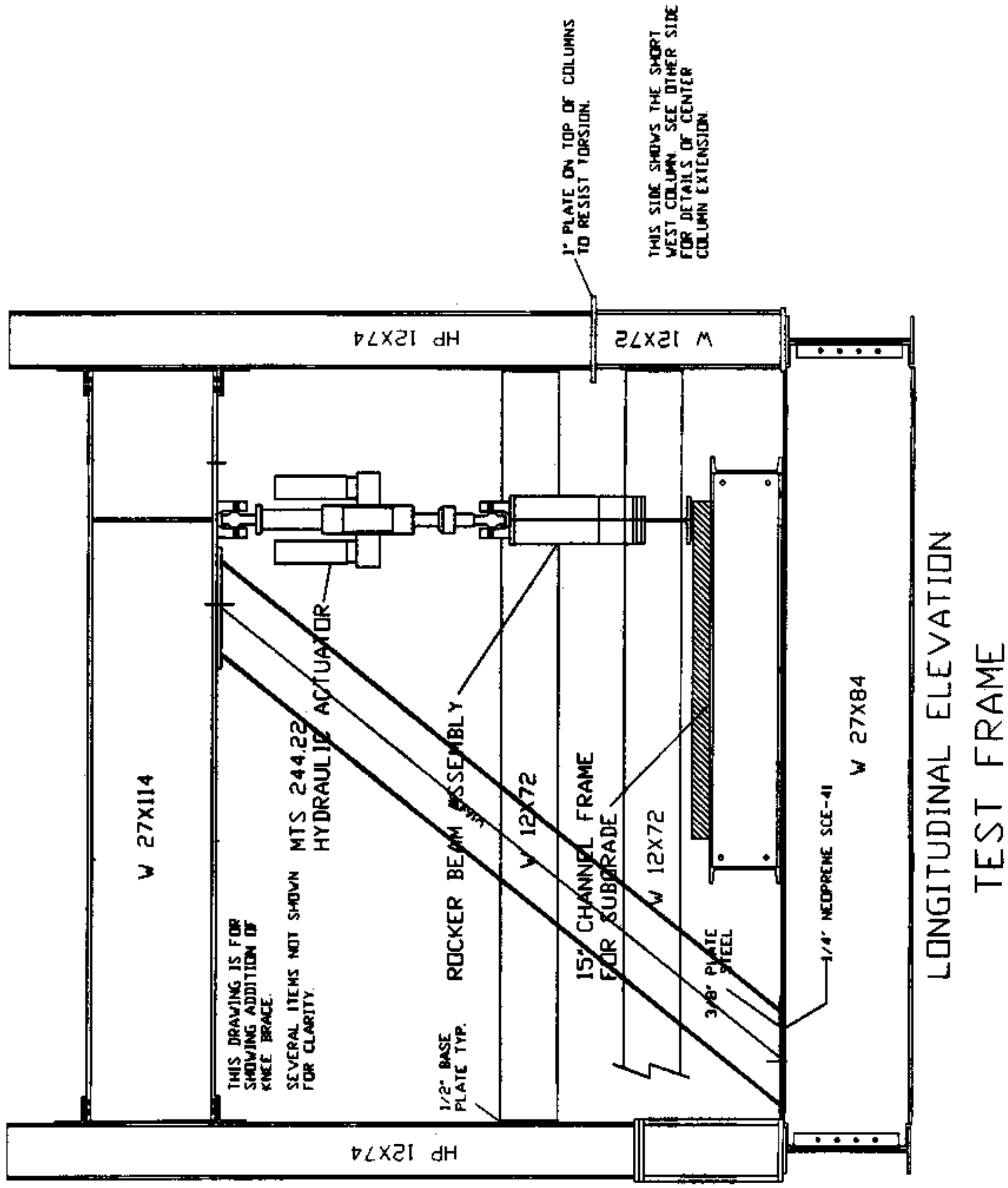

FIGURE A-2: LONGITUDINAL ELEVATION OF MINNE-ALF TEST FACILITY [12]

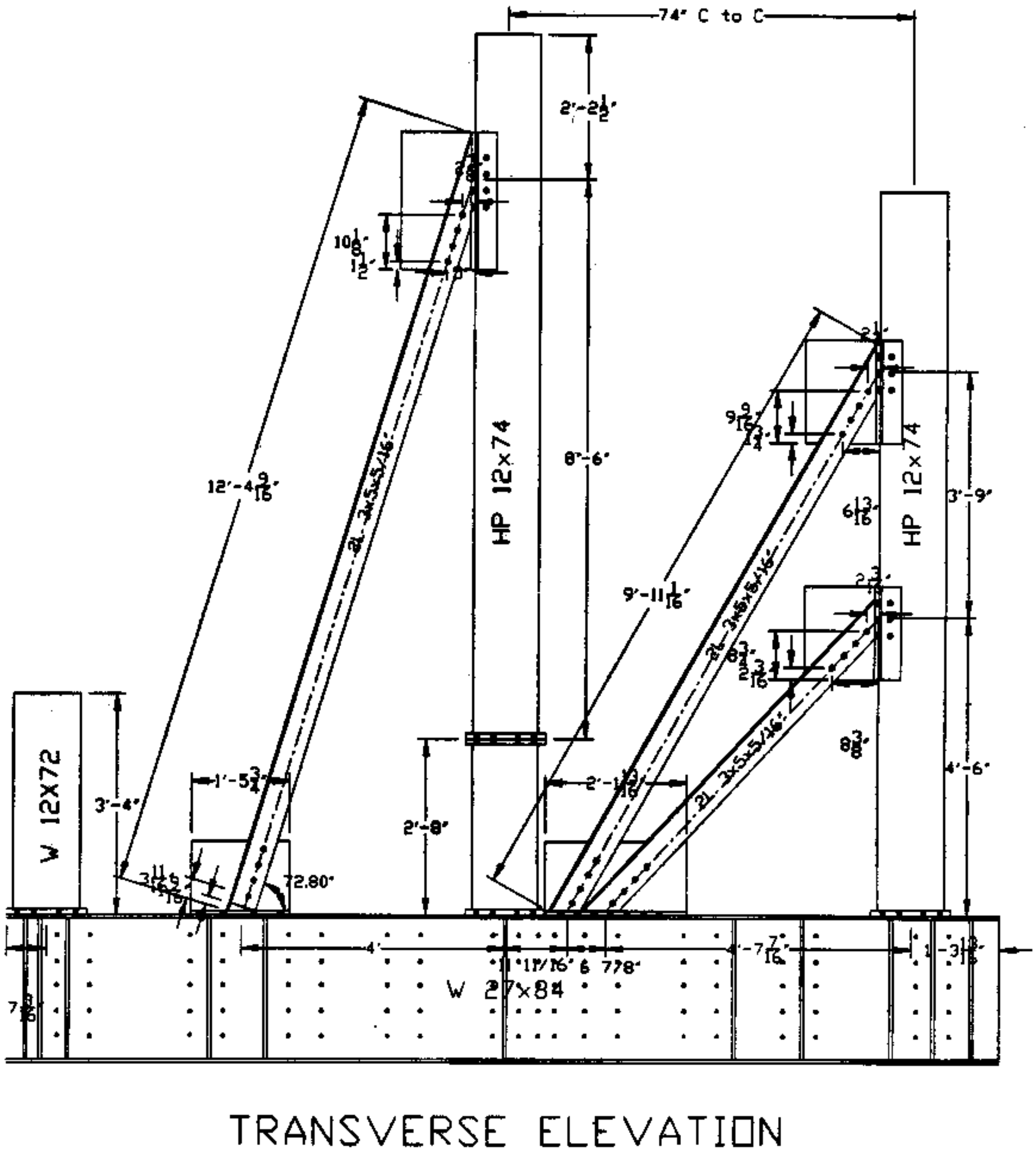

FIGURE A-3: TRANSVERSE ELEVATION OF MINNE-ALF TEST FACILITY [12]

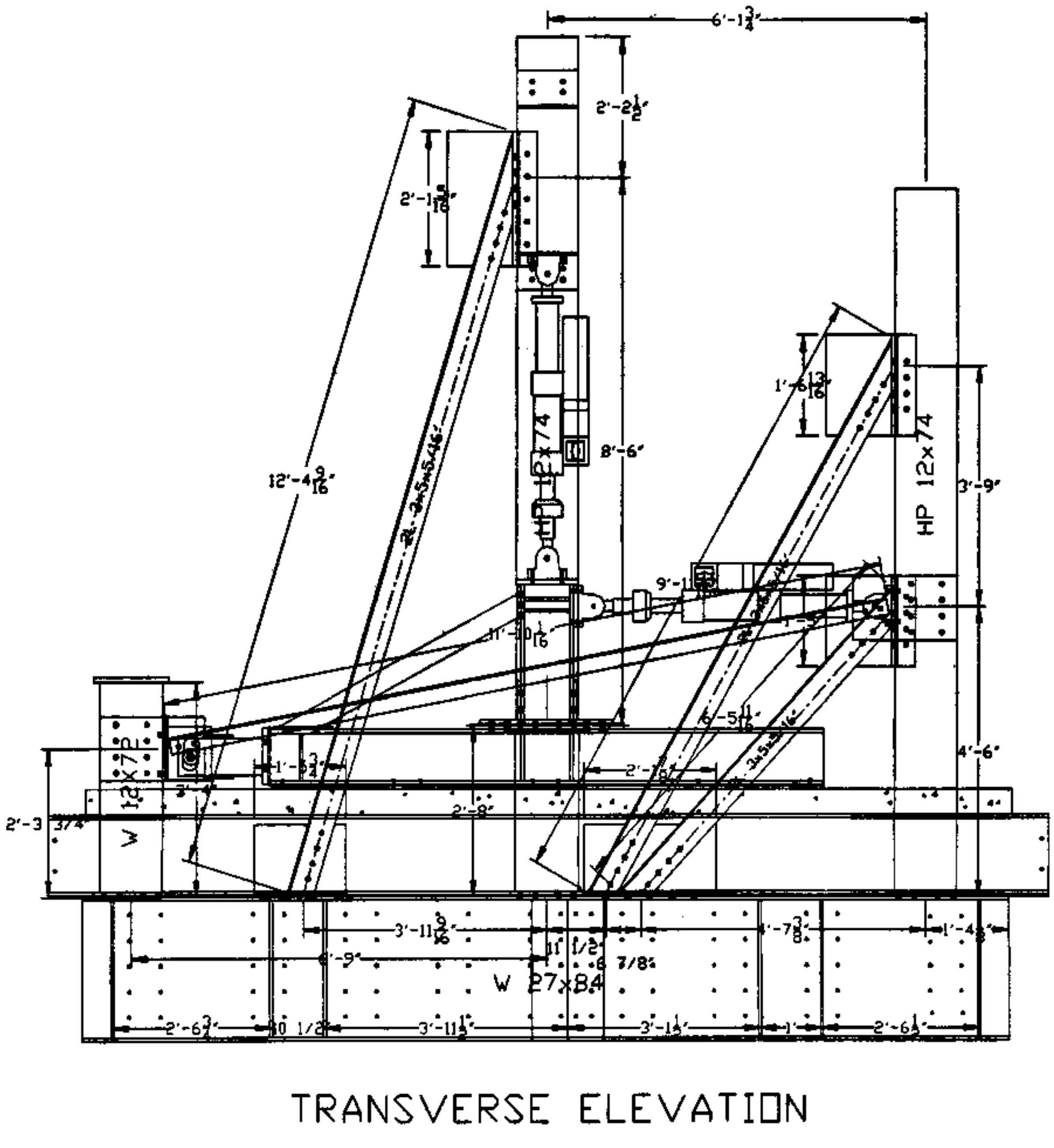

FIGURE A-4: TRANSVERSE ELEVATION OF MINNE-ALF FACILITY WITH ROCKER BEAM [12]

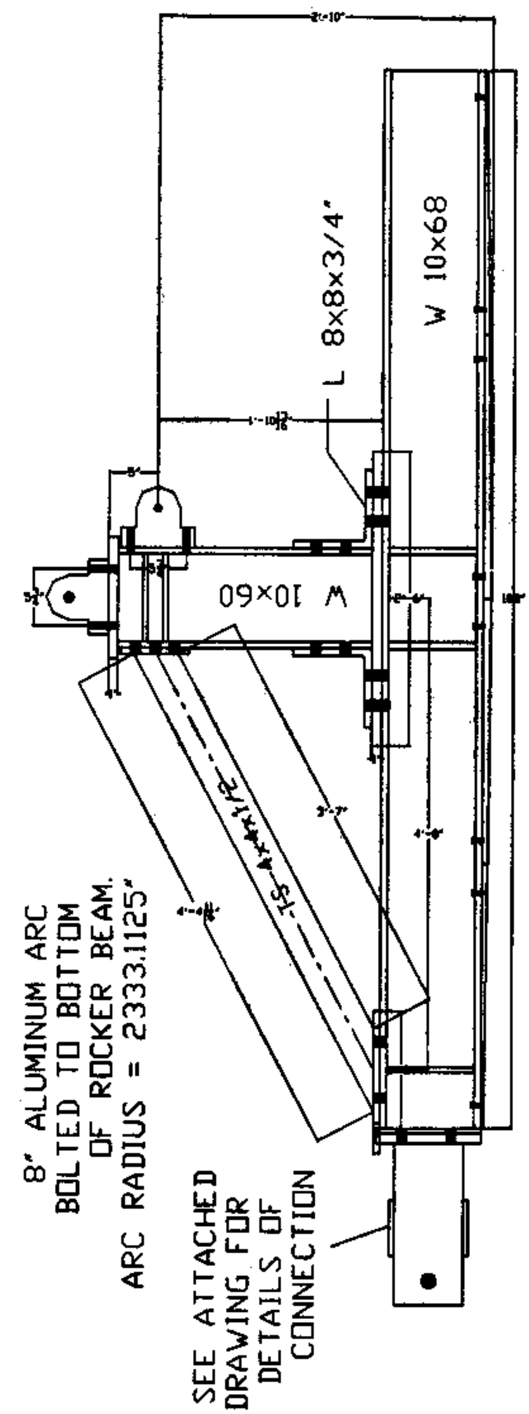

FIGURE A-5: TRANSVERSE ELEVATION OF ROCKER BEAM [12]

Appendix B: Previously Tested Dowel Bar Details

Table B-1 summarizes the results of tests performed in Phase 2A by Odden [14]. The results of this research were used for dowel bar detail comparisons in this report.

Table B-1: Summary of Slab Tests 1, 2, 3-4, and 5-6 in Phase 2A [14]

	Slab 1 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, placed at mid depth		**Slab 2** 1.5 inch diameter, 15 inch long, FRP dowels, mid depth placement		**Slab (3-4)** 1.66 inch diameter, 1/8 inch thick walled, 18 inch long, grouted stainless steel dowels, mid depth placement		**Slab (5-6)** 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, placed at 2 inches below surface	
Applied Load Cycles	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)
0.00005					95	1.2	94	1.3
0.0001					95	1.2	93	1.6
0.001			92	1.9	95	1.3	94	1.6
0.002			92	1.8	95	1.2	93	1.7
0.005			91	2.1	95	1.4	94	1.6
0.01			91	2.2	96	1.4	95	1.5
0.02			91	2.2	96	1.4	94	1.7
0.05			93	2.4	95	1.4	95	1.5
0.1			93	2.7	96	1.3	95	1.5
0.3			86	3.1	94	2.1	94	1.7
0.4	94	1.6						
0.5							93	1.9
0.6			86	3.9	96	1.4	95	1.7
0.7	95	1.6						
0.8							94	1.7
1.2	95	1.6	82	4.8	96	1.6		
1.5							94	2.6
1.8	96	1.5	84	4.2	95	1.8		
2							94	2
2.4	96	1.5	84	4.4	95	1.8	94	1.8
2.9	96	1.4						
3			83	4.7	96	2	93	2.2
3.3	94	1.7						
3.6	95	1.6	83	4.9	95	2.1	94	2.1
4.2	95	1.5	85	4.9	94	2.8	93	2.6
4.8			86	4.9	93	2.9	92	2.4
5.4			82	4.6	94	3		
6					94	2.7		
6.2			82	4.8				
6.4			84	4.9			92	2.4
6.6	95	1.8	83	4.8	95	2.5		
6.7			82	4.9				

Table B-1 (cont'd)

	Slab 1 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, placed at mid depth		Slab 2 1.5 inch diameter, 15 inch long, FRP dowels, mid depth placement		Slab (3-4) 1.66 inch diameter, 1/8 inch thick walled, 18 inch long, grouted stainless steel dowels, mid depth placement		Slab (5-6) 1.5 inch diameter, 15 inch long, epoxy-coated mild steel dowels, placed at 2 inches below surface	
Applied Load Cycles	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)	LTE (%)	Differential Deflection (mils)
6.8	93	2.2						
7	93	2.2						
7.2					94	3.1	92	2.5
7.6	93	2.2						
7.8					94	2.9		
8.1	93	2.2						
8.4					92	3.7	93	2.3
8.7	92	2.4						
9.6	93	2.3					91	2.6
10.3					91	3.9		
10.5	93	2.2						
11					93	2.9		
11.4					93	3.1	93	2.5
12					92	3.2	91	2.6
12.7					89	4.9	92	2.6
13					85	5.9		
13.2					87	5.2		