Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-10/0-1777-3		

4. Title and Subtitle	5. Report Date
TESTS OF HMA OVERLAYS USING GEOSYNTHETICS TO REDUCE REFLECTION CRACKING	February 2009 Published: December 2009
	6. Performing Organization Code
7. Author(s) Arif Chowdhury, Joe W. Button, and Robert L. Lytton	8. Performing Organization Report No. Report 0-1777-3
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 0-1777
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Technical Report: September 1999 - August 2007 14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Project Title: Field Synthesis of Geotextiles in Flexible and Rigid Pavement Rehabilitation Strategies Including Cost Consideration

URL: http://tti.tamu.edu/documents/0-1777-3.pdf

16. Abstract

The primary objective of this field phase of the research project was to evaluate geosynthetic products placed under or within hot mix asphalt overlays to reduce the severity or delay the appearance of reflection cracks and to calibrate and validate FPS-19 Design Check.

Multiple end-to-end test pavements incorporating geosynthetic products (fabrics, grids, and composites) and including control sections were constructed in three different regions of Texas (Amarillo, Waco, and Pharr Districts) with widely different climates and geological characteristics. Performance of these test pavements has been monitored for five to six years, depending on the date of construction. The oldest test pavements (Pharr) are exhibiting essentially no cracking. The Amarillo and Waco test pavements are exhibiting a fair amount of low severity and a very small amount of medium-severity reflective cracking. Based on measured cracks in the original pavement before overlaying, the percentage of reflective cracking in each test section was calculated and plotted with time of pavement in service.

Calibration of FPS-19 Design Check could not be accomplished due to the absence of sufficient amount of cracks with medium-severity level. Instead, using the field data, relative life ratio of test sections was projected. Field specimens obtained from these test pavements were tested using the large overlay tester. Field monitoring revealed that some geosynthetic products are effective in delaying reflective cracking. They were relatively more effective in the Waco test pavement (concrete in mild climate) than the Amarillo test pavement (flexible in harsh climate).

17. Key Words	18. Distribution Statement
Reflective Cracking, Geosynthetic, Geotextile, Fabric, Grid, Composite, Asphalt Overlay, FPS-19	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	100	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TESTS OF HMA OVERLAYS USING GEOSYNTHETICS TO REDUCE REFLECTION CRACKING

by

Arif Chowdhury
Assistant Research Engineer
Texas Transportation Institute

Joe W. Button
Senior Research Fellow
Texas Transportation Institute

and

Robert L. Lytton
Senior Research Fellow
Texas Transportation Institute

Report 0-1777-3
Project 0-1777
Project Title: Field Synthesis of Geotextiles in Flexible and Rigid Pavement Rehabilitation Strategies Including Cost Consideration

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

February 2009
Published: December 2009

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

The engineer in charge of the project was Joe W. Button, P.E. # 40874, until August 2006. Arif Chowdhury, PE # 9089, was in charge of the project from September 2006 to August 2007.

ACKNOWLEDGMENTS

During the initial stage of this project, Ms. Hua Chen, engineering specialist, of the TxDOT Design Division, served as project director, and Mr. Kenneth J. Boehme, P.E., served as project coordinator. Subsequently, Mr. Greg Cleveland served as project director during 2003–2004. Since July of 2005, Dr. German Claros has served as project director. These TxDOT leaders have been instrumental in guiding this project to completion. Their guidance, assistance, and support are gratefully acknowledged.

Three TxDOT districts cooperated in the placement of test pavements to evaluate the long-term performance of a variety of geosynthetic products. The engineers in these districts that were instrumental in securing these agreements and working with the researchers included the following: Amarillo – Joe Chappell, P.E., Randy Hochstein, P.E., and Sammy Harris; Pharr – Rosendo Garcia, P.E., Carlos Peralez, P.E., and Rene Castro; and Waco – Jeff Kennedy, P.E., and Larry Stewart, P.E. Their cooperation and assistance is gratefully acknowledged.

TxDOT and FHWA provided the funding for this research project.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER 1: INTRODUCTION

BACKGROUND

Many highway agencies commonly construct a thin hot mix asphalt (HMA) overlay as preventive maintenance and/or rehabilitation for flexible, rigid, and composite pavements. This thin overlay is normally between 1.5 and 2 inches thick. An HMA overlay is designed to restore smoothness and thus improve ride quality, increase structural capacity, restore skid resistance, and protect the pavement from water intrusion.

Many overlays prematurely exhibit a cracking pattern similar to that in the old underlying layers. Appearance of cracking on new overlay propagated from underlying layer(s) containing joints and/or cracks is termed as reflective cracking. Reflective cracking is one of the more serious concerns associated with the use of thin overlays. These cracks in the new overlay surface are due to the inability of the overlay to withstand shear and tensile stresses created by movements concentrated around preexisting cracks in the underlying pavements. These movements of the underlying pavements can be caused by one or more of the following reasons: traffic loading causing differential deflections at or near the cracks; expansion or contraction of subgrade soil; and/or expansion and contraction of the pavement itself due to changes in temperature (Cleveland et al., 2002).

Reflection cracking decreases the useful life of HMA overlays and/or increases the need for cost-effective preventive maintenance techniques. There have been significant efforts in the pavement industry to address this issue. Roberts et al. (1996) categorized four methods that are commonly used to mitigate reflective cracking: increasing the HMA overlay thickness; performing special treatments on the existing surface; performing treatments only on the cracks and/or joints; and adopting special considerations of the HMA overlay design. One of the techniques used to reduce reflection cracking on HMA overlay is to incorporate geosynthetic products into the existing pavement structure. Geosynthetic products are defined herein as fabrics, grids, or composites. Generally, in this procedure, the geosynthetic product is attached to the existing pavement (flexible or rigid) with an asphalt tack coat and then overlaid with a specified thickness of HMA pavement. Based on findings in Phase I of this project (Cleveland et al., 2002), these materials have exhibited varying degrees of success. The use of geosynthetics within a particular agency has been based primarily on local experience or a willingness to try a product that appears to have merit.

In Phase I of this project, Texas Transportation Institute (TTI) researchers in cooperation with the Texas Department of Transportation (TxDOT) and construction contractors installed multiple end-to-end geosynthetic test pavements at three different locations in Texas. During Phase I, the products evaluated in the laboratory were selected to represent the three major categories of geosynthetics (fabrics, grids, and composites) that are used in an attempt to address reflection cracking. Besides those geosynthetics tested in the laboratory, several other products and methods were included in the test pavements for evaluation. The three test locations selected in coordination with TxDOT were the Pharr District (McAllen), the Waco District (Marlin), and the Amarillo District (northeast of Amarillo city). It is evident that the products being evaluated in this experiment possess a wide variety of engineering properties that have been placed on different pavement types in very different climates.

OBJECTIVE AND SCOPE

The overall objective of the research project was to investigate and develop information that will aid in the evaluation of the relative effectiveness of commercially available geosynthetic materials in reducing the severity or delaying the appearance of reflective cracking in HMA overlays. Specific objectives of the second phase of this study were to monitor the relative performance of geosynthetic test pavements and control pavements that were constructed in the Amarillo, Pharr, and Waco Districts during Phase I (Cleveland et al., 2002) of this project and to calibrate and validate the FPS-19 Design Check using the field and laboratory data. When information from these construction projects permits, the ultimate project goals include determining the relative effectiveness of each category of geosynthetic product (fabric, grid, and composite) in reducing or delaying reflective cracking and determining which, if any, of these products can provide cost-effective extensions of service life of thin overlays that are typically applied for maintenance and rehabilitation of TxDOT pavements.

The research team has published two reports (Report No 0-1777-1 in 2002 and Report No 0-1777-2 in 2006) describing the research effort and results. This third and final report will focus on the research effort from the last two years of the project duration. This report is organized in six chapters. Chapter 1 presents the background and objective of this research project and the scope of this report. Chapter 2 is a brief review of current literature related to this project and focuses on field evaluation of geosynthetic products outside Texas. This literature review covers different ways of reducing reflection cracking and discusses how researchers or agencies are evaluating the efficiency of reflection cracking mitigation techniques. Chapter 3 describes the development and monitoring of the three test pavements that were established in Phase I of this research project. Test pavement field specimen collection, laboratory testing, and test results are discussed in Chapter 4. Chapter 5 documents the analyses of the results from laboratory tests and field monitoring. Chapter 6 documents a summary of the conclusions and recommendations.

CHAPTER 2:
LITERATURE REVIEW

Researchers, agencies, and pavement industries have been working closely for a long time to address the reflection cracking problems in HMA overlays. Many different treatments have been tried over the years to prevent the reflection cracking with no success. However, some treatments have shown varying degrees of success in delaying the appearance and/or reducing the severity of reflection cracking. In this chapter, the authors will briefly summarize the recent efforts to evaluate the treatments used to address this issue.

This literature review is limited to very recent field studies of products and techniques to address reflection cracking in hot mix asphalt overlays.

PERFORMANCE

From their review of current literature, Hajj et al. (2008) summarized findings regarding mitigation of reflective cracking in HMA overlays outside the state of Nevada, in Nevada, and in Washoe County, Nevada (Tables 2-1, 2-2, and 2-3, respectively).

Based on the limited success of stress relief courses (SRC) in Nevada and review of their specifications for SRC, Hajj et al. (2008) recommended that an extensive laboratory evaluation for the Texas Department of Transportation (DOT) and Utah DOT SRC designs using Nevada materials take place during 2008. Results of the laboratory evaluation supposed to be used to make recommendations for field evaluation during 2009. Field mixtures will be evaluated using dynamic modulus, fatigue resistance, rutting resistance using the repeated load triaxial (RLT) test, thermal cracking resistance using the thermal stress restrained specimen test (TSRST), reflective cracking resistance using the TTI upgraded overlay tester (Zhou and Scullion, 2005), and moisture sensitivity. Performance of the test sections will be monitored, and pavement cores will be evaluated in the TTI overlay tester. Based on the findings, the Nevada DOT specifications for reflective cracking resistance will be adjusted.

Table 2-1. Summary of Literature Review on Reflective Cracking (after Hajj et al., 2008).

Treatment	Description	Performance
Cold in-place recycling	Removing and milling the upper layers of the existing pavement with specialized recycling equipment; then mixing with virgin materials to produce a strong, flexible base course.	Promising performance for roads with up to 13,000 Average Annual Daily Traffic (AADT) and 200,000 annual equivalent single axle loads (ESAL).
GlasGrid®	Geosynthetic material consisting of connected parallel sets of intersecting ribs with openings of sufficient size.	Benefits in retarding or preventing reflective cracking are not clear. Field performance has varied from excellent to very poor. Concerns when used on rough surfaces.
Fabric interlayer	Geosynthetic comprised solely of textiles. A paving fabric interlayer provides the generally acknowledged functions of a stress-absorbing interlayer and a waterproofing membrane. The stress-related performance has been easily verified by the observed reductions of cracking in pavement overlays.	Effective when used for load-related fatigue distress. It did not perform well when used to delay or retard thermal cracking. Optimum performance highly associated with proper construction procedures. The key factor is proper tack-coat installation. In general, overlays reinforced with fabrics have shown better performance than unreinforced overlays under same conditions.
Asphalt rubber interlayer + thin overlay (about 1.5″)	Asphalt rubber chip seal overlaid with conventional dense-graded HMA or gap-graded HMA.	Reduced and/or delayed reflective cracking for a period of 5 years.
Stress-absorbing membrane interlayer (SAMI)	A thin layer placed between an underlying pavement and an HMA overlay for the purpose of dissipating movements and stresses at a crack in the underlying pavement before they create stresses in the overlay. SAMIs consist of a spray application of rubber or polymer-modified asphalt as the stress-relieving material, followed by placement and seating of aggregate chips.	Successful in reducing the rate of reflective cracking.
Crumb rubber overlay	Produced by adding ground tire rubber to HMA using the wet process.	Ranged from successful to devastating failures depending on percent of crumb rubber in mix.

Table 2-2. Summary of Nevada DOT Experience with Reflective Cracking Mitigation Techniques (after Hajj et al., 2008).

Treatment	Description of Treatment	Application Conditions		Performance
		Traffic	Pre-rehabilitation Condition	
Cold in-place recycling (CIR)	CIR of minimum top 2.0″ of existing HMA materials and overlaying it with a minimum of 2.5″ dense-graded HMA mixture.	Up to 14,000 AADT.	No severe alligator cracking.	Stopped reflective cracking for 5 years after construction.
Reinforced fabric (RF)	Cold milling 2.0″ of existing HMA layer, placing fiberglass yarns, and overlaying with 2.0″ Type II (1.0″ maximum size) dense-graded HMA.	Between 1,000 and 10,000 AADT.	No severe alligator cracking.	Retarded reflective cracking for at least 3 years after construction and reduced the rate of reflected transverse cracks 5 years after construction.
Stress relief course (SRC)	Cold milling 2.0″ of existing HMA layer, placing a 1.0″ stress relief course and overlaying with 2.0″ Type II (1.0″ maximum size) dense-graded HMA.	Up to 40,000 AADT.	N/A	Stopped reflective cracking for 3 years after construction. Rate of reflected transverse cracks accelerated 5 years after construction.
Mill and overlay (MOL)	Cold milling 1.0″ of existing HMA pavement and overlaying it by 1.0″ HMA mixture manufactured with an AC-10 asphalt binder.	Up to 40,000 AADT.	N/A	Reflected fatigue and transverse cracks 1 to 2 years after construction.
	Cold milling 1.0″ of existing HMA pavement and overlaying it by 1.0″ HMA mixture manufactured with an AC-20P asphalt binder.	Up to 4,000 AADT.	N/A	Stopped reflective cracking for 3 years after construction. Minor reflected transverse cracks 5 years after construction.
	Cold milling 1.5″ of existing HMA pavement and overlaying it by 1.5″ HMA mixture manufactured with an AC-20P asphalt binder. (*)	Up to 2,000 AADT.	N/A	Stopped reflective cracking for 3 years after construction. Minor reflected transverse cracks 5 years after construction. (*)

* This treatment was placed on pavements with a condition worse than the condition of the pavements where the other two mill and overlay treatments were applied.

Table 2-3. Summary of Washoe County, Nevada, Experience with Reflective Cracking Mitigation Techniques (after Hajj et al., 2008).

Treatment	Description	Performance
NF-1.5	No Fabric + 1.5″ HMA overlay	Retarded reflective cracking for 1 to 3 years after construction.
NF-2.0	No Fabric + 2.0″ HMA overlay	Retarded reflective cracking for 1 to 3 years after construction.
NF-2.5	No Fabric + 2.5″ HMA overlay	Retarded reflective cracking for 1 to 5 years after construction.
F-2.0	Non-woven Geotextile Fabric + 2.0″ HMA overlay	Retarded reflective cracking for 1 to 5 years after construction.
F-2.0s	Non-woven Geotextile Fabric + 2.0″ HMA overlay + slurry seal some years prior treatment application	Retarded reflective cracking for 3 to 5 years after construction with some sections showing reflective cracking within the first year after construction.
P-2.0	Petromat + 2.0″ HMA overlay	Retarded reflective cracking for 1 to 5 years after construction. Most of the sections exhibited reflective cracking, either fatigue or longitudinal, and transverse cracking at the end of the 5-year analysis period.
P-2.0s	Petromat + 2.0″ HMA overlay + slurry seal some years prior treatment application	Retarded reflective cracking for 1 to 5 years after construction on half of the sections and for at least 5 years on the remaining half of the sections. The sections did not develop fatigue cracking during the 5-year analysis period.

According to Loria et al. (2008), Nevada DOT has experimented with a number of techniques to reduce the impact of reflective cracking on HMA overlays. These include cold in-place recycling (CIR), reinforcing fabrics (RF), stress-relief courses, and mill and overlay (MOL). Several projects were constructed under each category. Long-term field performance of these reflective cracking mitigation techniques was evaluated on 33 field projects. Performance of the various projects was analyzed using fatigue, transverse, and block cracking measurements from the Nevada DOT pavement management system. In addition, a statistical approach called principal component analysis was used to assess the effectiveness of each of the reflective cracking techniques. The study indicated that CIR and MOL were the most effective treatments for delaying reflective cracking of HMA overlays over HMA pavements under Nevada environmental conditions. CIR-A (2.0-inch CIR + 2.5-inch overlay) and CIR-B (3.0-inch CIR + 3.0-inch overlay) treatments, regardless of traffic level, proved generally effective in stopping reflective cracking for three years and in retarding reflective cracking for five years. However, the CIR-C (2.0-inch CIR + 2.0-inch overlay) treatment was ineffective in resisting reflective cracking. SRCs showed excellent performance up to three years after construction, regardless of the traffic level and the existing pavement condition (including alligator cracking). However, five years after construction, SRCs exhibited considerable reflective transverse cracking. MOL was effective in stopping reflective cracking for up to three years for projects with Average Annual Daily Traffic (AADT) lower than 5,000. After five years, MOL showed marginal performance by slowing reflective cracking. RF treatment showed marginal performance at three and five years after construction. Except as noted, when the existing pavement exhibited severe alligator cracking, none of these treatments performed well. The authors recommended that the HMA pavement be subjected to reconstruction or full-depth reclamation when severe alligator cracking is present.

Bush and Brooks (2007) reported that the Oregon DOT evaluated five geotextile materials on a 4-mile stretch of US 97 from 1999 to 2007 in retarding reflective transverse cracks through an HMA overlay. In 1998, several cracks had reflected through the previous overlay, placed eight years earlier. Researchers chose a total of 140 transverse cracks for the study. Geosynthetic material was placed in strips over 98 of the cracks, 22 were treated with crack-fill only, and the remaining 22 were untreated. GlasGrid strips were 60 inches wide, and all other geotextiles were 24 inches wide. A 2.0-inch HMA overlay with 1.0-inch maximum size aggregate was constructed. The number and severity of reflective cracks was observed for nine years. There was no conclusive data to demonstrate that any of the geotextile materials reduced the total number of reflective cracks. No treatment was effective in preventing reflective cracks from returning. Overall, crack-fill outperformed geosynthetic materials. The least number of cracks reappeared in crack-fill sections (a total of 17 of 22 cracks) and 73 percent of the original crack length reappeared. Geosynthetics did, however, reduce the percentage of high-severity cracks by 80 percent, which delayed the need for a subsequent overlay. The best geosynthetic in reducing reflective crack severity was GlasGrid 8502®. Although other factors contributed to pavement deterioration, the authors concluded that, if transverse cracking is the only deterioration factor in a roadway, the placement of certain geosynthetic materials appears to be cost effective.

Hutter (2003) reported that, as part of a mandated pavement warranty pilot program, a 4-mile segment of I-25 south of Fountain, Colorado, was rehabilitated during the summer of 1998. Colorado DOT overlaid the northbound and southbound lanes with HMA under a warranty contract. Prior to the overlay, the roadway was milled to a depth of 1 inch throughout the project, with the exception of the first nine test section locations (approximately 3,600 ft), where the driving lane was milled an additional 1.5-inch depth and, after the specific treatments were applied, the trench was overlaid with HMA.

Eight experimental treatments and control sections were constructed with either a 4-inch or a 5.5-inch overlay (18 total). These sections included routing and not routing the existing cracks and sealing with two types of crack sealer, two weights of geotextile (Petromat 4597 [120 psi tensile] and Petromat 4599 [90 psi tensile]), and two types of heavily reinforced tape systems (T-Bond at longitudinal joints in both lifts and in only the second lift). The performance of each type of treatment was evaluated over a three-year period after construction. Findings confirmed that the least recurrence of cracks was observed in the section with the additional 1.5-inch HMA. After three years, only one crack was observed in the control section of the thicker overlay; no cracks appeared in any of the thicker sections with treatments. Further, the majority of the reflective cracking was observed after the first year, with additional cracking becoming visible after the third year.

Makowski et al. (2005) reported that reflection cracking through HMA overlays over joints and preexisting cracks in concrete pavement is a persistent problem, particularly in climates such as that in Wisconsin. In fact, reflective cracks often appear within a year or two. The Wisconsin DOT and the city of Milwaukee tried a fine-aggregate, asphalt-rich (7 percent minimum), polymer-modified asphalt mix interlayer (developed by Koch Pavement Solutions) to absorb stresses at joint movements, delay reflective cracking, and protect the existing pavement. Four projects were constructed. In the first project, constructed in 1996, the interlayer showed no effect on delaying reflection cracking within the first three years. Later projects, however, included specifications for use of a performance-related design test for flexural beam fatigue and Hveem stability and were overlaid with improved HMA mixtures (98 percent reliable binder) to complement the flexible interlayer. The later projects averaged 42 percent improvement in the time to the appearance of surface cracks when compared with the control sections. Further, cores taken from these projects showed that, even when the overlay cracked, some of the interlayer samples did not crack, even under severe conditions, thus continuing to protect the underlying pavement structure. Other major factors contributing to the cracking delay included the type of concrete pavement, concrete patches, and climate.

In 2000, the Maine DOT experimented with a geosynthetic on runway 17-35 of the Auburn-Lewiston Municipal Airport to determine its effectiveness in reducing reflective cracking of the subsequent HMA overlay (Soucie, 2007). GlasGrid 8502® was placed in 30-inch and 60-inch strips over individual cracks. Then, a 1.6-inch HMA overlay was constructed. After 4.6 years, Maine DOT observed significant cracking in both the test and control sections and determined that most of it was reflective cracking. They found that the geosynthetic did not significantly reduce reflective cracking in this case. However, they pointed out that there were serious concerns regarding installation of the geosynthetic due to inadequate adhesion of the GlasGrid to the runway, overbanding of crack sealant, and subsequent paving difficulties caused by the overbanding. These concerns prevented meaningful conclusions on the effectiveness of the product.

COST EFFECTIVENESS

A recent study (Buttlar et al., 2000) evaluated the cost-effectiveness of one Illinois DOT (IDOT) reflective crack control, which consists of a nonwoven polypropylene paving fabric, placed either in strips longitudinally over lane-widening joints or over the entire pavement (area treatment). The study was limited to projects originally constructed as rigid pavements and subsequently rehabilitated using one or more bituminous overlays. Performance of 52 projects across Illinois was assessed through crack mapping and from distress and serviceability data in IDOT's condition rating survey database. Comparisons of measured reflective cracking in treated and control sections revealed that this system retarded longitudinal reflective widening crack development, but it did not significantly retard transverse reflective cracking, which agrees with earlier studies. However, both strip and area applications of these fabrics appeared to improve overall pavement serviceability, and they were estimated to increase rehabilitation life spans by 1.1 and 3.6 years, respectively. Reductions in life-cycle costs were estimated to be 4.4

and 6.2 percent, when placed in medium and large quantities, respectively, and to be at a break-even level for small quantities. However, life-cycle benefits were found to be statistically insignificant. This conclusion pertains only to nonwoven polypropylene fabrics used over rigid bases. Limited permeability testing of field cores taken on severely distressed transverse joints suggested that waterproofing benefits could exist even after crack reflection had occurred. This was consistent with the observation that, although serviceability was generally improved with area treatment, crack reflection was not retarded relative to untreated areas.

Engle (2001) evaluated two engineering fabrics to determine their effectiveness in reducing reflective cracking. PavePrep® (Contech Construction Products Inc.) and ProGuard® (Phillips Fiber Corporation) were placed in 20-inch strips directly on cracks on HR-58. A 3.0-inch HMA overlay was placed in two 1.5-inch lifts in 1993. During a period of two to eight years, the data indicated a statistically significant decrease in reflective crack formation in the ProGuard sections when compared to control. However, the PavePrep sections performed similar to the control. After three years, the rate of cracking was similar for both fabrics and the control. They concluded that the benefits of using these fabrics on this project did not outweigh the costs of up to $4200 per lane-mile.

Vespa (2005) deduced that the various types of interlayer systems and geotextiles that have been used in an attempt to slow the development of reflective cracks have had mixed results. In 1993, the University of Illinois completed research directed by the IDOT on a prototype Interlayer Stress Absorbing Composite (ISAC). A prototype test section was placed on IL-38 near Rochelle, Illinois, in 1993. Other ISAC test sections were placed on five asphalt concrete overlay projects between 1997 and 2000. Some of these sections contained other reflective crack control methods, such as sand anti-fracture layer, strip, and area-wide reflective crack control fabric. ISAC consists of a three-layer system. The top layer is a high-strength, woven geotextile designed to resist stresses caused by underlying pavement movements. This layer has the ability, due to its weaving, to expand like a chain-link fence. This movement dissipates the stresses caused by the movement of the underlying pavement. Typically, this geotextile has a tensile strength greater than 4000 lb/inch at 5 percent strain (ASTM D 4595). High strength is needed to ensure that, when the geotextile is expanded to its full extent, the geotextile strength is greater than the strength of the bituminous concrete overlay. The bottom layer is a low-strength, nonwoven geotextile (meeting AASHTO M-288-92). The middle layer is a modified rubberized asphalt layer to absorb the strain energy and bond the two geotextiles together. The system bridges across the joint or crack and dissipates stresses resulting from opening movements. ISAC is bonded to the existing pavement using a tack coat, and then the overlay is placed. Formation of reflective cracks and the subsequent deterioration of these cracks were delayed at ISAC-treated joints and cracks at all five test sites. This delay ranged from more than one year to almost three years, when compared to the untreated and other crack control methods. Of special note, the ISAC areas consistently outperformed PavePrep and Roadtac. A sand anti-fracture layer and ISAC reached the same level of reflective cracking at four and six years, respectively. These two sections performed similarly after the cracks were routed and sealed. The cost analysis indicated that the higher the total cost of the asphalt concrete, the higher the number of cracks and joints that could be treated with ISAC. The 2005 cost of the ISAC strips, $10–$14 per ft, limits the conditions under which it would be cost effective. With the current higher cost of asphalt concrete, the benefit-cost of ISAC may be more attractive.

CHAPTER 3: DEVELOPMENT AND MONITORING OF FIELD TEST PAVEMENTS

INTRODUCTION

TTI researchers in cooperation with TxDOT and construction contractors installed multiple end-to-end geosynthetic test pavements at three different locations in Texas. The objective of these test pavements was to evaluate, as a minimum, the same geosynthetic products that were evaluated in the laboratory. In Phase I of this project, the products evaluated in the laboratory were selected to represent the three major categories of geosynthetics (fabrics, grids, and composites) that are often used to address reflection cracking. Besides those geosynthetics tested in the laboratory, several other products were included in the test pavements for evaluation. The Appendix of this report documents the detailed properties of the geosynthetic products used in these field sections. Most of these properties were obtained from the product brochure and/or manufacturers' websites. The three test locations selected in coordination with TxDOT were the Pharr District (McAllen), the Waco District (Marlin), and the Amarillo District (northeast of Amarillo city). These regions provided mild, moderate, and cool climates, respectively, for the long-term evaluation. Pharr and Amarillo provided flexible pavements while Waco provided a rigid pavement. Table 3-1 presents a summary of the three test pavements. Figure 3-1 shows the locations of the test pavements on the map of Texas divided into different climatic regions. Table 3-2 presents the description of different layers of all three test pavements.

Table 3-1. Summary of Test Pavements.

District	Highway Name	Pavement Type	Average Daily Temperature Range (°F)	Elevation (ft)	Annual Rainfall/ Precipitation (inch)	Traffic (2005)	
						AADT	ESAL
Amarillo	SH 136	Flexible	23 – 92	3585.0	18.0	4000	1933
Pharr	FM 1926	Flexible	48 – 96	100.0	24.0	27500	1279
Waco	BUS 6	Flexible over jointed concrete	34 - 97	388.0	36.0	3100	791

Before construction, the research team diagrammed and documented all the cracks on existing surfaces. After overlay construction, the research team periodically measured and documented the reflective cracking. At the beginning, the reflective cracks were monitored once a year. At a later stage, it was done twice per year. During the crack monitoring, the researchers followed the "Distress Identification Manual for the Long-Term Pavement Performance Studies" (1990), published by Strategic Highway Research Program, National Research Council, for crack measurement and classification.

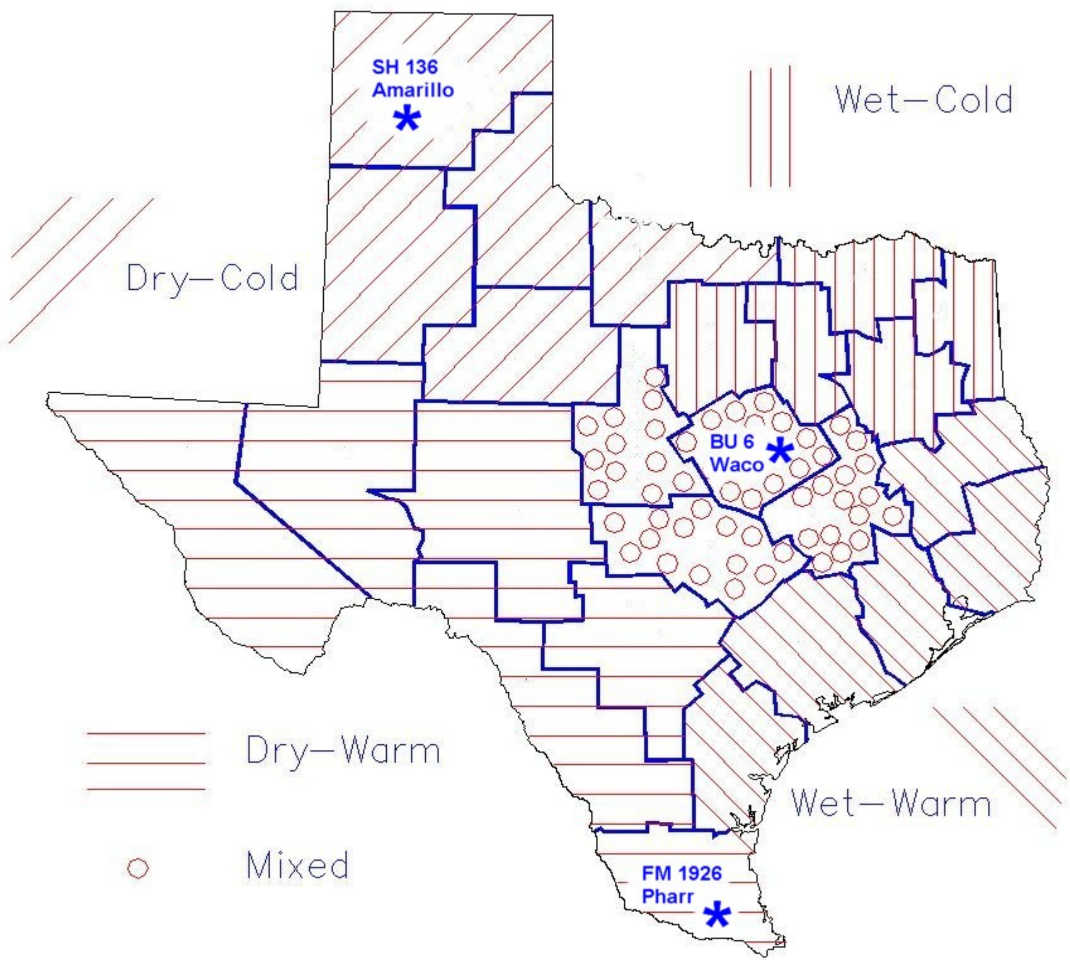


Figure 3-1. Location of Test Sections in Texas Map.

Table 3-2. Layer Descriptions of the Three Test Pavements.

Test Pavement	Layer	Description
Amarillo	Layer 1	2.0-inch Type D HMA
	Layer 2	Geosynthetic/grid/mesh
	Layer 3	0.75-inch to 1.0-inch Type D leveling course
	Layer 4	2.25- to 2.5-inch HMA
	Layer 5	3.5- to 4.0-inch ASB
	Layer 6	12.0-inch flexible base
	Layer 7	Subgrade (treatment status unknown)
Waco	Layer 1	1.75 to 2.0-inch HMA
	Layer 2	Geosynthetic/grid/mesh
	Layer 3	1.0-inch HMA level up
	Layer 4	0.2-inch to 0.25-inch seal coat with TR
	Layer 5	6.0-inch jointed concrete 20-ft spacing
	Layer 6	Subgrade (treatment status unknown)
Pharr	Layer 1	2.0-inch Type D HMA
	Layer 2	Geosynthetic/grid/mesh
	Layer 3	Type D ACP (1.0-inch inside, milled to zero thickness at outside)
	Layer 4	14-inch flexible base (2% lime stabilized)
	Layer 5	12-inch subgrade (3% lime stabilized)

PHARR DISTRICT TEST PAVEMENTS

This test pavement, constructed in April 2001, is located on a segment of FM 1926 in the city of McAllen, Texas. In the city limit, this highway is known as N 23rd Street. Details about development, construction, and placement of geosynthetics on this test pavement can be found in two earlier reports 0-1777-1 (Cleveland et al., 2002) and 0-1777-2 (Button and Chowdhury, 2006). Figure 3-2 shows the layout of this test pavement, which contains eight different test sections. Two of the test sections are less than 500 ft, but the others are 500-ft long.

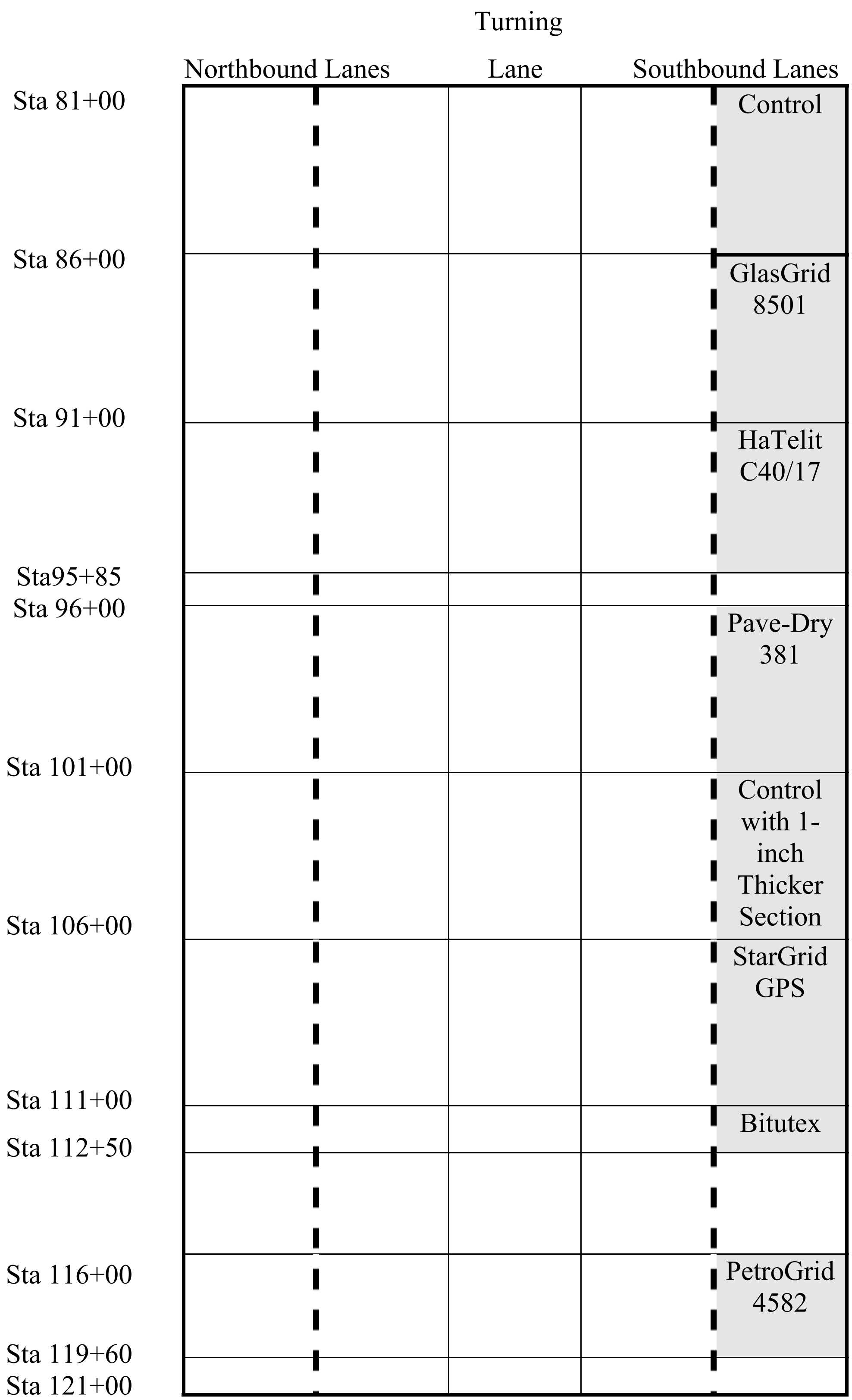


Figure 3-2. Plan View of Test Pavements Placed in McAllen – Pharr District.

Test Section Evaluation

Researchers have typically evaluated these test pavements each spring since construction. The researchers believe that, generally, most cracks appear during cooler weather, and further, cracks can sometimes disappear from view during hot weather due to pavement expansion and kneading action of traffic at the HMA surface. Towards the end of this project, crack monitoring was performed more frequently when crack development accelerated. During that time, test pavements were evaluated twice per year.

An evaluation of the pavements in May 2002 revealed a single crack less than 1/16 inch wide and about 40 ft long located about 6 inches from the curb in the Pave-Dry® 381 section. No other forms of distress were visible in any of the test or control pavements.

In May 2003, no cracks were visible at the surface of any of the pavements. The crack observed in 2002 had disappeared, probably due to lateral movement of the HMA in the warm South Texas climate. There were, however, a few flushed strips transversely across the lane. These flushed areas were expected due to one incident of asphalt spillage and overlaps of the tack when the truck would start too far back onto the previous shot of asphalt tack. These distresses are no fault of the geosynthetic product and likely would not have been produced by a crew experienced with placing geosynthetic products.

In April 2004, no cracking was observed nor were any other significant forms of pavement distress. Isolated shoving or rutting was observed in the outer wheelpath about 10 to 20 ft north of the Buddy Owens intersection (1-inch thicker overlay section). This rutting was apparently due to a base problem, as similar rutted areas were recorded during the initial evaluation of the pavement before the project began.

In April 2005, no cracking was observed nor were any other significant forms of pavement distress. Generally, the pavement surface exhibited a slight flushed appearance in the wheelpaths, but this was not significant. The transverse strips of flushing and a few isolated spots of shoving in the outer wheelpath at the approach of a couple of intersections were still visible.

In November 2005, three test sections (GlasGrid, Pave-Dry, and HaTelit) had developed few longitudinal cracks. Their reflective cracking percentages (with respect to before-construction cracking) were only 12, 8, and 4 percent, respectively. About 150 ft of the thicker HMA section had suffered significant rutting in both wheelpaths in the approach to a major intersection with a truck route. Additionally, a few isolated areas showed flushing. More than four years after construction, the overall condition of the test pavements was very good.

Subsequent monitoring in October 2006 and May 2007 did not reveal any significant crack growth in these test sections. Table A5 documents the crack lengths observed in all test sections of this test pavement. Only one 5-ft long longitudinal crack was observed in the control section in October 2006, and this crack did not grow after one year. These test sections were constructed on a lane with a very thin asphalt layer due to the milling operation to match the curb and gutter, which may have contributed to a very small number of reflected cracks. Figure 3-3 depicts the total reflective cracking percentage. The maximum cracking observed on Pave-Dry section is only 16 percent after six years in service. All of the cracks shown here are with low severity. Besides Pave-Dry, only HaTelit and GlasGrid exhibited notable cracks. Otherwise, the remainder of the test sections exhibited very little or no cracking.

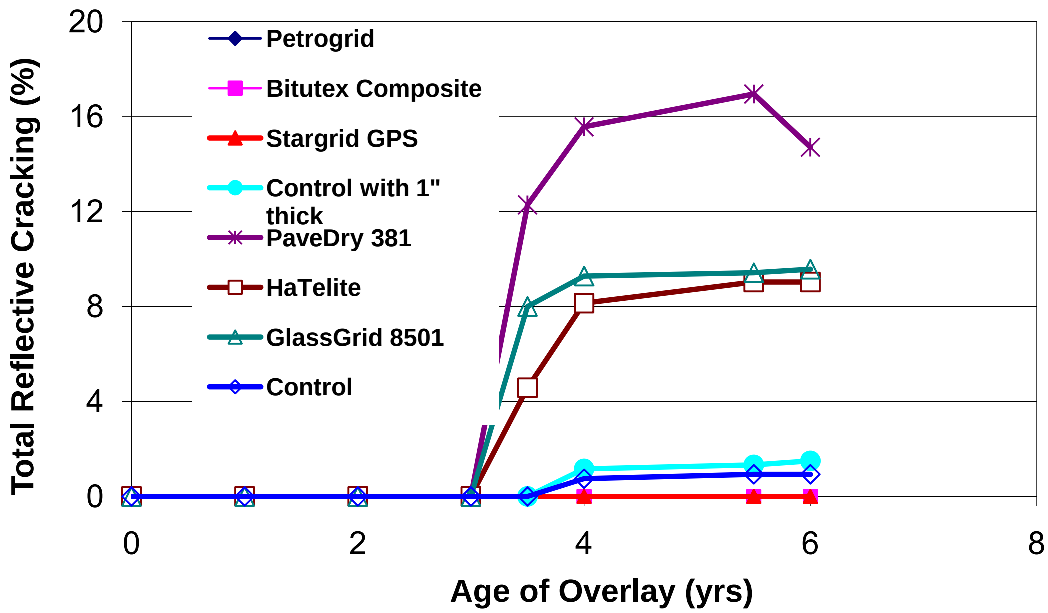


Figure 3-3. Reflective (Total) Cracking vs. Time – Pharr District.

Percentage reflection cracking was calculated separately for transverse, longitudinal, and total cracks using the following equation:

$$\text{Reflective cracking (\%)} = \frac{\text{Length of cracks for a given year (ft)}}{\text{Length of cracks before construction (ft)}} \times 100$$

Ironically, the performance of this whole test pavement, including the control section, was so good (i.e., very low amount of reflective cracking even after six years of service) that the evaluation of geosynthetic products could not be accomplished. Again, the milling operations, which exposed the base layer in some locations adjacent to the curb, may have aided in drastically reducing reflection cracking. This test pavement was probably not a good location to study reflection cracking. The thickness of the existing HMA layer was milled to match curb and gutter. Note, when this project site was initially selected for reflection cracking study there were significant reflection cracking on the existing layer, and TxDOT did not have any plan for milling of the existing layer. Milling of existing layer was included later during construction when the researchers did not have enough time to locate alternate site.

WACO DISTRICT TEST PAVEMENTS

This test pavement is located in the city of Marlin. Lindsey Contractors of Waco, Texas, constructed the test pavements in 2002/2003 on Business 6 in Marlin, as part of TxDOT construction contract CPM 0049-05-006. The seven 500-ft test sections begin at the junction of Business 6 (BUS 6) with State Highway 7 in downtown Marlin and proceed south 3500 ft. Figure 3-4 shows the layout of test pavement.

BUS 6 is a two-lane urban facility, northern part with curb and gutter and southern part without curb and gutter. The terrain is rolling hills with a few large trees in the vicinity of the roadway that shade parts of the pavement in early morning and late afternoon. The existing structure is an old 6-inch jointed concrete pavement with several thin HMA overlays. Construction plans required milling of the HMA down to the existing concrete and repairing any failures in the concrete pavement.

The leveling course was placed in the fall of 2002 and turned over to traffic until the summer of 2003. During this period, some joints and cracks reflected through the thin leveling course, so, on June 10, 2003, the researchers mapped the cracks that were visible at the surface of the leveling course; more than one-half of the original joints/cracks had reflected through the leveling course. The geosynthetic test sections were constructed on BUS 6 during July 2003.

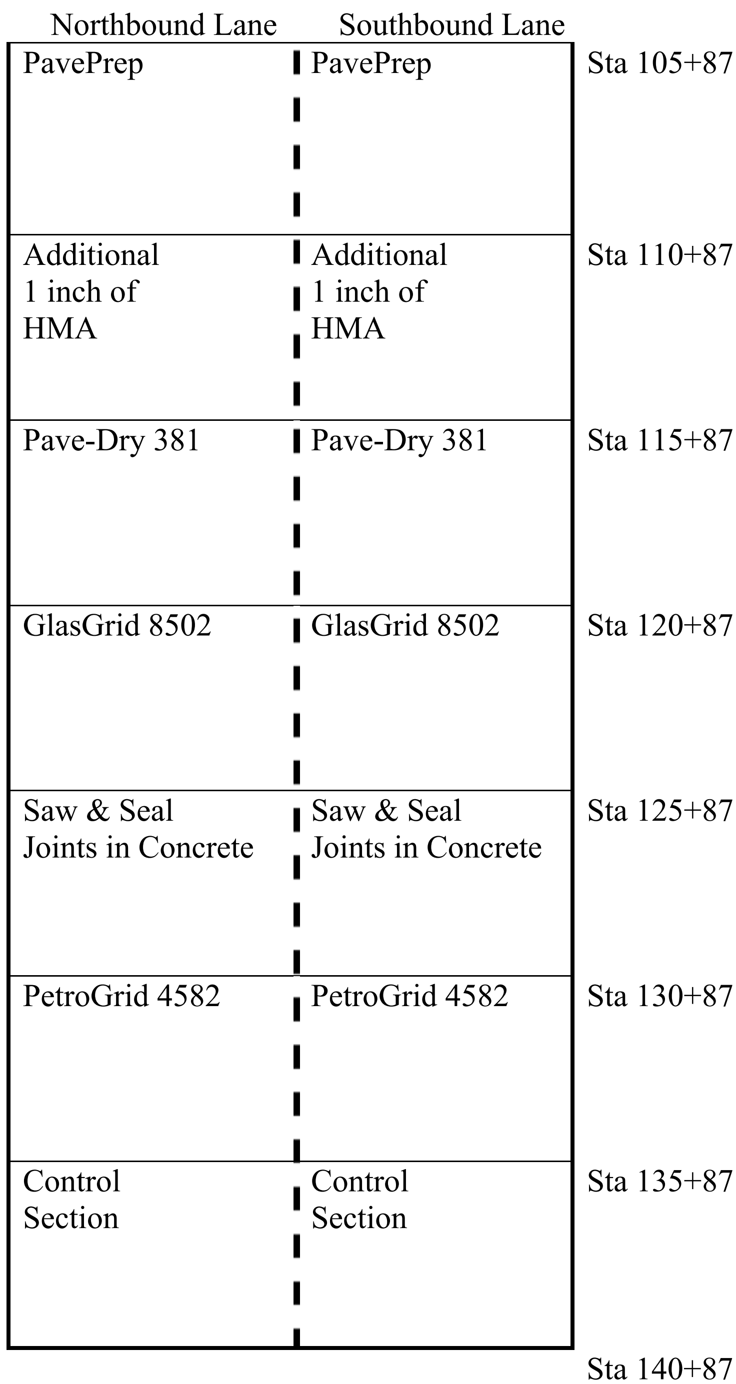


Figure 3-4. Plan View of Test Pavements Placed in Marlin – Waco District.

Details about construction of this test pavement and the placement of geosynthetics along with mixture information can be obtained in Report 0-1777-2 (Button and Chowdhury, 2006).

Test Section Evaluation

Detailed maps showing all cracks and joints visible at the concrete pavement surface after milling were prepared and filed. As mentioned earlier, the research team prepared maps for the cracks that reflected through the leveling course before overlay placement. Researchers evaluated these test pavements on an annual basis until May 2005 to record (map) all cracks or any other forms of distress that appeared. Starting in 2006, visual surveys were conducted on a semi-annual basis. The rationale behind frequent monitoring lies with the fact that the crack propagation rate accelerates as the overlay gets older.

In May 2004, several of the transverse joints in the underlying concrete had reflected through the overlay. The visible cracks matched quite well with the original joints/cracks mapped at the beginning of the project. There were no other signs of pavement distress.

In May 2005, several more joints/cracks had reflected through the overlay. The most notable ones were located at the transverse joints. Figure 3-5 exhibit the cracks observed in 2007 parallel to saw cutting.

Figure 3-5. Cracking Parallel to Saw & Seal in May 2007.

Percentage reflection cracking was calculated separately for transverse, longitudinal, and total cracks using the equation mentioned earlier.

Plots of percentage reflection cracking (transverse, longitudinal, and total) versus time (Figures 3-6, 3-7, and 3-8, respectively) illustrate that most of the reflection cracking is from the transverse joints in the underlying concrete pavement. Recall that the geosynthetic products, except for PavePrep, were placed approximately one year after placement of the leveling course. Therefore, the first points on the graphs represent only the leveling course and the PavePrep. The PavePrep has shown the least reflective cracking from the beginning. Two years after placement of the remaining geosynthetic products, all four geosynthetic products (PavePrep, PetroGrid, Pave-Dry, and GlasGrid) showed less than about 40 percent reflection of the transverse joints, whereas those sections without a geosynthetic product (control, thicker section, and Saw & Seal) exhibited approximately 40 percent or more reflection of the transverse cracks.

Regarding reflection of longitudinal cracks (Figure 3-7) two years after placement of the geosynthetic products, all of the geosynthetic products exhibited less reflection cracking than the control section. All geosynthetic test pavements exhibited less than 10 percent reflection of the longitudinal cracks, whereas the control section exhibited greater than 15 percent.

Subsequent monitoring during in 2006 and 2007 revealed that most test sections developed more transverse and longitudinal reflective cracking at a faster rate compared to the first two years after overlay placement. During this period, some new cracks developed, and the previous cracks grew longer and wider. Most of the reflective cracks observed during the field observation appeared to be of low severity. In some sections, a small amount of medium-severity cracks appeared. During the last visit, only a very small amount of high-severity cracks appeared in the control, thick control, and Pave-Dry sections.

The control section exhibited the most reflective cracks from the beginning, and the same trend continued until the last inspection (Figures 3-6, 3-7, and 3-8). The thick HMA section appeared slightly better than the control section. All other treatments exhibited some improvement until three and a half years after overlay placement. After this time, the Pave-Dry section suddenly exhibited more reflective cracking. All others (except PavePrep) followed a similar trend of a faster rate of cracking after four years.

Performance of Saw & Seal with respect to resisting transverse reflective cracks is among the worst, whereas its resistance of longitudinal cracks is among the best. Again, these cracks developed only one year after overlay construction. Most transverse cracks appeared parallel to the Saw & Seal line and about 6 to 12 inches away (Figure 3-5). This is because, during construction, the transverse saw cuts were not right along the concrete joint. Even though the Saw & Seal section exhibited cracks early, its growth was slower in later years (Figures 3-6–3-8). The overall performance of the Saw & Seal section is somewhat in the middle of all other sections.

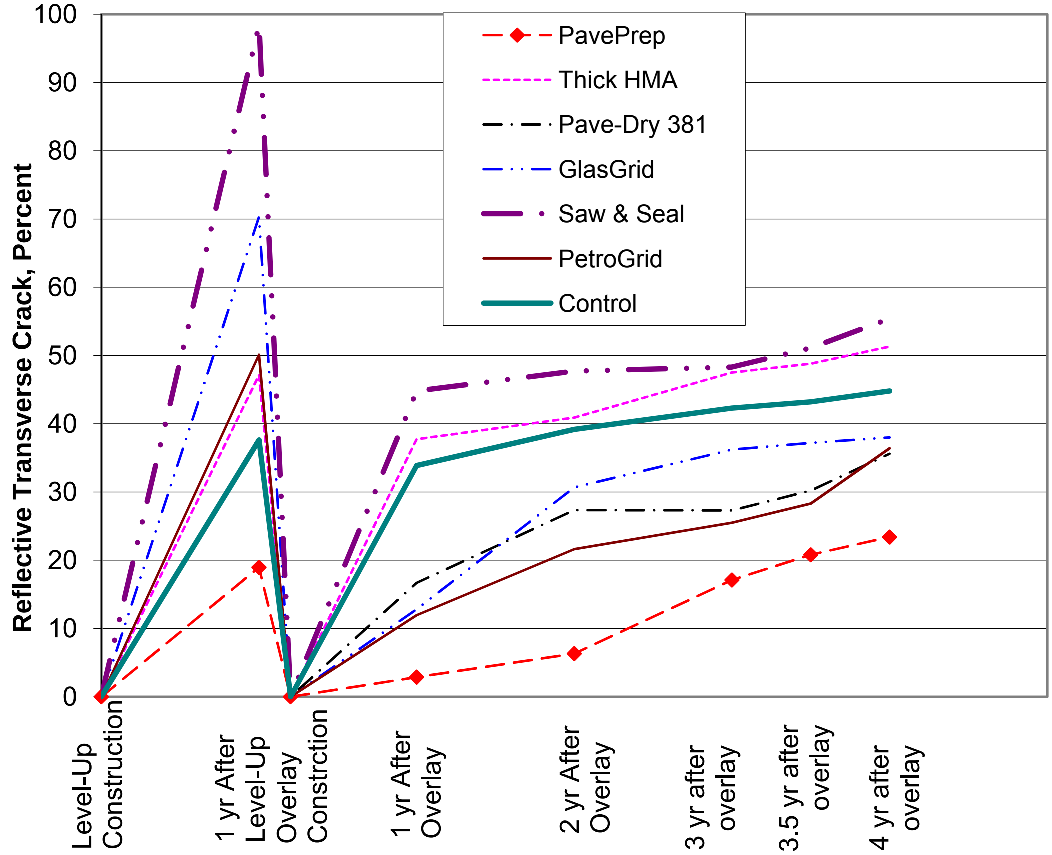


Figure 3-6. Reflective (Transverse) Cracking vs. Time – Waco District.

In the Waco test pavement, PavePrep consistently showed the best performance. Recall that the PavePrep was placed on the top of repaired joints before the placement of the leveling course. The overall performance of all the products and techniques proved to be effective to various degrees compared to the performance of the control section.

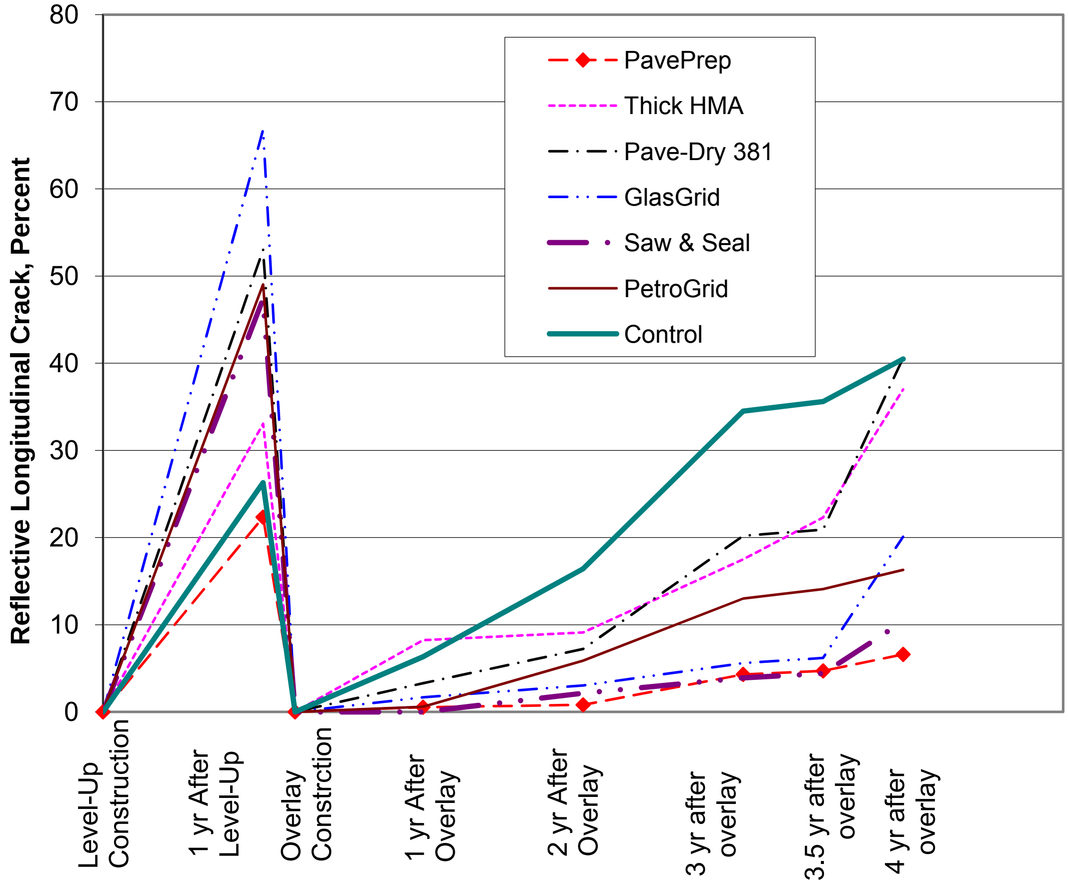


Figure 3-7. Reflective (Longitudinal) Cracking vs. Time – Waco District.

Alternatively, percent cracking after overlaying was recalculated based on the cracks measured on the leveling course instead of the original cracks/joints in the concrete measured before construction. Graphs similar to Figure 3-6, 3-7, and 3-8 were redrawn based on the new calculation and documented in the Appendix. These new graphs show that some sections have more than 100 percent reflective cracking, which indicates that the leveling course did not exhibit 100 percent reflective cracking during the cracking measurement of the leveling course (just prior to placement of overlay).

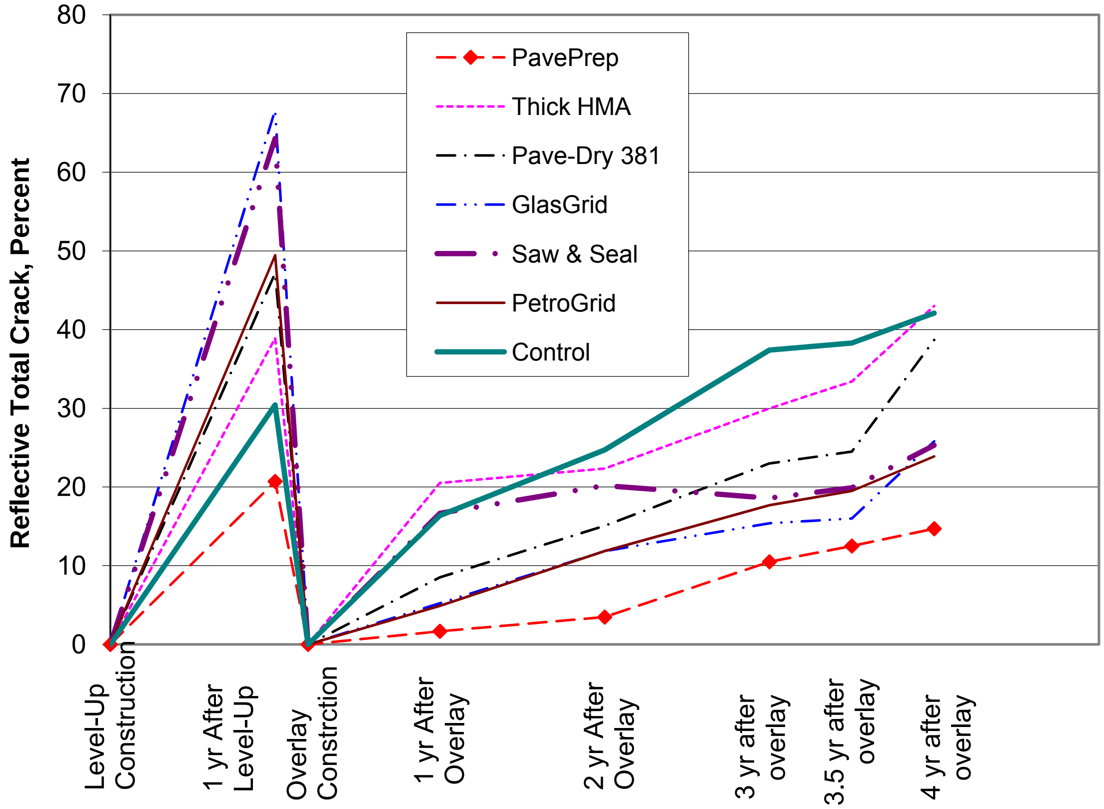


Figure 3-8. Reflective (Total) Cracking vs. Time – Waco District.

The local TxDOT maintenance office filled most of the cracks with crack sealant during the 2007–08 season.

AMARILLO DISTRICT TEST PAVEMENTS

Test pavements were constructed in the Amarillo District on SH 136 just northeast of Amarillo in the summer of 2002. Details of this project are found in the plans for TxDOT project CPM 379-3-19. However, the actual locations (Figure 3-9) of some of the test pavements were modified from those station numbers listed on the TxDOT plans.

This segment of SH 136 is a two-lane, rural facility in a relatively flat plain. The existing structure consists of 12 inches of flexible base, 4 inches of asphalt-stabilized base, and 3 inches of asphalt concrete pavement. Typically, the construction plans require placement of a 1-inch leveling course of Type D containing PG 70-28, reflection cracking treatment, and then a 2-inch HMA overlay of Type D containing PG 70-28. All geosynthetic products were placed on top of the leveling course in 500-ft test sections in both travel lanes. There were 11 different test sections with and without geosynthetic products. Besides the control and grid/fabric sections, there were sections with 1-inch thicker HMA, porous friction course (PFC) with and without underlying seal coat, and hot-in-place recycling of HMA. Figure 3-9 presents the plan view of all Amarillo test sections.

Detailed maps showing all cracks visible at the surface of the original pavements were prepared prior to construction for future comparisons. The original pavement had a very large number of both longitudinal and transverse cracks. Before construction, there were approximately 150 ft of longitudinal cracks per 100-ft station per lane. There were also six to seven transverse cracks per 100-ft station. More details about construction, placement of geosynthetic products, and mixture design can be found in Report 0-1777-2 (Button and Chowdhury, 2006).

Test Section Evaluation

These test pavements have been evaluated each spring since construction. Detailed crack maps have been prepared for each section. Findings from each evaluation are tabulated in the Appendix. Percentages of reflective cracking were calculated each year for each section based on the total cracks observed for that particular section before construction.

In June 2003, one year after overlay construction, the surfaces of the test pavements were in excellent condition with no signs of cracking, rutting, flushing, or raveling. Although a few short transverse cracks had developed in the shoulder (where no geosynthetic products were placed), the researchers did not detect any cracks in the travel lanes. Only one crack was observed at the transverse joint (transition) between the PaveTrac and HaTelit sections. Figures 3-10 and 3-11 show some pictures from more recent visits at Amarillo test pavements in 2007.

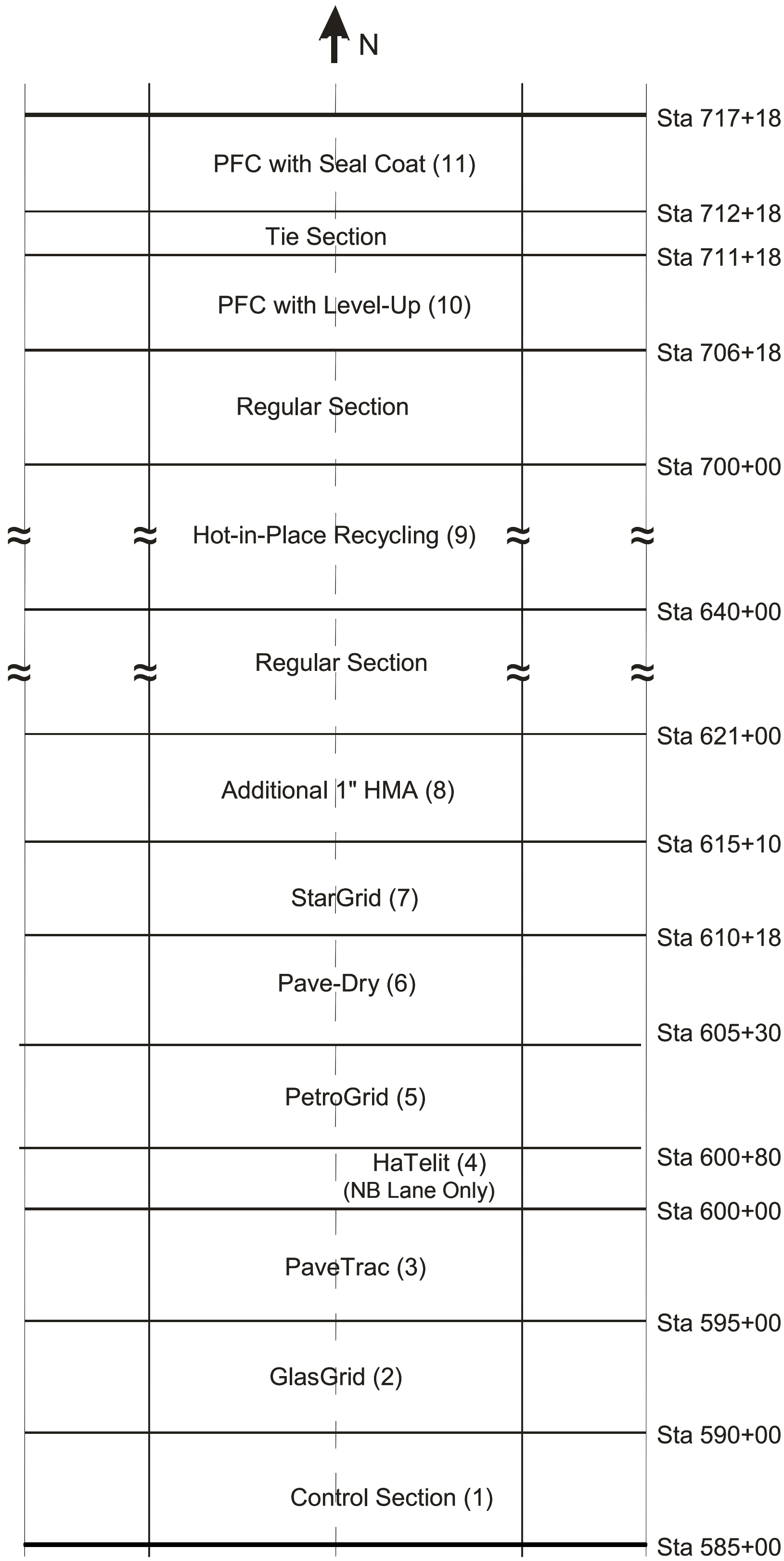


Figure 3-9. Amarillo Test Pavement Layout.

Figure 3-10. Reflective Crack on Amarillo Test Pavement in 2007.

Figure 3-11. Typical Reflective Crack on Amarillo Test Pavement in 2007.

In April 2004, the surfaces of the test pavements generally appeared to be in excellent condition. Minor transverse and longitudinal cracks were observed in some of the test sections. The PFC with seal coat did not exhibit any cracking, but the PFC with a leveling course exhibited a few short, narrow longitudinal and transverse cracks. The PFC with seal coat developed a few small potholes.

The hot-in-place recycled section is quite long (almost 6000 ft). Only the first 500-ft segment from the north end was selected for evaluation. The hot-in-place recycled section exhibited very few transverse cracks. Only one transverse crack developed by 2004 in the southbound lane of the StarGrid® section. The Pave-Dry section showed only a few very short transverse cracks. No cracks were observed in the travel lane of the PetroGrid® section. HaTelit comprised a very short section (80 ft) and only in the northbound lane. The researchers observed the HaTelit section, realizing that the findings were not statistically valid. A few short, narrow cracks were noticed in the PaveTrac® section, and the longitudinal joint along its centerline was prominent. A few spots in the southbound lane of PaveTrac experienced mild raveling (Figure 3-12) in 2004 and some potholes (Figure 3-13) in 2006. Several cracks initiated on the shoulder and barely penetrated the travel lane of the GlasGrid section. Some places on the surface of the GlasGrid and control sections exhibited a few very thin, alligator-like cracks, probably due to the checking that occurred during construction. Otherwise, the GlasGrid and control sections looked good.

Figure 3-12. Raveling Observed in the PaveTrac Section in 2004.

Figure 3-13. Pothole Observed in PaveTrac Section in 2006.

By April 2005, some of the cracks in the overlay had grown longer, and in some cases, wider. Development of some totally new cracks was observed as well. TxDOT had repaired small pot holes that developed in 2004 in the PFC/seal coat section. This section had very few cracks. The PFC/leveling course exhibited a few new transverse cracks, particularly in the northbound lane. The northbound lane of the hot-in-place recycled section had almost no transverse cracks, but a significant number of new cracks had developed in the southbound lane since the 2004 evaluation.

A few new cracks developed in the StarGrid section. Some of the transverse cracks that had developed in the shoulder were beginning to enter the main lane. The northbound lane and shoulder of the Pave-Dry section exhibited no cracks, but the southbound lane had a few transverse cracks that initiated in the shoulder in 2004 and entered the main lane in 2005. The Pave-Dry surface looked good. A few short transverse cracks had initiated during the past 12 months. A few short transverse cracks appeared in the southbound lane of the PetroGrid section during the year, whereas no crack was noticed in the northbound lane or shoulder.

No new cracks developed in the short HaTelit® section. The transverse crack that originally developed two years before grew somewhat longer. A few new short, narrow transverse cracks had initiated during the past year in the PaveTrac section. The longitudinal joint along the centerline was quite prominent. A few longitudinal cracks were observed in the southbound shoulder. Raveling was observed in the southbound lane of the PaveTrac section. The PaveTrac section exhibited several short, parallel transverse cracks in a short segment that appeared to have initiated from the centerline. Most likely, these cracks developed due to lateral movement of wire mesh underneath the paving machine during the construction. The PaveTrac surface was not as good as the other sections.

In 2005, the GlasGrid section exhibited several cracks that had initiated in 2004 and grew longer and a few more short transverse cracks that initiated during 2005. Some places on the surface of the northbound GlasGrid section still showed the checking observed during construction. The control section developed a few new transverse cracks in the main lane and shoulder as well, and the cracks that developed in 2004 had grown a little longer and wider.

During the field visits in 2006 and 2007, the research team observed more cracking in these test sections. Very few new cracks developed; but some of the previous cracks grew longer and wider. During this period, growth of longitudinal cracks on PFC/leveling course significantly slowed down. On the contrary, transverse cracks on the same section grew rapidly. GlasGrid and hot-in place recycling sections exhibited rapid growth of both transverse and longitudinal cracks. Figures 3-14 through 3-16 present the growth of transverse, longitudinal, and total reflective cracks, respectively.

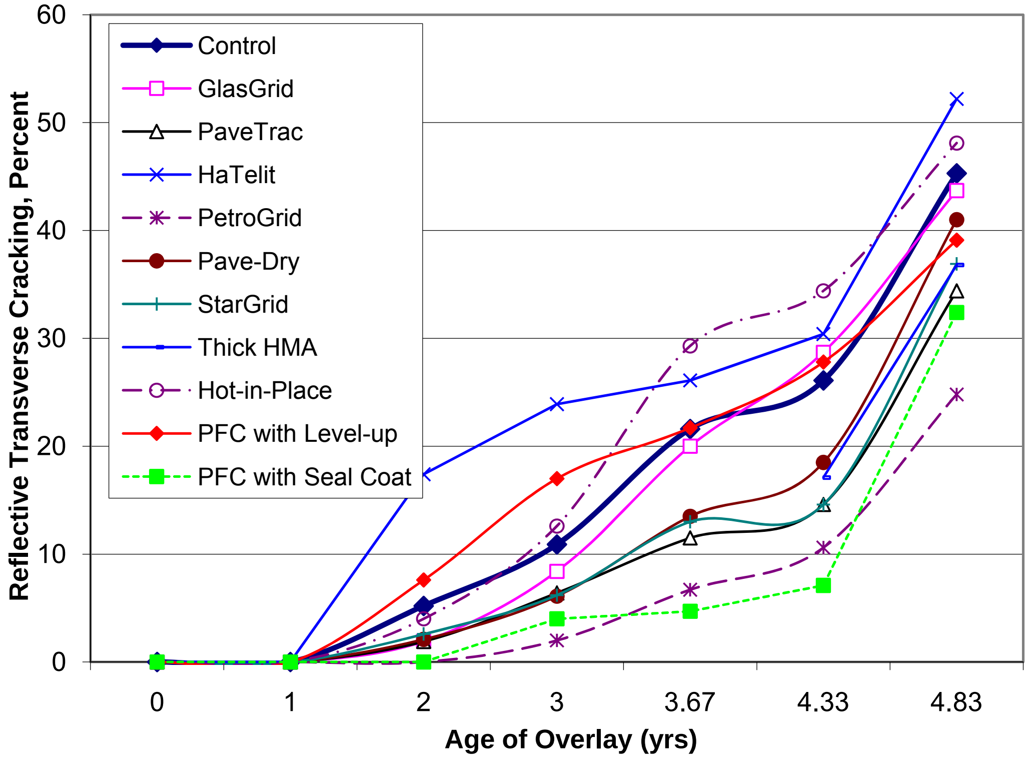


Figure 3-14. Reflective (Transverse) Cracking vs. Time after Placement.

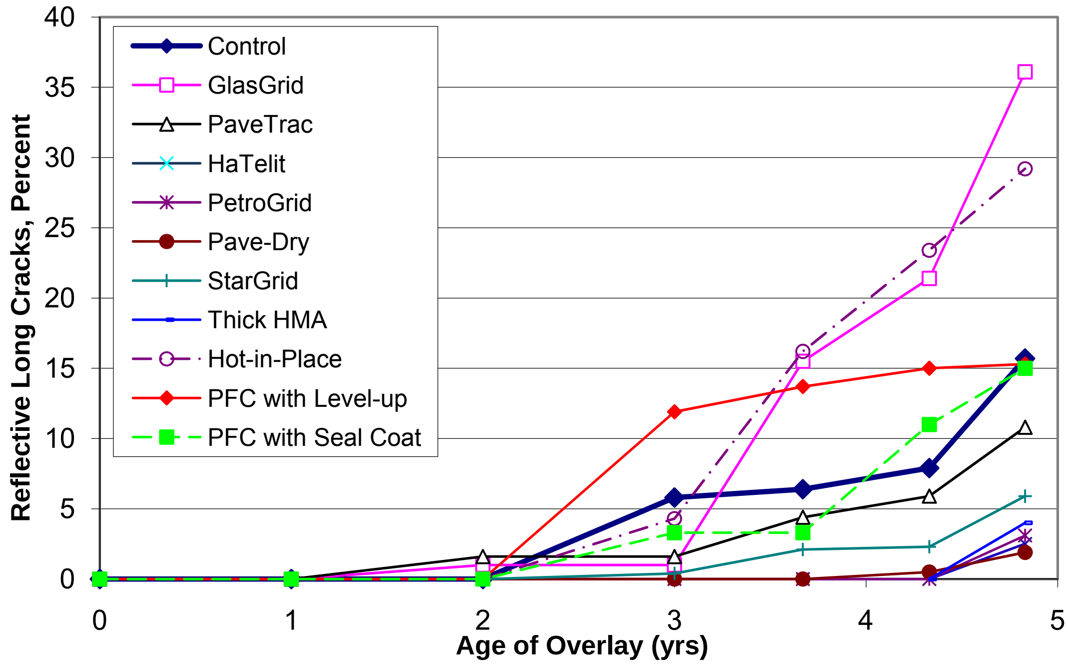


Figure 3-15. Reflective (Longitudinal) Cracking vs. Time after Placement.

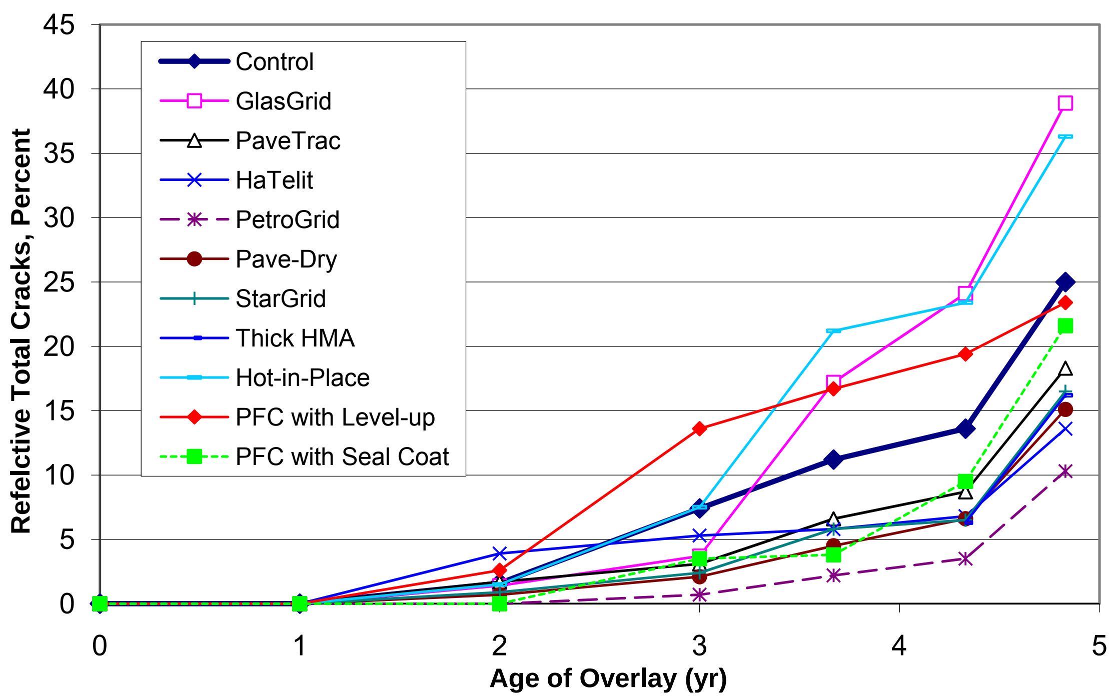


Figure 3-16. Reflective (Total) Cracking vs. Time after Placement.

Until the last field visit, most of the transverse and longitudinal cracks observed in this test pavement were with low severity. Only a few sections exhibited very small amounts of medium-severity cracks. Most of the sections (including control and GlasGrid and hot-in-place recycling) exhibited slowly increasing crack growth until four years after overlay; thereafter, the growth suddenly increased at a faster rate. GlasGrid and Hot-in-Place recycling sections started showing faster crack growth from the third year. The southbound lane with GlasGrid performed significantly better than the northbound lane with GlasGrid. In this section, only the southbound lane used tack coat. The HaTelit section performed poorly in resisting transverse reflective cracking but performed well in resisting longitudinal reflective cracking. Only 80 ft of HaTelit was placed in only one direction due to difficulties of placement during construction.

Overall, the composite products performed better than the other types of treatments. In this test pavement, their (composite geosynthetics) relative crack resisting potential began diminishing after four years in service. Compared to the performance of the control section, they demonstrated better performance until about five years in service. The local TxDOT maintenance office filled some of the cracks during the 2007–08 season.

SUMMARY

Among these three test pavements, the Pharr site was probably not a good location to study reflection cracking due to milling of the existing HMA layer. The minimal reflection cracking observed at this site was not included in overall analyses. Among the two other sites, one was with composed of jointed concrete pavement, which is typically subjected to more severe stresses that lead to reflection cracking. Considering these facts, it is noted that the field data are limited in their representation of the development of reflection cracking on pavements.

CHAPTER 4:
LABORATORY TESTING OF FIELD SPECIEMENS

BACKGROUND

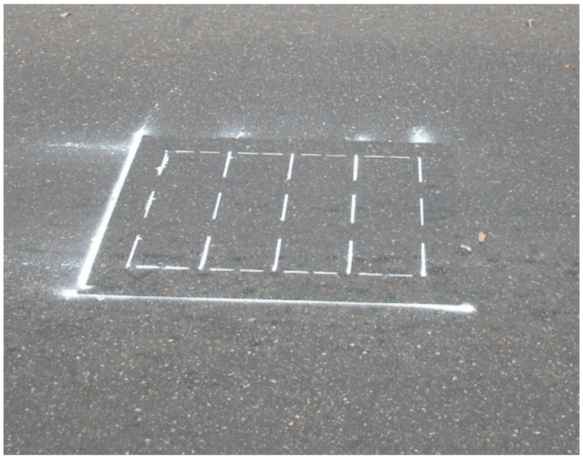
One of the objectives of this phase of the project was to utilize the resulting field data to calibrate and validate the FPS-19 Design Check software that was developed during the original project period. In order to properly calibrate and validate the FPS-19 Design Check model, it was necessary to measure not only the cracking but also the material properties that were used in the development of the model. These material properties were obtained from laboratory tests using the large (6-inch specimen width) TTI overlay tester and derived using fracture mechanics on the test results.

Further, TxDOT invested significant resources in procuring several small TTI overlay testers for routine testing. The small overlay tester typically tests with 6-inch long and 3-inch wide HMA specimens. TxDOT personnel desired to determine the material properties of this wide variety of actual in-place test pavements to calibrate/validate the Design Check software and to determine whether the large and small overlay testers yield essentially the same values for HMA and HMA composite material properties. Another rationale behind using the small overlay tester is that preparing large composite beam specimens in the laboratory or obtaining large beam specimens from the field is very cumbersome and labor intensive.

Sample Collection

The research team initially decided to obtain four large specimens from each of the test sections at all three test locations and three small specimens from each of the test sections at one location. If the small specimens collected from one test pavement could produce comparable results with large specimens from the same test pavements, the research team would collect small specimens from the two other locations. Herein, large specimens typically refer to the specimens that are 15- to 18-inches long and 6-inches wide.

All four large and small specimens from a given test section were obtained from one single location. This was done to minimize variability between the specimens. Sectional specimens were obtained in a location where there were no cracks. Figure 4-1 shows the typical specimen collection sequence.



(a) Setting Template Marking (b) Sawing Along the Template Marking

(c) Pavement after Saw Cut (d) Removal of Specimens

(e) Empty Trench (f) Trench Filled up with Coldmix

Figure 4-1. Specimen Collection Sequence at Pharr Test Section.

A location between the wheelpaths was marked with paint over a prefabricated template as shown in Figure 4-1(a). The research team planned to test the specimens with overlay plus leveling course, including any geosynthetic materials in the interface. A large saw was used to cut along the white lines. Figure 4-1(c) shows the pavement after saw cutting. Specimens were very carefully removed from the pavement using a crowbar in order to maintain the specimen integrity. Removal of some of the surrounding material made it easier to retrieve large specimens and minimize damage. The trench was patched by filling with cold mix and compacting using a portable compactor.

Obtaining specimens from each test pavement posed unique challenges. Figure 4-1 shows specimen retrieval from the Pharr test pavements, which was the easiest among the three locations. The main challenge was to separate the desired layers (top two layers) from the underlying layer(s) without damaging the specimen. The Amarillo test pavement consisted of almost 8 inches of asphalt layers (including asphalt stabilized base). In order to retrieve undamaged large specimens, the research team removed 8-inch thick rectangular specimens, which resulted in very deep trenches in the pavement. Later, these specimens were trimmed to the appropriate size in the laboratory. Due to the application of a seal coat (underseal) with tire rubber at the Waco test site, the bonding between the leveling course and existing concrete layer was very strong, which made it very difficult to separate the HMA layers from concrete layer. As a result, the research team could not obtain the desired number of specimens from some of the Waco test sections. No PetroGrid specimen could be obtained from the Waco section due to its strong bonding with concrete. District personnel were reluctant to allow the researchers to keep sawing holes until specimens could be successfully obtained.

In Amarillo, specimens were not obtained from the two PFC sections. No GlasGrid (without tack) specimen could be retrieved from the northbound lane due to separation at grid interlayer. However, GlasGrid specimens from the southbound lane (with tack coat) were obtained. Specimens from all eight sections in Pharr were successfully collected. But the PetroGrid specimens from Pharr had such a thin leveling course layer that they were unsuitable for testing in the overlay tester. At the Waco site, specimens from PavePrep and Saw & Seal sections were not planned because of the technical difficulties of meaningfully testing those specimens using the overlay tester.

Sample Preparation

Specimens from the field were transported to the TTI laboratory with great care so that specimens were not damaged. Once the specimens were brought to the laboratory, they were further processed for testing. The bottom part of the specimens was trimmed to obtain a smooth, flat surface with a uniform thickness of leveling layer. A smooth, flat bottom surface was necessary for proper gluing to the test plates. The top surface was not disturbed. The large specimens were sawed to 18 inches in length and 6 inches in width. Some of the specimens from the Pharr test pavements had variable leveling thickness. The small overlay specimens were sawed to 6 inches in length and 3 inches in width. For a given test section, the same thickness was maintained for both small and large specimens. After sawing, all the dimensions of each specimen were measured, including thickness of the leveling layer and overlay. Density of the whole specimen was measured. The specimens were dried using a fan at room temperature for one week. Removal of all the moisture was necessary to facilitate proper bonding with overlay tester plates. All four vertical sides were painted with white paint in order to track the crack propagation during testing with overlay tester.

TESTING WITH TTI OVERLAY TESTERS

Germann and Lytton (1979) designed the original TTI overlay tester to simulate the opening and closing of joints or cracks, which are the main driving force inducing reflection crack initiation and propagation. Later, this overlay tester was further modified and developed (Zhou and Scullion, 2003). Two types of overlay testers have been successfully used at TTI to evaluate the effectiveness of geosynthetic materials on retarding reflection cracking.

The overlay tester data include the time, displacement, and load corresponding to a certain number of loading cycles. In addition, crack length can be manually measured. Two types of information can be gained from the overlay tester: one is the reflection cracking life of a hot mix asphalt concrete mixture under certain test conditions; the other is fracture parameters of a hot mix asphalt concrete mixture.

Figure 4-2 depicts the key parts of the apparatus. The dimensions shown in this figure correspond to the small overlay tester. The large overlay tester works in a similar way, except that the width and length of testing plates are larger. An overlay tester consists of two steel plates; one is fixed, and the other moves horizontally to simulate movement of the underlying layer. Load is applied in a cyclic, triangular waveform that maintains consistent plate displacement during each cycle. Typically, the overlay test is conducted at room temperature (77°F) in a controlled displacement mode at a loading rate of one cycle per 10 seconds with a maximum displacement of 0.025 inches until failure occurs. This amount of horizontal movement is approximately equal to the displacement experienced by portland cement concrete (PCC) pavements undergoing a 30°F temperature change with a 15-ft joint or crack spacing (Zhou and Scullion, 2003).

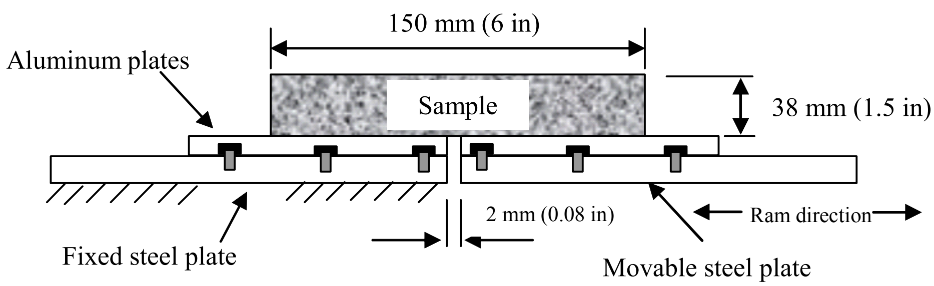


Figure 4-2. Schematic Diagram of TTI Overlay Tester System.

As mentioned earlier, the research team wanted to test field specimens to obtain the input for the calibration FPS-19 Design Check. More details about the overlay testers can be found in Research Report 0-1777-1 (Cleveland et al., 2002). Typically, the large overlay tester is used for testing large specimens and composite (specimens with different layers) specimens, whereas the small overlay tester is used for smaller specimens of monolithic HMA. During this project, as per TxDOT's request, the research team made an attempt to test specimens from the same test section using large and small overlay testers.

During Phase I, the research team used only the large overlay tester. The large overlay tester was needed to accommodate the samples that have geosynthetic materials since the large specimens represent the field conditions of failure better for composite materials. This conclusion is later supported by the laboratory testing. The test protocol followed in this project is shown in Figure 4-3. The rationale behind selecting this loading sequence can be found in Research Report 0-1777-1 (Cleveland et al., 2002). There was a slight difference between the protocols used in Phase I and Phase II. Previous protocol used 0.07-inch displacement for cyclic loading. TxDOT currently uses 0.025 inches of displacement for the evaluation of HMA cracking potential using the small overlay tester. As per TxDOT's suggestion, the research team adopted the 0.025-inch displacement for the cyclic loading segment while testing these composite beam specimens obtained from the field.

All the beam specimens were tested to failure in a controlled displacement mode in two phases, as shown in Figure 4-3. Phase I consists of a constant displacement waveform having a ram displacement of 0.01 inch. Measurement of displacement and load from 5 to 35 seconds was used to determine the relaxation modulus curve. Phase II testing was continued until failure occurred at a loading rate of one cycle per 10 seconds using a cyclic triangular displacement waveform having a ram displacement of 0.025 inches.

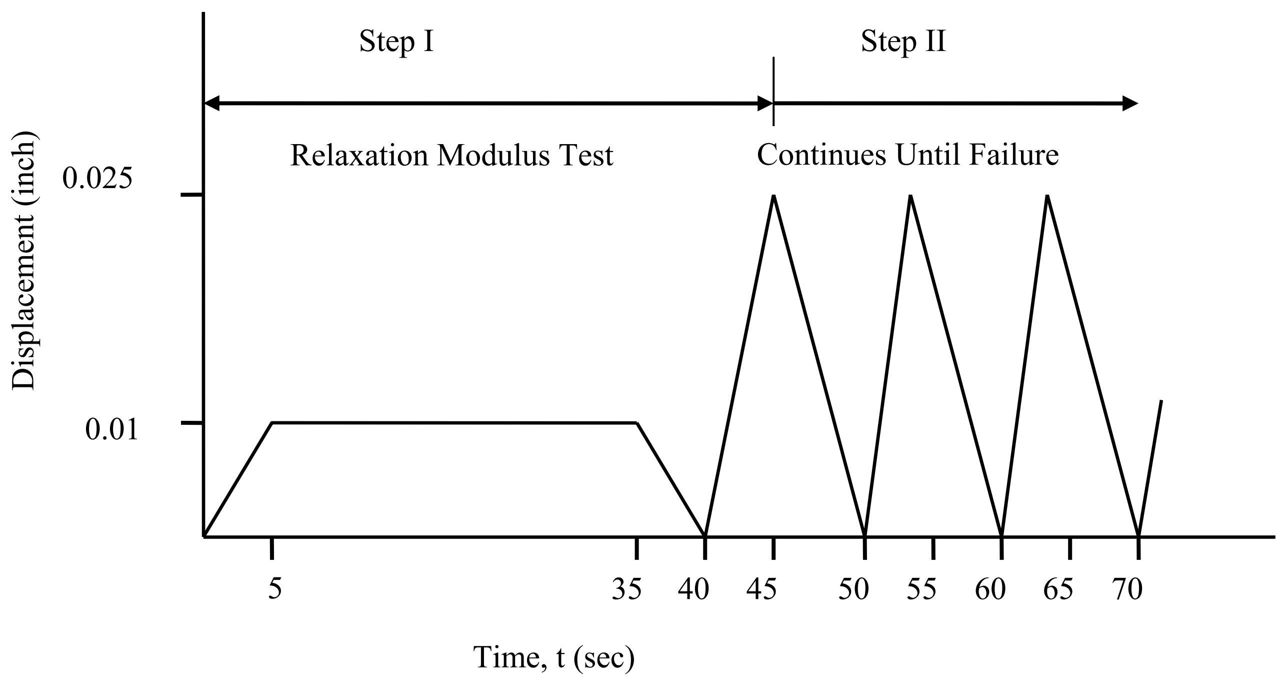


Figure 4-3. Schematic Diagram of Loading Used in Overlay Tester.

During the test period, an automated data acquisition system recorded the displacement and load at every 0.01 second. Figure 4-4 exhibits a typical data set acquired during the first 100 seconds for a specimen tested using the large overlay tester. The small overlay tester produced a similar graph, except that the magnitude of load is much smaller. Since the cyclic displacement was kept constant at 0.025 inches, the load required to cause such displacement started decreasing. Propagation of the crack reduced the load required to induce constant displacement. Throughout the test procedure, propagation of crack was closely monitored by drawing a parallel line along the crack(s) observed on the three sides of the beam specimens. Cyclic displacement was continued until failure of the specimen. Failure is defined as the condition when continuous crack(s) are visible along both sides and the top of the specimen. But, on occasion, this condition was not observed; instead, intermittent cracks were observed and remained like that for several cycles. In those situations, the test was discontinued when the observed load remained constant for a long time (several hundred cycles). At the end of the test, the crack propagation map was photographed from all three sides of the specimens and filed for future analyses (Figure 4-5, Figure 4-6).

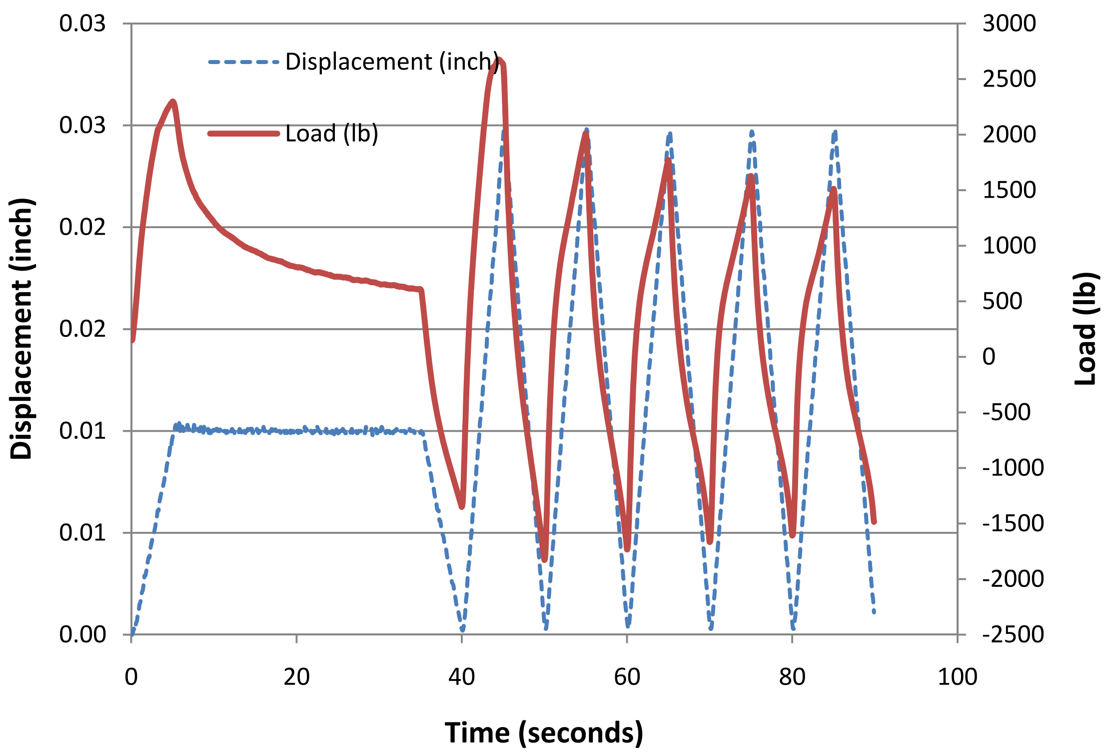


Figure 4-4. Data Acquired during the Overlay Test of a Large Specimen.

Large Overlay Tester

Fifty-four large specimens from the three test locations were successfully evaluated using the large overlay tester. Testing with a few specimens ended abruptly due to failure of the glue between the specimen and the testing plate. These specimens could not be retested. Crack propagation was manually recorded along with the automated data acquisition. Tables 4-1 through 4-3 show the number of load cycles required to fail the specimens from Amarillo, Pharr, and Waco test pavements, respectively. Figures 4-9 through 4-11 depict the same results in a graphical form. In a few cases, cracks initiated at the bottom near the joint during the first part of the relaxation modulus test, even though the displacement was only 0.01 inch. Usually, vertical cracks reached the geosynthetic interlayer rather quickly. In general, it took much longer for the cracks to propagate vertically upward into the top layer (overlay). A few specimens with geosynthetics showed propagation of horizontal cracking along the interlayer (as shown in Figure 4-5) rather than moving upward.

Figure 4-5. Test Setup with Large Overlay Tester.

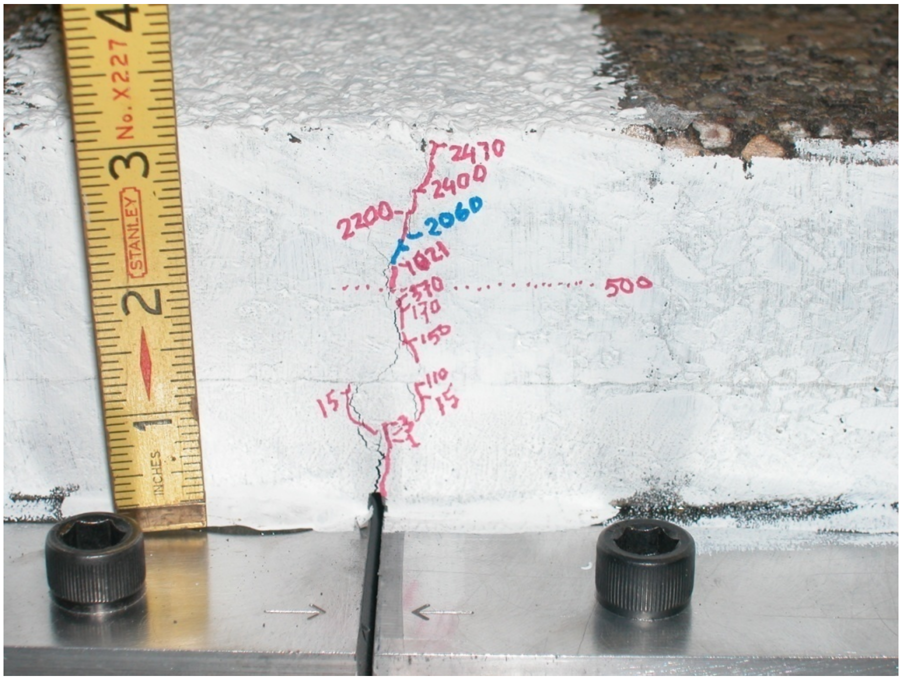


Figure 4-6. Monitoring of Crack Propagation with Large Specimens.

Small Overlay Tester

The researchers made an attempt to test small composite beams using the small overlay tester to evaluate whether it can deliver results similar to the large overlay tester. Approximately 15 specimens (6-inches long and 3-inches wide) from the Amarillo test pavements were tested. Crack propagation was manually recorded along with automated data acquisition. Figure 4-7 shows the test setup.

Most of the small specimens failed due to separation along the interlayer instead of crack propagation vertically upward to the top surface. Therefore, in most cases, tests were terminated very quickly. The reason for this is that the shearing strength at the interlayer was relatively low due to its smaller surface area relative to the larger overlay specimens. Consequently, specimens from other test pavements were not tested using the small overlay tester.

Figure 4-7. Testing of Small Specimen with Small Overlay Tester.

Testing of Medium Sample Using Small Overlay Tester

Since TxDOT already invested significant resources in the small overlay tester, TxDOT engineers were interested in further evaluating whether the small overlay tester was capable of testing composite specimens. Once the research team was confident that composite specimens with 6-inch length and 3-inch width could not be tested using the small overlay tester, they made an attempt to test slightly larger specimens. Specimens were trimmed to 9-inches long and 3-inches wide. Figure 4-8 shows this medium-sized specimen setup for testing using the small overlay tester. Four specimens from Pharr (GlasGrid and HaTelit) were prepared and tested accordingly. Unfortunately, all four specimens separated at the interlayer during the testing. Testing of medium-sized composite beams using the large overlay tester yielded similar results. This led the research team to believe that composite beams can be tested only by using large specimens with the large overlay tester.

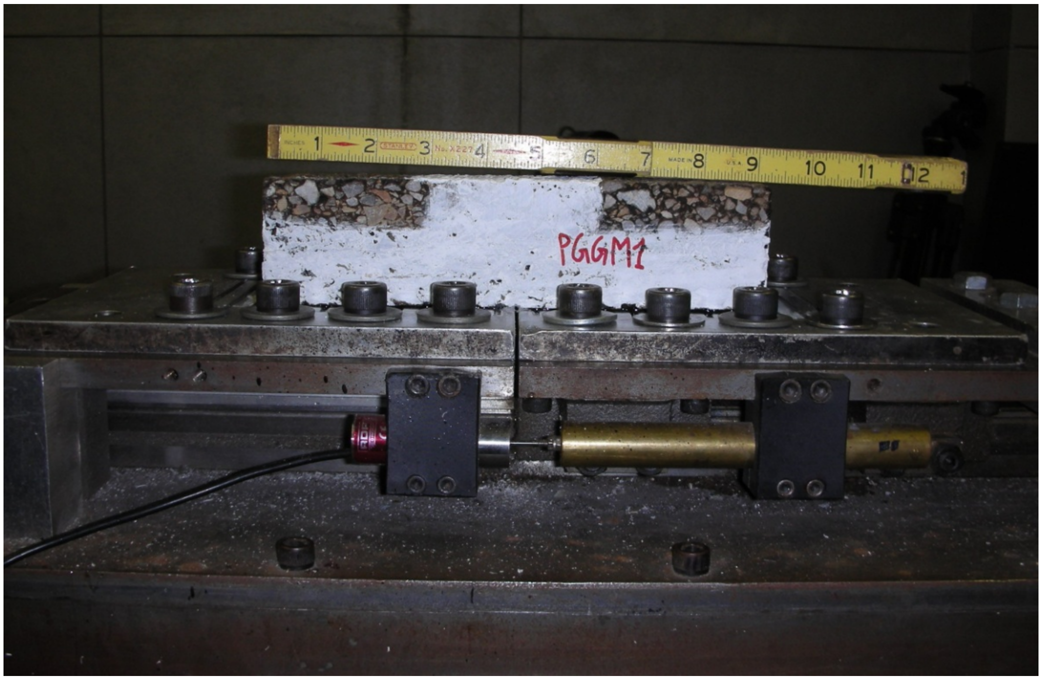


Figure 4-8. Test Setup of Medium-Sized Specimen with Small Overlay Tester.

OVERLAY TEST RESULTS

Most of the small- and medium-sized specimens that were tested using the small or large overlay tester failed due to separation of the layers at the interface between the leveling course (bottom layer) and overlay (top layer). This was contrary to expectations that the crack would propagate upward to the top surface. Due to this fact, researchers could not further analyze the results with these small specimens.

Tables 4-1 through 4-3 and Figures 4-9 through 4-11 present results from the large overlay tester using beam specimens from all three test pavements. Table 4-1 and Figure 4-9 exhibit significant variation in load cycles to failure for the sections near Amarillo. The control section demonstrated the lowest load cycles, whereas StarGrid survived the most load cycles. PetroGrid survived the second highest number of load cycles. Thick HMA and hot-in-place recycle sections were somewhat better than the control section. GlasGrid, Pave-Dry, and PaveTrac were more in the medium category. Overall, there was large variability in the number of cycles to failure for most of the test sections.

Table 4-1. Large Overlay Tester Results with Amarillo Specimens.

Section Name	Specimen ID	Cycles to Failure
Control	ACL1	14
	ACL2	180
	ACL3	571
	Average	**255**
GlasGrid (Southbound lane only)	AGGL1	325
	AGGL3	650
	AGGL4	800
	Average	**592**
PaveTrac	APTL1	754
	APTL2	1105
	APTL3	800
	Average	**886**
HaTelit	AHTL1	400
	AHTL3	540
	Average	**470**
PetroGrid	APGL1	2600
	APGL2	1500
	APGL3	1500
	Average	**1867**
Pave-Dry	APDL1	130
	APDL2	1209
	Average	**670**
StarGrid	ASGL1	2800
	ASGL2	2000
	Average	**2400**
Thick HMA	ATHL1	576
	ATHL2	360
	ATHL3	397
	Average	**444**
Hot-in-Place Recycle	ARL1	45
	ARL2	652
	ARL3	641
	Average	**446**

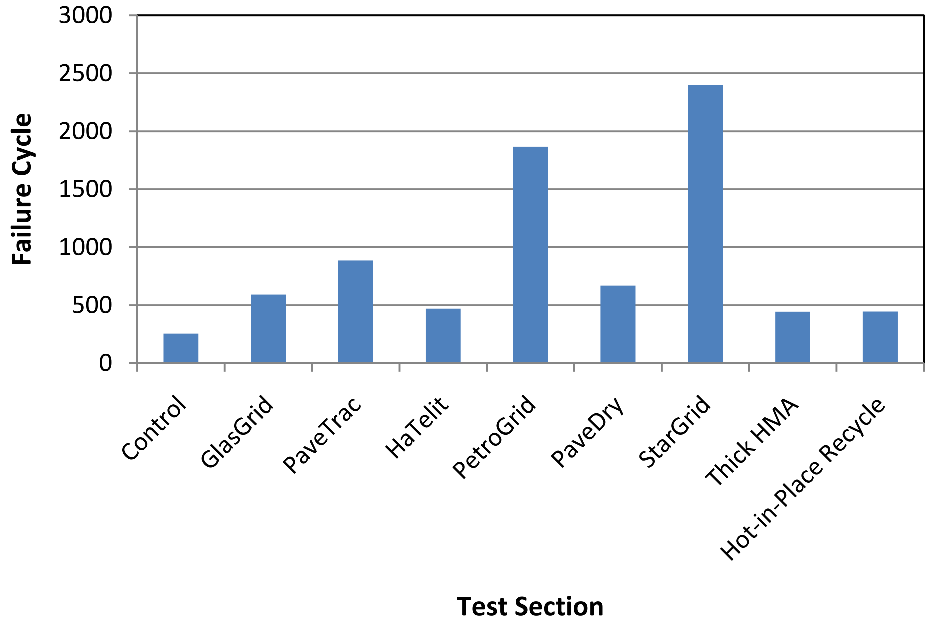


Figure 4-9. Large Overlay Tester Results with Amarillo Specimens.

Specimens from the control section in the Pharr District survived a large number of load cycles compared to the other test pavements. This indicates that the overlay mixture itself was comparatively very crack resistant. The idea that the HMA used in this overlay is very crack resistant is supported by the field observations. Even after six years in service, only a very small amount of cracks were reflected in this test pavement. HaTelit and Pave-Dry specimens from the Pharr pavement exhibited relatively early failure. Most likely, this early failure is attributed to the specimens' configuration rather than their geosynthetic properties. Some specimens had a very thin bottom layer (due to milling of existing HMA surface). Milling away of most of the cracks in the existing HMA layer may have contributed to lower cracking reflection potential in the overlay.

Table 4-2. Large Overlay Tester Results with Pharr Specimens.

Section	Specimen ID	Cycles to Failure
Control	PCL1	1000
	PCL3	1500
	Average	**1250**
GlasGrid	PGGL1	1280
	PGGL2	1000
	PGGL3	500
	Average	**927**
HaTelit	AHTL2	100
	AHTL4	450
	Average	**275**
Pave-Dry	APDL1	480
	APDL3	17
	Average	**249**
Thick Control	PTHL1	2000
	PTHL3	1500
	Average	**1750**
StarGrid	PSGL2	1500
	PSGL4	1500
	Average	**1500**
Bitutex	PBCL1	400
	PBCL3	3000
	PBCL4	2000
	Average	**1800**

Table 4-3 and Figure 4-11 present results from the large overlay tester for the Waco test pavement. Specimens containing a geosynthetic survived a significantly large number of load cycles compared to the specimens without a geosynthetic (control and thick control). During the field observations, it was noted that these same test sections performed better than the control section but not as much as their superior performance observed in laboratory testing.

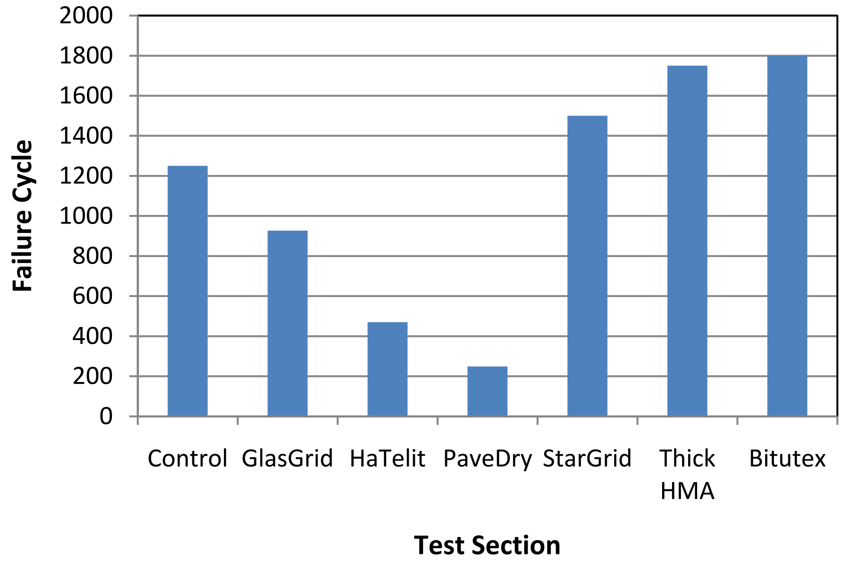


Figure 4-10. Large Overlay Tester Results with Pharr Specimens.

Table 4-3. Large Overlay Tester Results with Waco Specimens.

Section Name	Specimen ID	Cycles to Failure
Control	WCL1	67
	WCL2	170
	WCL3	60
	WCL4	30
	Average	**82**
GlasGrid	WGGL2	1100
	WGGL3	750
	WGGL5	900
	Average	**917**
Pave-Dry	WPDL1	2000
	WPDL2	457
	WPDL3	300
	Average	**919**
Thick HMA	WTHL1	35
	WTHL2	48
	Average	**42**

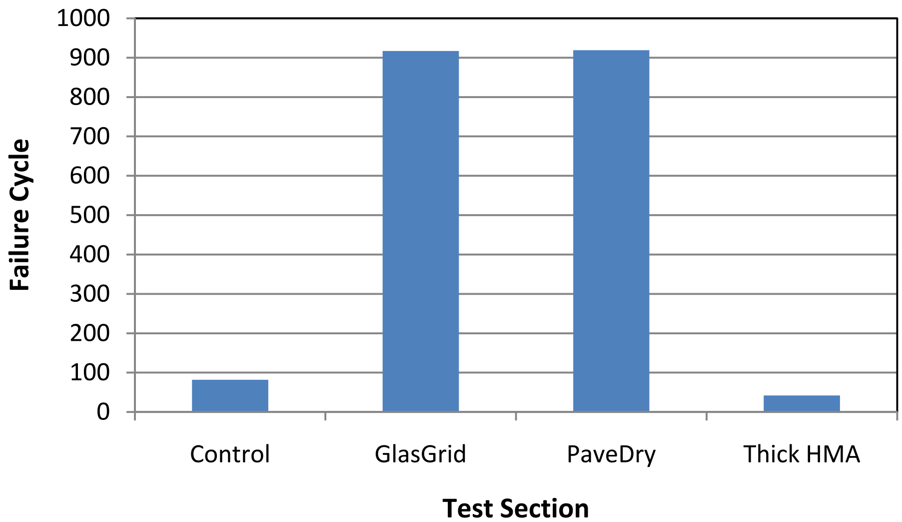


Figure 4-11. Large Overlay Tester Results with Waco Specimens.

Fracture Mechanics Analyses

The researchers attempted to analyze the overlay data using the fracture mechanics principles used in the initial phase of this project (Cleveland et al., 2002). These analyses were required to calibrate FPS-19 Design Check. During the earlier phase of this project, when the research team members tested laboratory-prepared specimens, they used a constant displacement of 0.07 inches. The number of cycles to fail the laboratory-prepared specimens ranged between 3 to 68 cycles, with 17 cycles as an average value. But the field specimens tested using a 0.025-inch displacement lasted up to 3000 cycles to failure with an average value of 1500 cycles. Cleveland et al. (2002) followed an analysis technique that involved manual calculation of the area under the graph of measured load versus reference displacement. Typically, these graphs for composite beams exhibit a complicated shape. They determined all the area under the curve for each load cycle using manual calculations. Since those laboratory-prepared specimens failed in a relatively low number of cycles, this manual calculation was feasible. The current research team experienced extreme difficulty in manually analyzing the relatively huge number of cycles for these data. Moreover, due to the absence of any significant medium-severity cracks in the field, the calibration of FPS-19 Design Check was not possible. As a result, the researchers did not pursue the analyses of laboratory data using fracture mechanics.

Details of the calculation and fracture mechanics analyses procedure using the large overlay test data can be found in Report 0-1777-1 (Cleveland et al., 2002). Cleveland et al. (2002) calculated two crack propagation parameter ‘A’ and ‘n’; and two regression parameter ‘B’ and ‘m’ for each specimen with geosynthetic product in it.

Many factors contribute to the performance of a geosynthetic material in reducing the occurrence of reflective cracking in HMA overlays. Cleveland et al. (2002) summarized the interactions of the values of A, n, B, and m and to compare the relative effectiveness of each geosynthetic material. Following equation was developed and termed the “crack speed index.”

$$\log\left(\frac{dc}{dN}\right) = \left[\log A + n \log \bar{J}_R\right] - \left[\log B + m \log\left(\bar{R} + 1\right)\right]$$

where:

$\log\left(\frac{dc}{dN}\right)$ = crack speed index

$\bar{J}_R$ = average pseudo J-Integral for each geosynthetic material

$\bar{R}$ = average reinforcing factor for each geosynthetic material

The more negative the crack speed index, the better the geosynthetic material reduces the rate of crack growth in the HMA overlay. The crack speed index, as defined by above equation, summarizes the interactions of the material properties calculated in this investigation and can be used to compare the relative effectiveness of each geosynthetic material. Smaller values indicate more successful products in reducing the rate of crack growth in HMA overlays.

Testing specimens from the field provides the cracking parameters, which ultimately provide the crack speed index. At the same time, field observations provide the actual cracking performance. Combining these laboratory test data and field observation data, one should be able to calibrate the FPS-19 reflection cracking design check program. The reflection cracking design check module of FPS-19 program is intended for designing an asphalt overlay with or without reinforcement.

CHAPTER 5: SUMMARY OF ANALYSES

ANALYSES OF FIELD REFLECTION CRACKING DATA

The reflection cracking design check program in the FS-19W program predicts the time when the medium level of severity of reflection cracking appears at the surface of the pavement. The predicted numerical level is 0.333 and is based upon the numerical rating method that was used by TxDOT in the 1970s and 1980s. The severity levels were rated as in Table 5-1 below.

Table 5-1. Severity Level of Cracking.

Severity Levels	Numerical Value	Rating Used in the Reflection Cracking Program
Low	1	1/6 = 0.167
Medium	2	2/6 = 0.333
High	3	3/6 = 0.500
Sum	**6**	**1.000**

The method being used at present takes into account both the severity level and the percentage of the pavement surface area that is occupied by the different levels of reflection cracking. This has led to the use of three curves that show the total length that is occupied by the different levels of severity of the cracking. Figure 5-1 illustrates this crack development and severity level.

The lowest curve is for the high level of severity. The intermediate curve is for the sum of the lengths of high- and medium-severity levels. The third is the highest curve, which is the sum of the lengths of all three levels of severity. At any given time, the vertical difference between any two curves gives the current area covered by the level of severity that is the difference between the two curves. This makes it possible to summarize the reflection cracking history of the pavement in one graph. The equation for each curve is the equation of the Gumbel cumulative probability function. Analyzing field reflection cracking data with this probability distribution makes it possible to estimate the original length of the cracks in the existing pavement surface layer prior to placing the overlay. Almost no reflection cracks appeared in the overlays in the Pharr District. The overlay in the Waco District was placed on a jointed plain concrete pavement in Marlin, Texas. The overlay in the Amarillo District was placed on a transversely cracked asphalt pavement. A control section was built in each of the latter two sites with a 3.0-inch thick overlay (including leveling course) to provide a basis of comparison of the performance of thicker overlays that are not reinforced with those having some reinforcing product. Only a few overlay sections in Waco and Amarillo showed reflection cracking severity greater than the low level (0.167 in the FPS-19W reflection cracking prediction method). Further, the amounts of medium-level severity cracking observed were very small compared to the cracking observed before construction. Thus, the properties of only low-level severity cracks could be analyzed.

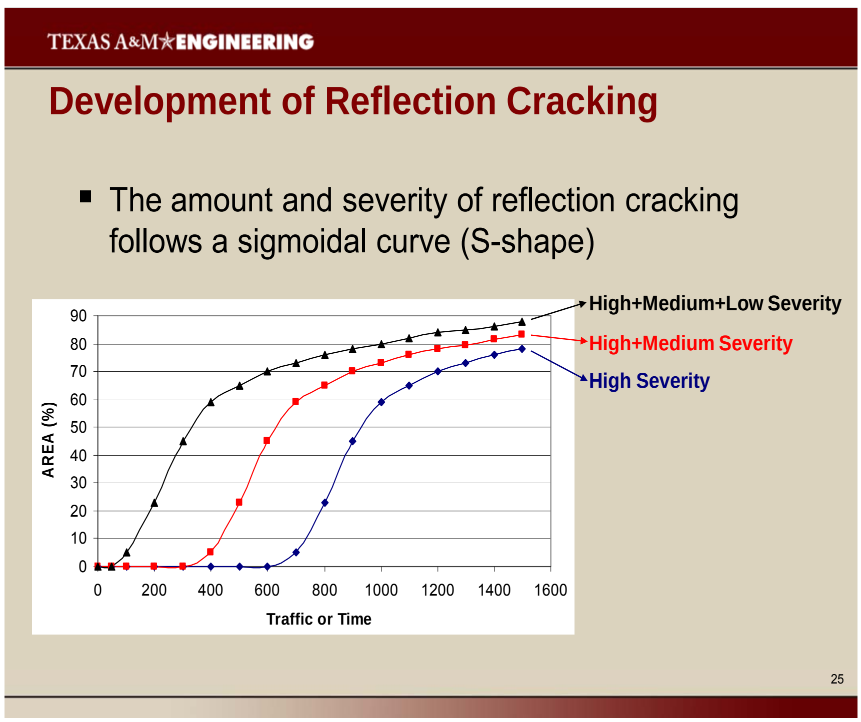


Figure 5-1. S-Curve Showing Crack Development and Severity Level.

Figures 5-2 and 5-3 exhibit the transverse reflective cracking of different severity levels on the control section in the Amarillo test pavement. Figure 5-4 demonstrates the trend curve prepared from observed data. Since the amount of medium-severity cracks was very small (if any), all the cracks were considered as low severity. Similarly, graphs were produced for each test section of Amarillo and Waco test pavements for further analyses.

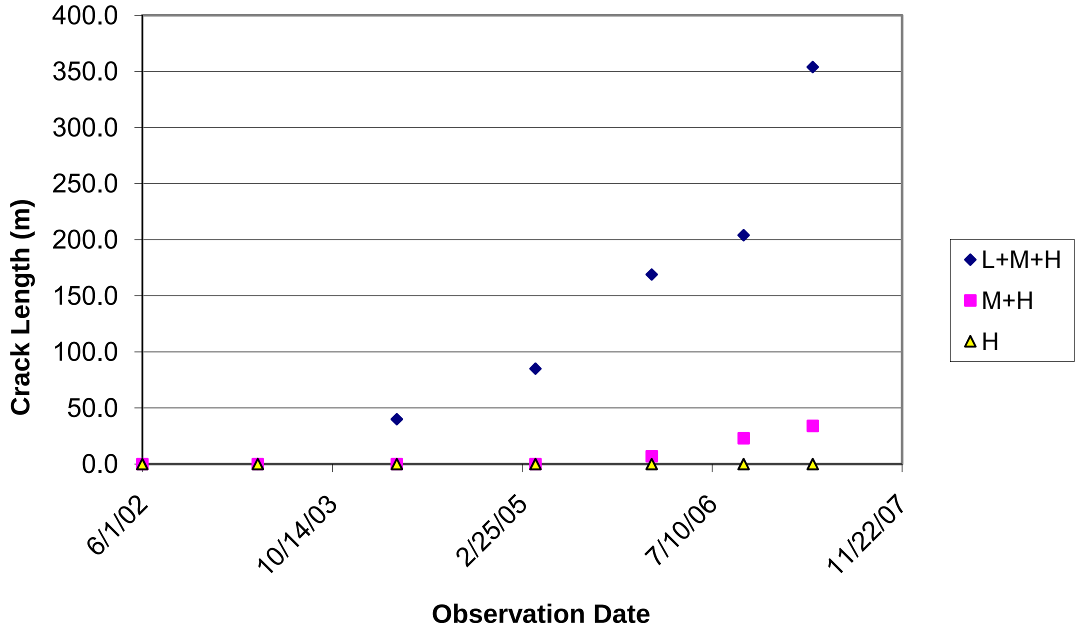


Figure 5-2. Amarillo Control Section Transverse Reflective Cracks.

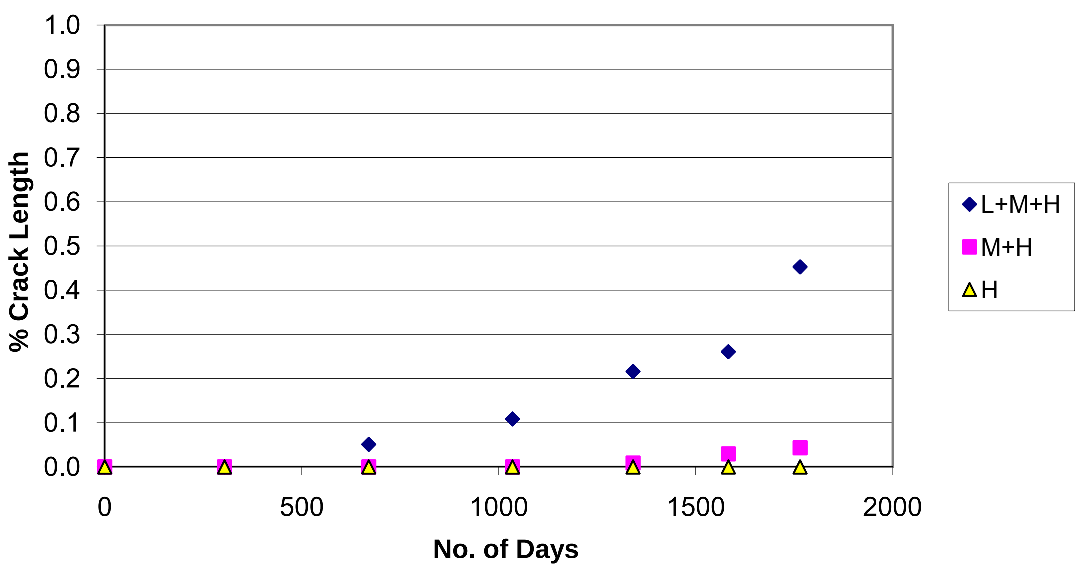


Figure 5-3. Amarillo Control Section Transverse Reflective Cracks Percentage.

Tables 5-2, 5-3, and 5-4 summarize the results of the analyses that were made. The ρ-value is the scale parameter and is the number of days required for the length of the reflection cracking to reach the maximum length divided by e, the base of the natural logarithms. The β-value is the shape parameter. A β-value that is greater than about 1.0 has a characteristic S-shaped curve. With this shape of curve, the amount of cracking stays low for a long time and then climbs exponentially after it reaches the number of days represented by the ρ-value. The β-value of the original curve in the reflection cracking severity prediction method was set at 1.0. The maximum crack length value was determined by analyzing the trend of the growth of the cumulative distribution curve.

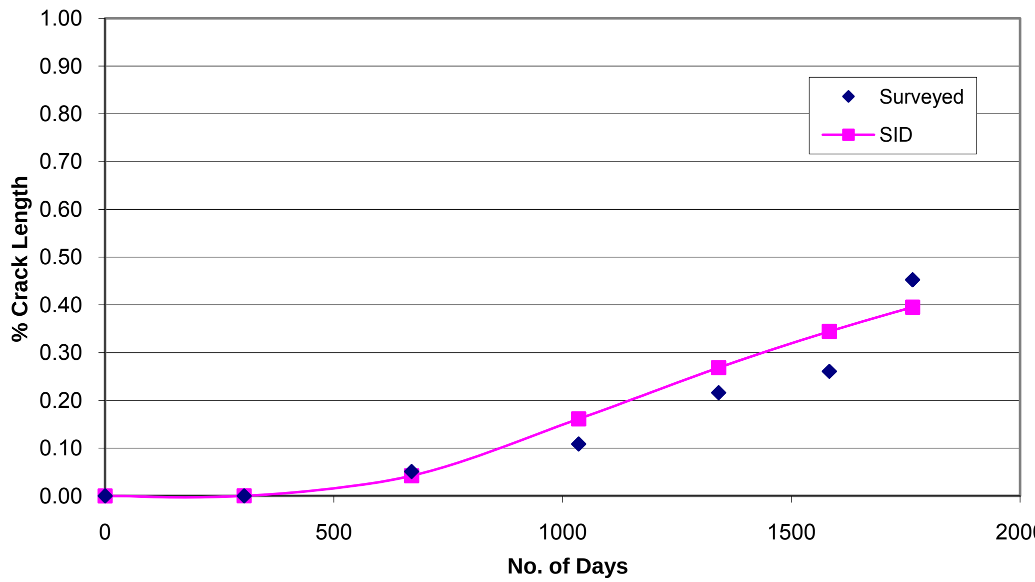


Figure 5-4. Amarillo Control Section Transverse Reflective Cracks Prediction.

Table 5-2. Calibration of β and ρ in Reflection Cracking Model: Pharr Test Section.

No	Test Section	Max Crack Length (inches)	H+M+L		H+M		H		Remark
			β	ρ	β	ρ	β	ρ	
1	Control	44							No crack
2	GlasGrid	15							No crack
3	HaTelit	65							No crack
4	Pave-Dry	34							No crack
5	Add 1" HMA	85							No crack
6	StarGrid	48							No crack
7	Bitutex	103							No crack
8	PetroGrid	26							No crack

Table 5-3. Calibration of β and ρ in Reflection Cracking Model: Waco Test Section.

No	Test Section	Max Crack Length (inches)	H+M+L		H+M		H		Remark
			β	ρ	β	ρ	β	ρ	
1	Control	906	0.360	906.71					
2	PetroGrid	828	0.800	1881.81					
3	Saw & Seal	507	0.427	308.27					
4	GlasGrid	616	1.043	1427.13					
5	Pave-Dry	929	0.606	1873.72					
6	Add 1" HMA	885	0.447	729.85					
7	PavePrep	696	1.074	2379.75					

Reflection Cracking Model:

$$D(N_i)\,(\%) = e^{-\left(\frac{\rho}{N_i}\right)^{\beta}}$$

Where,

$D(N_i)$ = percent of reflection crack length on maximum crack length at N_i,

N_i = number of days after overlay,

β = shape factor, and

ρ = scale factor.

Using the reflection cracking model, β and ρ values were calibrated for the test sections (Table 5-3 and 5-4). Calibration refers to the mathematical process through which the total error or difference between observed and predicted values of distress is minimized. The process used to achieve the calibration, which determines β and ρ in the reflection cracking model, was conducted using observed field reflection cracking data and an iterative method of the System Identification process. Details about this calibration procedure along with some examples are included in the Appendix.

Using the mathematics of the Gumbel distribution, it is possible to estimate the number of days required for each of the control sections to reach the different levels of severity used in the reflection cracking design check program. Table 5-5 presents the calculated multiplier for the control sections in Waco and Amarillo test sections. The Pharr test section was ignored due to very small amount of cracks. These multipliers are basically the ρ value obtained from Table 5-3 and 5-4 for a given section. Subsequently, the latter three columns of Table 5-5 show the number days required to reach the various severity levels of cracks for the two control sections.

Table 5-4. Calibration of β and ρ in Reflection Cracking Model: Amarillo Test Section.

No.	Test Section	Max Crack Length (inches)	H+M+L		H+M		H		Remark
			β	ρ	β	ρ	β	ρ	
1	Control Section	782	1.266	1664.90					
2	GlasGrid	835	1.355	1758.09					
3	PaveTrac	738	1.490	1819.89					
4	HaTelit	46	0.667	1619.74					
5	PetroGrid	658	2.383	2036.85					
6	Pave-Dry	654	1.494	1766.20					
7	StarGrid	616	1.436	2015.39					
8	Add 1" HMA	796	6.784	1762.73					
9	Hot-in-Place Recycling	847	1.345	1633.91					
10	1.25" PFC over 1" Leveling Course	834	0.896	1929.89					
11	1.25" PFC over Seal Coat	930	2.806	1997.73					

Table 5-5. Multiplier of Two Control Sections.

Location of Control Section	**Multiplier ρ (days) 1.000**	**Low Severity t_{LMH} (days) 0.5581**	**Medium Severity t_{MH} (days) 1.4845**	**High Severity t_H (days) 3.7293**
Waco	906.71	506.0	1346.0	3381.4
Amarillo	1664.90	929.2	2471.5	6208.9

Using the ratio of the ρ-values of each of the products that were placed in each of the test sections, it is possible to extrapolate, using the multiplying factors in the table above, to determine the number of days that are expected to elapse before each overlay reinforced with a different product reaches a medium level of severity. Table 5-6 presents the relative life ratio and number of days required to reach medium severity for each section in the Waco and Amarillo test sections. For example, the relative life ratio of PetroGrid in Waco was calculated as 2.075 ($\rho_{PetroGrid} / \rho_{Control}$ or 1881.81 / 906.71). The number of days required to reach medium severity level was calculated by multiplying the relative life ratio of given section (or geosynthetic product) with the number days required to reach medium severity for the control section (2794 = 2.075 × 1346) in that area. These expected, but not yet observed, numbers of days and the ρ-value ratios (relative life) are shown in Table 5-6. The control overlay to which all of the other overlays are compared has a 3.0-inch thick asphalt overlay.

Table 5-6. Relative Lives of Test Sections.

Product Name	Relative Life Ratio	Number of Days to Medium Severity	Generic
Waco Test Section			
Control	1.000	1346	
PetroGrid	2.075	2794	Composite
Saw & Seal*	0.340	458	
GlasGrid	1.574	2119	Fiberglass Grid
Pave-Dry	2.067	2782	Fabric
Extra 1" HMA	0.805	1083	
PavePrep	2.625	3533	
Amarillo Test Section			
Control	1.000	2472	
GlasGrid	1.056	2610	Fiberglas Grid
PaveTrac	1.093	2702	Steel Wire Mesh
HaTelit	0.973	2405	Composite
PetroGrid	1.223	3204	Composite
Pave-Dry	1.061	2622	Fabric
StarGrid	1.211	2992	Composite
Extra 1" HMA	1.059	2618	
Hot-in-Place Recycling	0.981	2426	
1.25" PFC over 1" Level-up	1.159	2865	
1.25" PFC over Seal Coat	1.200	2966	
Mean Composite	1.160	2867	
Mean 1.25 PFC	1.180	2916	

* Note that Saw & Seal in Waco District was not properly executed during construction.

The overlays over the jointed concrete pavements in Marlin, Texas, have a wide range of relative life ratios spanning between 0.340 and 2.625. The different products in the overlays placed in Amarillo, Texas, had a much smaller range of relative life ratios, between 0.973 and 1.223. The most readily apparent reason for this is that the overlays in the Amarillo test sections were subjected to severe thermal stresses; whereas, the overlays in Marlin, a more moderate climate, depended more on the load transfer across the joints in the old concrete pavement. Load transfer can vary greatly within the same project and provides a wide variability of the observed results.

The relative life ratios given above can be used to predict the life of 3-inch thick overlays with and without the listed reinforcing products imbedded in them. These same ratios would not apply to overlay thicknesses other than the 2-inch overlays that were used as the control sections in both the Marlin and Amarillo test sections. The numbers of days to reach a medium level of severity are extrapolated from the field data, all of which had progressed little or no farther than to a low level of severity at the time of this writing. The extrapolation was done mathematically, which carries with it a number of assumptions about the damaging process that each overlay is undergoing. Consequently, it is not recommended that these extrapolated numbers be used as a basis for calibrating computer programs for the design of overlays to resist reflection cracking.

COMPARISON BETWEEN LAB AND FIELD DATA

An attempt was made to find a relationship between laboratory test results using the large overlay tester and the field crack survey. For the Amarillo test pavement, those products that performed very well during overlay testing in the laboratory also performed very well in the field. Although the hot-in-place recycling and GlasGrid sections exhibited relatively better performance than the control section when they were tested with the overlay tester, their performance in the field was worse than the control section.

The performance of all the sections in the Pharr test, including the control section, was so good (i.e., very low amount of reflective cracking even after six years in service) that the evaluation of geosynthetic products could not be accomplished. With a few exceptions, overlay tests performed in the laboratory using beams from the Pharr sections exhibited very good performance. Overall, the number of cycles to failure for the Pharr specimens was relatively high compared to the other test pavements. Even the Pharr control section survived a relatively large number of load cycles. This indicates that the overlay mixture itself was very crack resistant. Field performance in Pharr matches very well with laboratory performance. It was mentioned earlier that due to alteration in original construction plan Pharr test section became unsuitable for analysis and it was probably not an ideal test section for reflective cracking evaluation.

Specimens from only four out of seven test sections in the Waco pavements could be tested using the large overlay tester. Specimens from two of the best performing sections (PavePrep and PetroGrid) were not available for overlay testing. Two sections (GlasGrid and Pave-Dry) demonstrated very good performance during overlay testing compared to the control and thick HMA sections. GlasGrid and Pave-Dry also performed better in field observations than the control and thick HMA sections. But their field performance was not as good as that observed in overlay testing of beams cut from the pavements. This is normal and is the reason why research engineers have developed transfer functions in an effort to accurately transfer laboratory data to the field.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

TTI researchers, in cooperation with TxDOT and construction contractors, installed multiple end-to-end geosynthetic test pavements at three different locations in Texas. The three test locations selected in coordination with TxDOT were the Pharr District (McAllen), the Waco District (Marlin), and the Amarillo District (northeast of Amarillo city). Test sections in the Amarillo and Pharr Districts utilized flexible pavements, whereas the test sections in the Waco District utilized an old, jointed, rigid pavement. There was a total of 26 test sections at these three test locations. Along with a control section in each location, there were several different geosynthetic products and other techniques designed to mitigate reflective cracking.

The research team monitored the performance of the test pavements for five to six years, depending on the date of construction. Performance monitoring was accomplished through visual surveys of reflective cracks and other distresses. During each inspection period, the research team measured and compared the reflection cracking with the cracking originally diagrammed before construction. Field specimens were obtained from the test sections and were tested using TTI overlay testers. Attempts were made to calibrate FPS-19 Design Check software using the field and laboratory data.

CONCLUSIONS

Based on the laboratory and field testing, the following conclusions are presented.

- The findings of this project and the literature review of other recent field evaluations of geosynthetic products show that their effectiveness in reducing the number of reflective cracks is marginal. The literature review indicated that certain geosynthetic products can, however, reduce the severity of reflective cracks that appear.
- Specimens of two sizes containing geosynthetics were tested using the small overlay tester. Both specimen sizes always exhibited failure due to separation at the geosynthetic interlayer. Occasionally, specimens tested using the large overlay tester exhibited a similar failure mechanism. This failure mechanism negated the utility of those data in analyses of reflection cracking in pavements and in calibration or validation of the FPS-19 Design Check.

- The Design Check for FPS-19 was developed based on the development of medium-severity reflection cracks. Since hardly any medium-severity cracks developed in any of the test pavements, the resulting data were unsuitable for calibration or validation of the Design Check for FPS-19.
- Using the field performance data, the researchers computed the relative life ratio for the various products tested in the Amarillo and Waco test sections. On average, when a geosynthetic product was used, these calculated values showed significant reduction in reflection cracking in Waco on the concrete pavement and marginal improvement in Amarillo on the flexible pavement. These computations involved extrapolations and should, therefore, be viewed with caution. Since very little cracking occurred in the Pharr test pavements, these data could not be used to determine relative life ratio.
- The small overlay tester appears inappropriate for evaluating specimens containing a geosynthetic interlayer.
- Based on this project and several previous projects, the large overlay tester provides a valuable tool for evaluating the cracking potential of composite beam specimens. However, one should expect specimens to occasionally separate at the interlayer when testing certain geosynthetic products.
- Usually, for the first couple of years, geosynthetic products perform somewhat better than the control section; but as the overlay gets older, the difference diminishes.

RECOMMENDATIONS

Based on the literature review, test results, and conclusions, researchers recommended the following.

- The test pavements in the Amarillo and Waco Districts are, potentially, very valuable resources for TxDOT. Their performance should be monitored for a few more years (or throughout the life cycle of the overlay) to determine the relative value of the products installed to reduce reflective cracking. This will be a relatively inexpensive exercise that could provide very valuable information.
- The Design Check Reflection Cracking Program in the FS-19W Program predicts the time when the medium level of severity of reflection cracking appears at the surface of

the pavement. It is recommended that the extrapolated values for relative life ratio should not be used as a basis for calibrating computer programs for the design of overlays to resist reflection cracking.

- Further research should be conducted including a set of new test sections with known and clear reflective cracking history. The proposed test sections should be constructed using more popular and relatively good performing geosynthetic products. This study should be performed for a more in-depth analysis of these materials and to verify their usefulness and cost effectiveness. This type of study requires monitoring for a significantly longer period.

REFERENCES

Bush, A.J. and E.W. Brooks. Geosynthetic Materials in Reflective Crack Prevention. Research Report No. SR 537, Research Unit, Oregon Department of Transportation, Salem, Oregon, 2007.

Buttlar, W.G., D. Bozkurt, and B.J. Dempsey. Cost-Effectiveness of Paving Fabrics Used to Control Reflective Cracking. *Transportation Research Record 1730*, Transportation Research Board, National Academy of Sciences, 2000, pp. 139–149.

Button, J. W. and A. Chowdhury. Field Tests Using Geosynthetics in Flexible and Rigid Pavements to Reduce Reflection Cracking. Research Report No. FHWA/TX-06/1777-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2006.

Cleveland, G.S., J.W. Button, and R.L. Lytton. Geosynthetics in Flexible and Rigid Pavement Overlay Systems to Reduce Reflection Cracking. Research Report No. FHWA/TX-02/1777-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2002.

Distress Identification Manual for the Long-Term Pavement Performance Studies. Report No. SHRP-LTPP/FR-90-001, Strategic Highway Research Program, National Research Council, Washington, D.C., 1990.

Engle, E. Field Evaluation of Engineering Fabrics for Asphalt Concrete Resurfacing – Audubon County Secondary Road Research Coordinator. Report No. HR-360, Office of Materials, Project Development Division, Iowa Department of Transportation, Ames, Iowa, 2001.

Germann, F.P. and R.L. Lytton. Methodology for Predicting the Reflection Cracking Life of Asphalt Concrete Overlays. Research Report FHWA/TX-79/09+207-5, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1979.

Hajj, E.Y., P.E. Sebaaly, and L. Loria. Reflective Cracking of Flexible Pavements – Phase I and II Recommendations. Pavements/Materials Program, Department of Civil and Environmental Engineering, College of Engineering, University of Nevada, Reno, Nevada, 2008.

Hutter, W. Crack Reduction Strategies on a Pavement Warranty Project (Interstate 25 at Fountain, Colorado). Report No. CDOT-DTD-R-2003-5, Colorado Department of Transportation, Denver, Colorado, 2003.

Loria, L., P.E. Sebaaly, and E.Y. Hajj. Long-Term Performance of Reflective Cracking Mitigation Techniques in Nevada. *Transportation Research Record 2044,* Transportation Research Board, National Academy of Sciences, Washington, D.C., 2008, pp. 86–95.

Makowski, L., D.L. Bischoff, P. Blankenship, D. Sobczak, and F. Haulter. Wisconsin Experiences with Reflective Crack Relief Projects. *Transportation Research Record 1905,* Transportation Research Board, National Academy of Sciences, Washington, D.C., 2005, pp. 44–55.

Natke, H. G. Identification of Vibrating Structures, Springer-Verlag. New York. 1982.

Roberts, F.L., P.S. Kandhal, E.R. Brown, D.Y. Lee, and T.W. Kennedy. Hot Mix Asphalt Materials, Mixture Design and Construction. NAPA Research and Education Foundation, Lanham, Maryland, 1996.

Soucie, T. Experimental Installation of Geosynthetic Pavement Reinforcement to Reduce Reflective Cracking. Report No. 01-3, Transportation Research Division, Maine Department of Transportation, Augusta, Maine, 2007.

Vespa, J.W. An Evaluation of Interlayer Stress Absorbing Composite (ISAC) Reflective Crack Relief System. Report No. FHWA/IL/PRR 150, Illinois Department of Transportation, Bureau of Materials and Physical Research, Springfield, Illinois, 2005.

Wang, F. and R. L. Lytton, System Identification Method for Backcalculating Pavement Layer Properties. *Transportation Research Record 1384*, Transportation Research Board, National Academy of Sciences, Washington, D.C., pp.1-7. 1993

Zhou, F. and T. Scullion. Upgraded Overlay Tester and its Application to Characterize Reflection Cracking Resistance of Asphalt Mixtures. Research Report FHWA/TX-04/4467-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2003.

Zhou, F. and T. Scullion. Overlay Tester: A Rapid Performance Related Crack Resistance Test. Report FHWA/TX-05/0-4667-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2005.

Zollinger, D. G., S. Lee, J. Puccinelli, and N. Jackson. LTPP Computed Parameter: Moisture Content. Research Report No. FHWA-HRT-08-035. Federal Highway Administration, 2008.

APPENDIX:
GEOSYNTHETIC DATA
AND
REFLECTION CRACKING DATA

Table A1. Summary of Geosynthetics Used in the Different Test Pavements.

Brand Name	Manufacturer	Type/Description	Recommended Tack Use (gal/yd^2)	Comment
PavePrep®	Crafco, Inc.	Woven Polyester Composite	0.15	
GlasGrid® 8501	Bayex, Inc.	Woven/Coated Fiberglass Grid,	Tack not required except for wet pavement	
GlasGrid® 8502	Bayex, Inc.	Woven/Coated Fiberglass Grid, wider string and double strength compared to 8501	Tack not required except for wet pavement	
PaveDry® 381	Synthetic Industries	Polypropylene Nonwoven Fabric	0.20	
StarGrid® GPS	Luckenhaus, N.A.	Woven/Coated Fiberglass Grid/Nonwoven Composite	0.25	
HaTelit® C40/17	Huesker	Woven/Coated Fiberglass Grid	0.10	
PetroGrid® 4582	Amoco Fabrics	Woven/Coated Polyester Grid/Nonwoven Composite	0.23	
PaveTrac®	Bekaert Corporation	Woven steel mesh with torsioned flat-bar	--	Steel wire mesh (not geosynthetic)
Bitutex® Composite	Synteen USA	Woven/Coated Polyester Grid/Nonwoven Composite	0.25	

-- data not available

Table A2. Description of Geosynthetic Products Used in Amarillo Test Pavements.

Section / Product Name	Model	Type	Strand X-sectional Area	Strand Spacing	Strand Modulus	Thickness for fabric	Weight	Tensile Stregth	Elong-ation	Material
Control	N/A	N/A								
GlasGrid	8501	Grid	1.6 mm^2	0.5 inch (both direction	10 mil psi			100 KN/m		Fiberglass Reinforcement coated with an elastometric polymer and pressure sensitive adhesive becking
PaveTrac		Wire Mesh	round wire dia 0.097 inch, flat bar 0.275 in X 0.118 inch	4.65 X 3.15, flat bar spacing 9.65 inch	29 mil psi			long 2700 lb/ft, trans 3425 lbs/ft		Steel with Zn and Al coating
HaTelit	C 40/17	Composite	(3.3 +3.3) x 0.7 mm	40 mm x 40 mm		very thin (have to measure)	composite 360 gm/sq m,	50 kn/m, ASTM D 4595 -Warp		Polyester geogrid combined with ultralight non-woven fabric, grid and fabric both coated with bitumen
PetroGrid	4582	Composite	5mm x 0.5 mm	1.18 inch (both direction)			542 gm/sq m	2500 lbs/ft	5% max	nonwoven needle-punched polypropylene paving fabric, grid composed of epoxy resin coated fiberglass.
Pave-Dry	381	Fabric	N/A	N/A	N/A	0.8 mm	118 gm/ sq yd	Grab tensile str 400 N by ASTM D 4632		nonwoven needle-punched polypropylene
StarGrid	G-PS	More like composite		1.2 inch			10.5 oz/sq yd	3500 lb/ft		Glass yarns, woven into a stable interlocking grid and coated with polymer modified bitumen adhesive.
Add 1 inch HMA	N/A	N/A	N/A							
Recycle	N/A	N/A	N/A							
1.25 inch PFC w/ level-up w/o seal coat	N/A	N/A	N/A							
1.25 inch PFC w/o level-up w/ seal coat	N/A	N/A	N/A							

Table A3. Description of Geosynthetic Products Used in Pharr Test Pavements.

Section / Product Name	Model	Type	Strand X-sectional Area	Strand Spacing	Strand Modulus	Thickness for fabric	Weight	Tensile Stregth	Elong-ation	Material
Control	N/A	N/A	N/A							
GlasGrid	8501	Grid	1.6 mm^2	0.5 inch (both direction	10 mil psi					Fiberglass Reinforcement coated with an elastometric polymer and pressure sensitive adhesive becking
HaTelit	C 40/17	Composite	(3.3 +3.3) x 0.7 mm	40 mm x 40 mm		very thin (have to measure)	composite 360 gm/sq m,	50 kn/m, ASTM D 4595 -Warp		Polyester geogrid combined with ultralight non-woven fabric, grid and fabric both coated with bitumen
Pave-Dry	381	Fabric	N/A	N/A	N/A	0.8 mm	118 gm/ sq yd	Grab tensile str 400 N by ASTM D 4632		nonwoven needle-punched polypropylene
Add 1inch HMA	N/A	N/A								
StarGrid	G-PS	More like composite	3.7 mm x 0.7 mm	1.2 inch			10.5 oz/sq yd	3500 lb/ft		(Fiber Glass) Glass yarns, woven into a stable interlocking grid and coated with polymer modified bitumen adhesive.
Bitutex		Composite	8mm X 0.6 mm	1.18 inch (Both direction)		0.09 inch	380 gm/ sq m for grid, 11.2 oz/sq yd for fabric	60 kn/m		Non-woven polyester fabric with woven coated polyester grid. Grid coated with styrol butadien Rubber (SBR)
PetroGrid	4582	Composite		1.18 inch (both direction)			542 gm/sq m	2500 lbs/ft	5% maz	nonwoven needle-punched polypropylene paving fabric, grid composed of epoxy resin coated fiberglass.

Table A4. Description of Geosynthetic Products Used in Waco Test Pavements.

Section / Product Name	Model	Type	Strand X-sectional Area	Strand Spacing	Strand Modulus	Thickness for fabric	Weight	Tensile Stregth	Elong-ation	Material
Control	N/A	N/A	N/A							
PetroGrid	4582	Composite		1.18 inch (both direction)			542 gm/sq m	2500 lbs/ft	5% maz	nonwoven needle-punched polypropylene paving fabric, grid composed of epoxy resin coated fiberglass.
Saw & Seal	N/A	N/A	N/A							
GlasGrid	8502		3.0 mm^2	0.5 inch	10 mil psi		370 gm/sq meter	200 KN/m		Fiberglass Reinforcement coated with an elastometric polymer and pressure sensitive adhesive becking
Pave-Dry	381	Fabric	N/A	N/A	N/A	0.8 mm	118 gm/ sq yd	Grab tensile str 400 N by ASTM D 4632		nonwoven needle-punched polypropylene
PavePrep			N/A			0.135 inch	0.9 lb/sq ft	2380 lb/sq in	10% max	High density mastic between two layers of polyester fabric

Table A5. Crack Length Measurement of Test Pavements in Pharr District (2001-07).

Test Section	Length of Cracks (ft)											
	Before Construction, 2001			4.5 yr After Overlay November 2005			5.5 yr After Overlay October 2006			6 yrs After Overlay May 2007		
	Trans	Long	Total	Trans	Long	Total	Trans	Long	Total	Trans	Long	Total
PetroGrid	26	1097	1123	0	0	0	0	0	0	0	0	0
Bitutex	103	548	651	0	0	0	0	0	0	0	0	0
StarGrid	48	666	674	0	0	0	0	0	0	0	0	0
Thick Control	85	601	686	0	0	0	0	8 rutting	8	0	9 rutting	9
Pave-Dry	34	578	612	0	71	71	2	96	98	2	83	85
HaTelit	65	786	851	0	36	36	0	64	64	0	71	71
GlasGrid	15	700	715	0	56	56	0	66	66	0	67	67
Control	44	535	579	0	0	0	0	5	5	0	5	5

Table A6. Crack Length Measurement of Test Pavements in Waco District (2002-05).

Test Section	Length of Cracks (ft)											
	Before Construction			1 yr After Level-Up			1 yr After Overlay			2 yrs After Overlay		
	Trans	Long	Total	Trans	Long	Total	Trans	Long	Total	Trans	Long	Total
PavePrep	696	743	1439	132	166	298	20	4	24	44	6	50
Add 1-inch HMA	885	1240	2125	417	410	827	334	102	436	362	113	475
GlasGrid	929	1454	2383	353	771	1124	155	48	203	254	105	359
Pave-Dry	616	1316	1932	433	879	1312	79	22	101	189	40	229
Saw & Seal	507	1024	1531	499	485	984	255	0	255	287	22	309
PetroGrid	828	1358	2186	415	666	1081	99	8	107	179	80	259
Control	906	1578	2484	341	415	756	307	100	407	355	259	614

Table A7. Crack Length Measurement of Test Pavements in Amarillo District (2002-05).

Test Section	Length of Cracks (ft)											
	Before Construction, May 2002			1 yr After Overlay June 2003			2 yrs After Overlay April 2004			3 yrs After Overlay April 2005		
	Trans	Long	Total	Trans	Long	Total	Trans	Long	Total	Trans	Long	Total
Control	782	1712	2494	0	0	0	40	0	40	85	100	185
GlasGrid	835	1450	2285	0	0	0	16	15	31	70	15	85
PaveTrac	738	1601	2339	0	0	0	14	26	40	47	26	73
HaTelit (80 ft - One lane)	46	160	206	0	0	0	8	0	8	11	0	11
PetroGrid	658	1315	1973	0	0	0	0	0	0	13	0	13
Pave-Dry	654	1284	1938	0	0	0	14	0	14	40	0	40
StarGrid	616	1184	1800	0	0	0	16	0	16	38	5	43
Thick Control	847*	1388*	2235*	0	0	0	--	--	--	--	--	--
Hot-in-Place[#]	847	1388	2235	0	0	0	34	0	34	107	60	167
PFC with Level-Up	834	1603	2437	0	0	0	63	0	63	142	190	332
PFC with Seal Coat	930	1524	2454	0	0	0	0	0	0	37	50	87

[#] Considered only 500 ft of much longer test section
* Original crack data were not available; used same original crack as Hot-in-Place Recycle Section

Table A8. Crack Length Measurement of Test Pavements in Amarillo District (2006-07).

Section ID	Lengths of Cracks (in ft)													
	Original, Before Construction, June 2001		3.67 yrs After Overlay February 2006				4.33 yrs After Overlay October 2006				4.83 yrs After Overlay April 2007			
	Trans	Long	Medium		Low		Medium		Low		Medium		Low	
			Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long
Control	782	1712	7	0	162	110	23	0	181	135	34	121	320	148
GlasGrid	835	1450	0	10	167	215	8	30	232	280	8	70	357	454
PaveTrac	738	1601	2	5	83	65	11	0	97	95	15	28	239	145
HaTelit 80 ft-1 lane	46	160	0	0	12	0	0	0	14	0	0	0	24	4
PetroGrid	658	1315	1	0	43	0	4	0	66	0	19	0	144	41
Pave-Dry	654	1284	3	0	85	0	11	0	110	6	23	0	245	24
StarGrid	616	1184	1	0	79	25	3	0	87	27	14	0	213	70
Thick Control	847*	1388*	0	0	0	0	11	0	124	0	31	0	262	54
Hot-in-Place#	847	1388	3	20	245	205	21	150	270	175	43	270	364	135
PFC with Level-Up	834	1603	5	0	181	220	14	40	218	200	14	40	312	205
PFC with Seal Coat	930	1524	0	0	44	50	2	48	64	120	2	48	299	180

Considered only 500 feet of much longer test section

* Original crack data were not available; used same original crack as Hot-in-Place Recycle Section

Table A9. Crack Length Measurement of Test Pavements in Waco District (2006-07).

Section ID	Lengths of Cracks (in ft)															
	Original, Before Construction, June 2001		3 yrs After Overlay May 2006				3.5 yrs After Overlay December 2006				4 yrs After Overlay April 2007					
	--		Medium		Low		Medium		Low		High		Medium		Low	
	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long
PavePrep	696	743	0	0	119	32	10	0	135	35	0	0	20	0	143	49
Add 1-inch HMA	885	1240	18	64	402	153	19	64	413	213	0	34	42	52	412	373
Pave-Dry	929	1454	45	0	209	294	45	0	236	304	10	0	59	0	262	591
GlasGrid	616	1316	5	0	218	74	5	0	224	81	0	0	5	11	229	253
Saw & Seal	507	1024	15	2	230	38	17	2	242	43	0	0	4	10	277	97
PetroGrid	828	1358	7	0	204	177	8	0	226	192	9	0	6	0	286	221
Control	906	1578	17	0	366	545	19	49	372	512	0	48	26	34	380	557

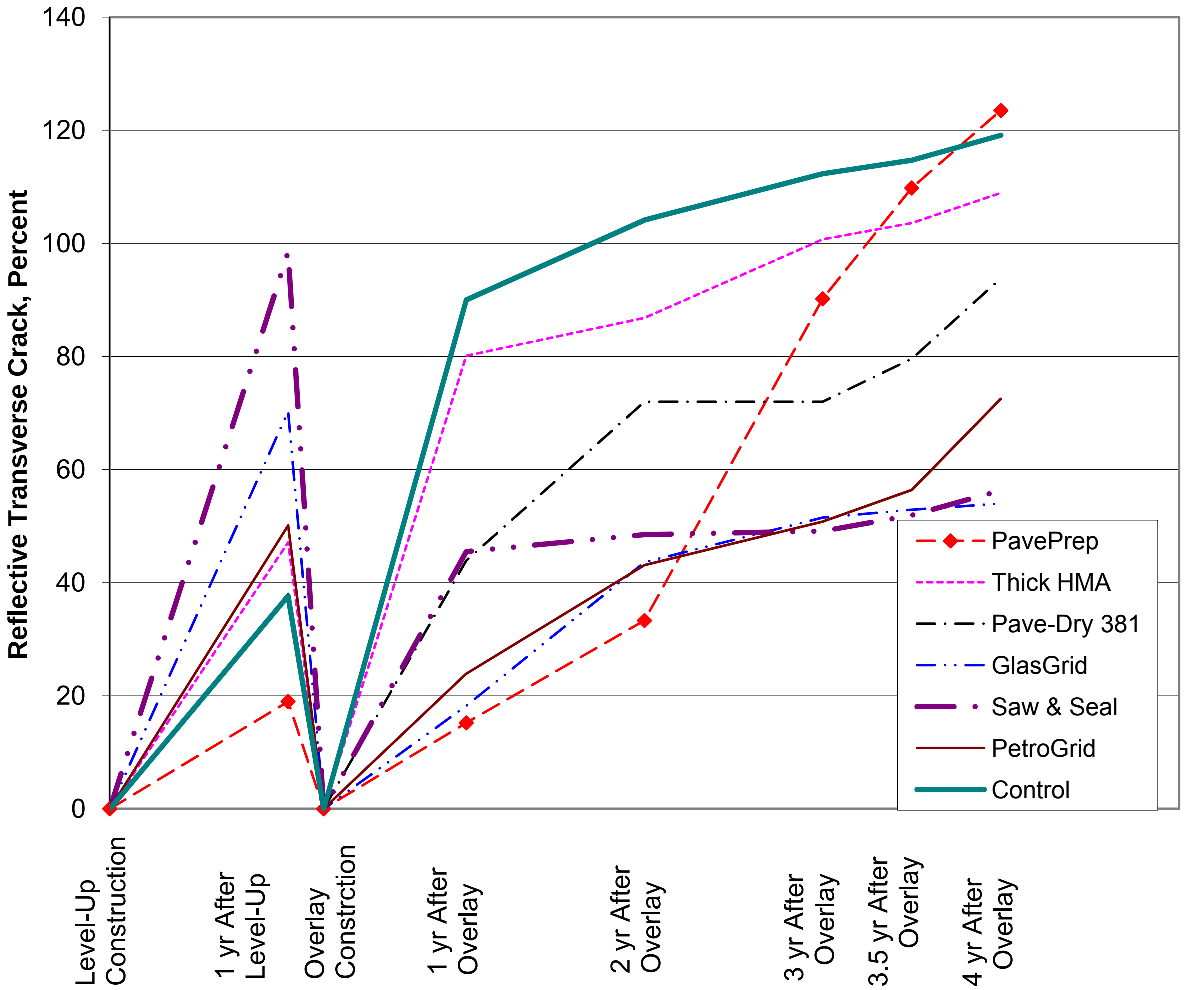


Figure A1. Waco District Reflective (Transverse) Cracking vs. Time — Based on Cracking Measured on Leveling Course before Overlay.

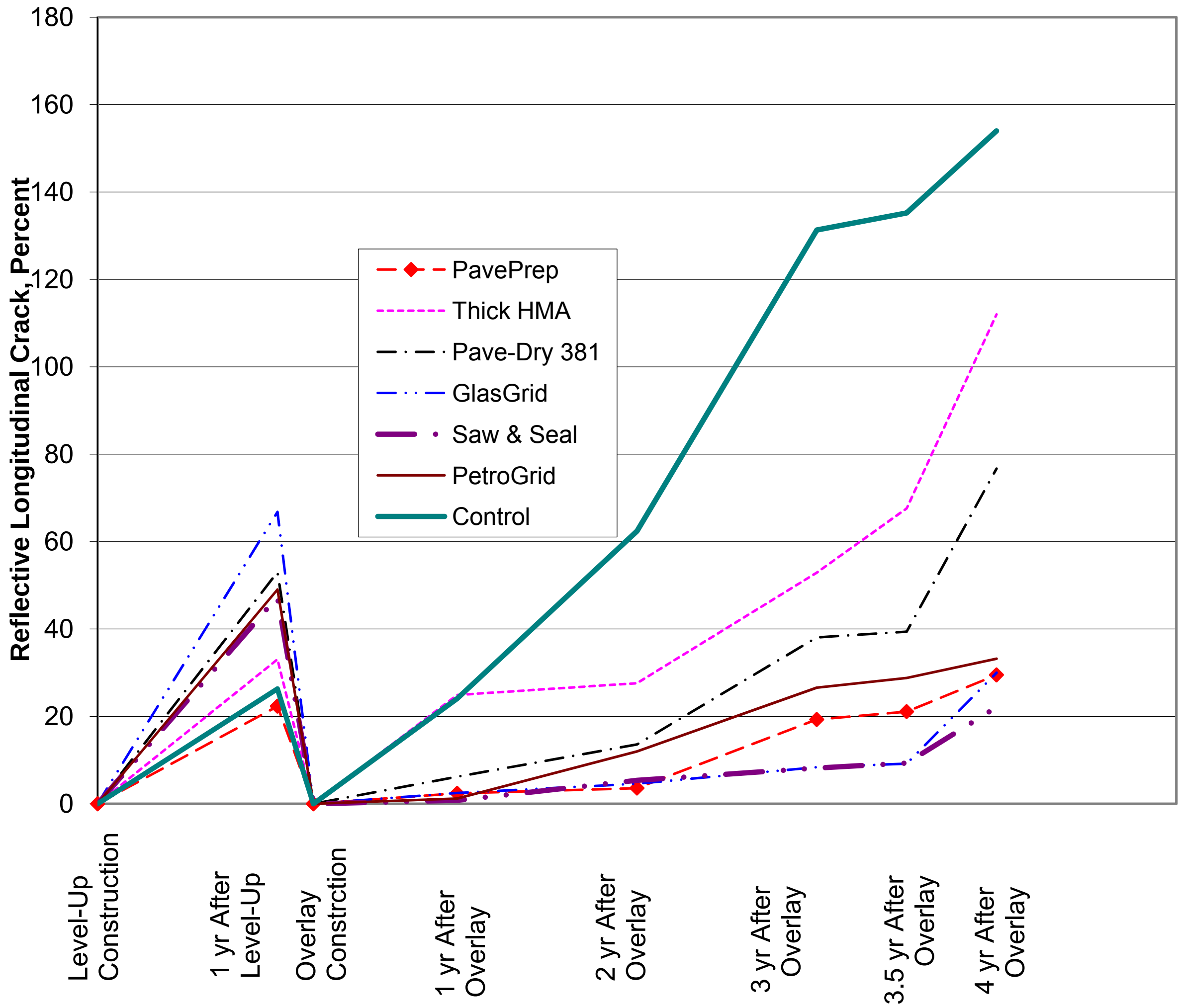


Figure A2. Waco District Reflective (Longitudinal) Cracking vs. Time — Based on Cracking Measured on Leveling Course before Overlay.

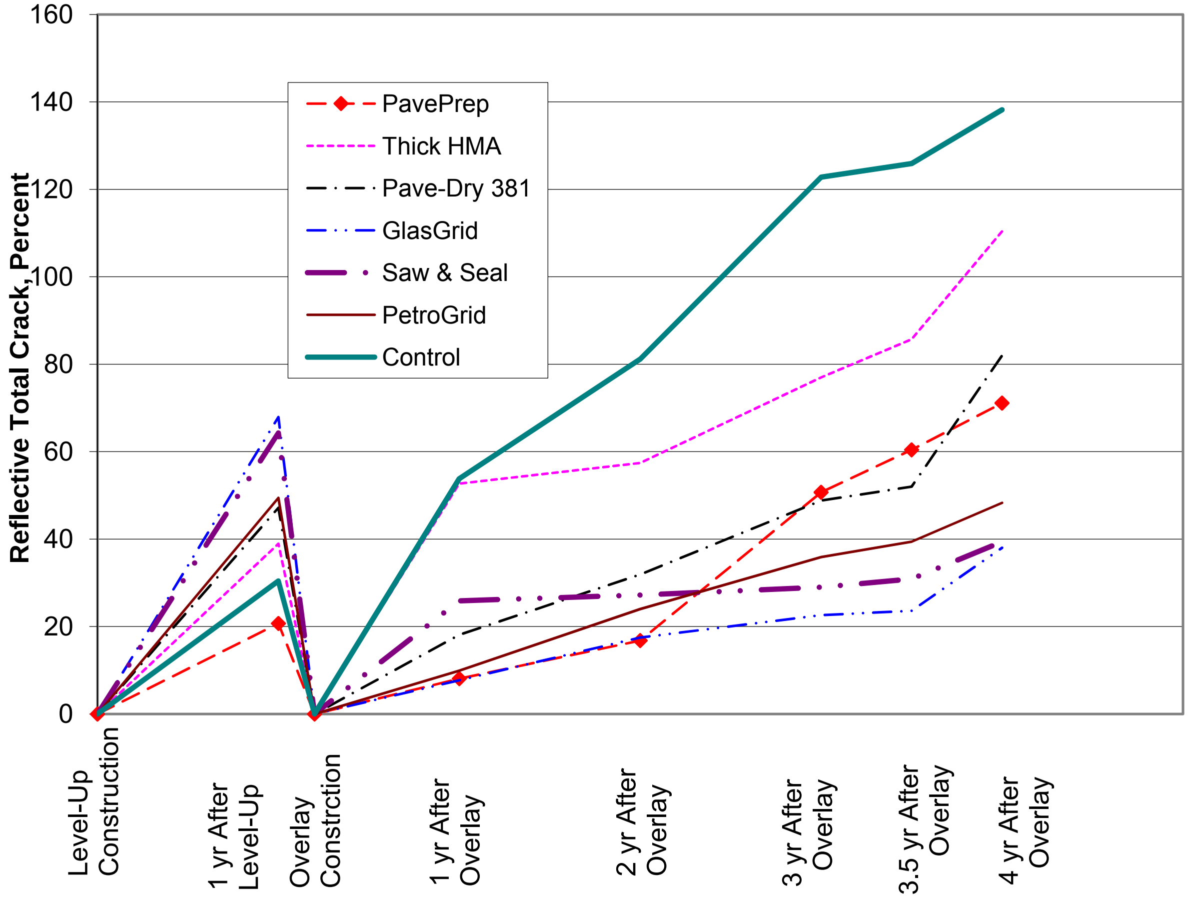


Figure A3. Waco District Reflective (Total) Cracking vs. Time — Based on Cracking Measured on Leveling Course before Overlay.

5. Reflection Cracking at Joints

Description

- Cracks in asphalt concrete (AC) overlay surfaces over jointed concrete pavements at original joints.
- Knowing slab dimensions beneath AC surface helps identify these cracks.

Severity Levels

Low - Cracks with low severity or no spalling; mean unsealed crack width of 1/4" or less; sealant material in good condition.

Moderate - Cracks with moderate severity spalling; mean unsealed crack width of greater than 1/4"; sealant material in bad condition; low severity random cracking near the crack.

High - Cracks with high severity spalling; moderate or high severity random cracking near the crack.

How to Measure

- Number and linear feet of longitudinal and transverse cracks at each severity level.
- Measurements for longitudinal and transverse cracks shall be recorded separately.

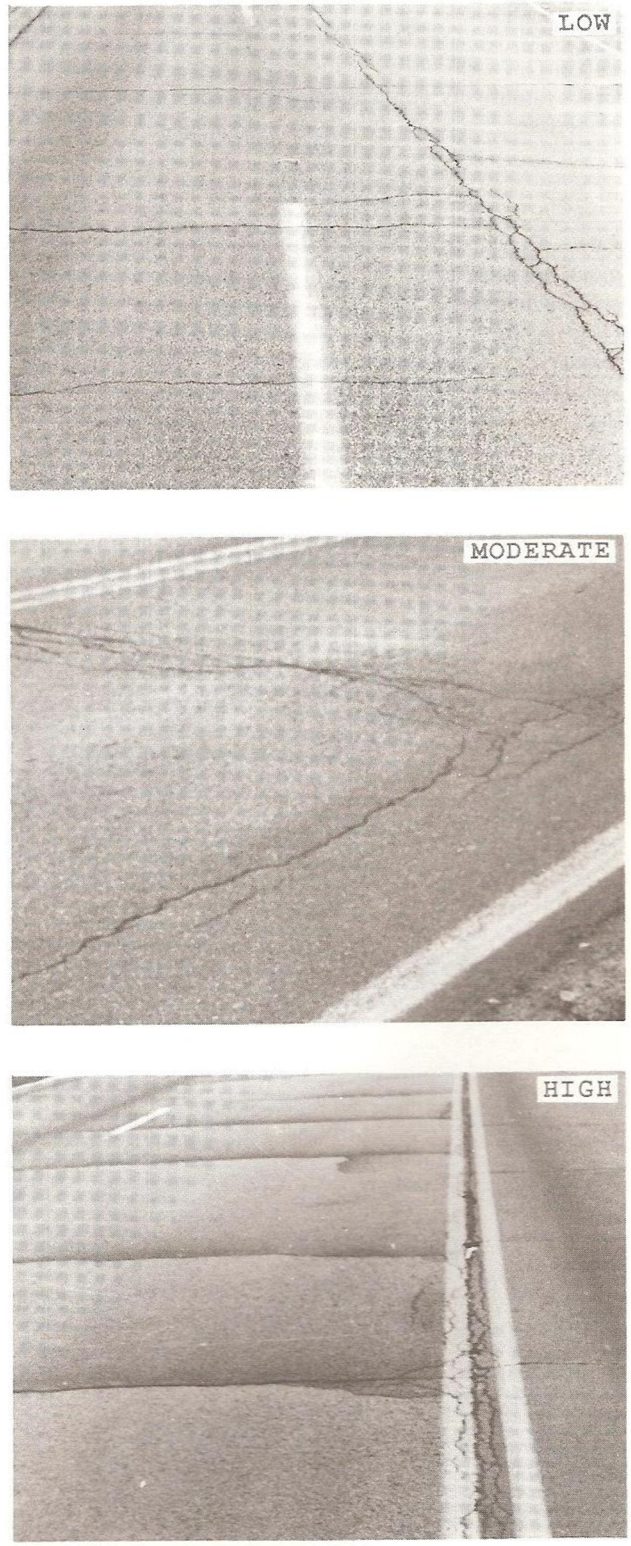
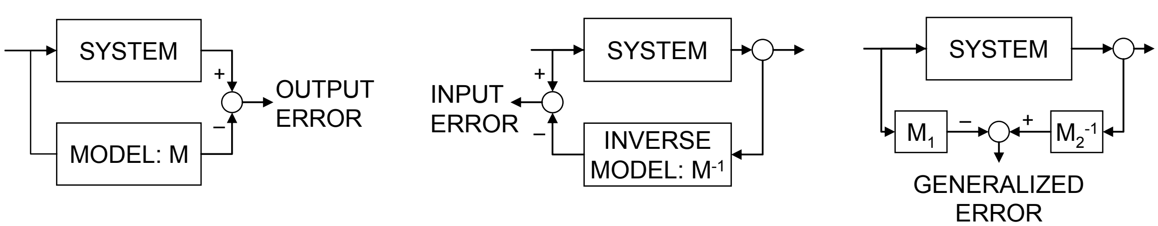


Figure A4. Classification of Reflection Cracking (after SHRP-LTTP/FR-90-001).

System Identification Process

The reflection cracking amount and severity model at a given severity level was considered to have been calibrated when the error between observed and predicted crack lengths was minimized in some sense. Since the predicted crack length is calculated by the calibrated model at each test section, a solution method was required to figure out parameter, ρ and β, in the model. In this study, the method of solving for the parameters is done by using of the system identification process.

The simplest method for representing the real process is to model it with mathematical representation. The purpose of system identification process is to develop a mathematical model which describes the behavior of a system (real physical process) in a rationally satisfying method. The actual system and the mathematical model are identified when the error between them is minimized or satisfies the error criteria; otherwise, the model should be adjusted until the error is reduced sufficiently (Natke, 1982). Three different error minimization models are available in the system identification process, depending on the choice or residuals combined with the model: forward model, inverse model, and generalized model, as shown in Figure A5. The forward approach employs output error between the model and the system to minimize them using same input. In the inverse approach, the input error is used to be minimized based on same output. The generalized model is a combination of the forward and inverse approach when the model is invertible (Natke, 1982).



(a) Forward Model (a) Inverse Model (c) Generalized Model

Figure A5. Methods for System Identification Process (Natke, 192).

As in the case of the calibration process in this study, when the system output is fixed because it is observed or obtained from actual system, the output from model must be refined to calibrate the mathematical model including of parameters. That is, the reflection cracking amount and severity model (mathematical model) should be calibrated based on observed reflection crack data (actual system output) to produce predicted crack data (model output) that was closed to observed field crack data. Therefore, the system identification process, based on the forward model, was used for calibrating the reflection cracking model.

When the output error between system and model is small enough to meet an error criterion, it is assumed that an optimal model for the system is obtained. However, if the error does not meet the criterion, the parameters in the mathematical model should be corrected by a parameter adjustment and adaptation algorithm. The correction process is performed iteratively until the error becomes small enough using the algorithm. Figure A6 depicts the scheme of a system identification process based on the forward model and parameter adjustment and adaptation algorithm for the reflection cracking model calibration.

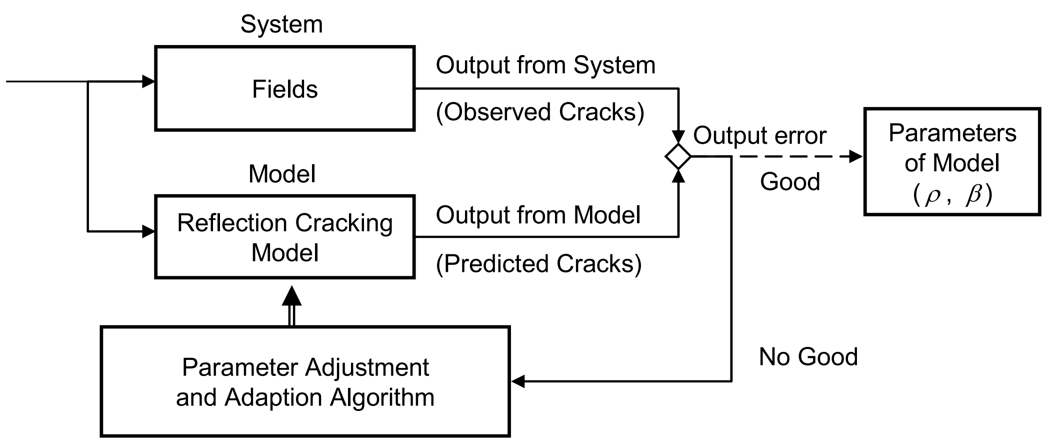


Figure A6. Scheme of System Identification Process.

Parameter Adjustment and Adaption Algorithm

A parameter adjustment and adaption algorithm was developed based on the Taylor series expansion as follows (Wang and Lytton, 1993):

$$[F_{ki}]\{\alpha_i\} = \{r_k\} \tag{1}$$

where

$[F_{ki}]$ = sensitivity matrix = $\sum_{k=1}^{m}\sum_{i=1}^{n}\frac{\partial f_k}{\partial p_i}\frac{p_i}{f_k}$ ($m \times n$ matrix),

m, n = number of output data and model parameters, respectively,

f_k = mathematical model,

p_i = model parameters,

$\{\alpha_i\}$ = change vector (relative change of parameters) = $[\alpha_1\ \alpha_2 \ldots\ \alpha_n]^T$, and

$\{r_k\}$ = residual vector (error between system and model outputs) = $[r_1\ \ r_2 \ldots\ \ r_m]^T$

The minimization of error contained within the residual vector $\{r_k\}$is analogous to the reduction of error employed in least squared error analysis. The squared error between actual output and predicted output is calculated by using a mathematical model to determine the sensitivity of the weighting parameters for allocating the squared error. It is possible to adjust the model parameters until there is no squared error remaining. However, because of the presence of random error, the values in the residual matrix $\{r_k\}$ should not be forced to zero (Zollinger, 2008). Since the elements in the residual vector $\{r_k\}$ which represents errors between the actual and model outputs are determined based on model parameters, p_i, assumed at each iteration process, they are known values. The sensitivity matrix $[F_{ki}]$ which reflects the sensitivity of the output from mathematical model, f_k, to the assumed parameters, p_i, is also a known value. Therefore, the unknown change vector $\{\alpha_i\}$ presents the relative changes of the model parameters and is the target matrix to be determined in the process. Equation 1 can be rewritten as:

$$\{\alpha_i\} = \left[F_{ki}^T F_{ki}\right]^{-1} \left[F_{ki}\right]^T \{r_k\} \tag{2}$$

As soon as change vector $\{\alpha_i\}$ is obtained using initial assumption of parameters, a new set of parameters is determined as

$$p_i^{j+1} = p_i^j \left(1 + 0.6\alpha_i\right) \tag{3}$$

where

j = iteration count

By minimizing the change vector $\{\alpha_i\}$, solutions for the parameters in model are found. In order to achieve the solution, the iteration process using Equation 3 was continued until there is no squared error remaining or the desired convergence was reached. In this study, the convergence criterion was set to 1.0 percent; that is, the iteration should be repeated until the elements in changes vector $\{\alpha_i\}$ are less than 0.01.

Calibrating Reflection Cracking Model of Test Sections

Based on the system identification and the parameter adjustment algorithm addressed previously, the reflection cracking models were calibrated using the data obtained from three test pavements. Due to minimum cracks observed in Pharr test pavements calibration was performed only with two other test pavements. The process was used to fit the predicted crack length to the measured crack length by iteration. The parameter adjustment algorithm of Equation 1 can be expressed for determining the parameters in the reflection cracking model as follows:

$$[F] \qquad \{\alpha\} \qquad = \qquad \{r\}$$

$$\begin{bmatrix} \frac{\partial \overline{D}(N_1)}{\partial \rho^j} \frac{\rho^j}{\overline{D}(N_1)} & \frac{\partial \overline{D}(N_1)}{\partial \beta^j} \frac{\beta^j}{\overline{D}(N_1)} \\ \frac{\partial \overline{D}(N_2)}{\partial \rho^j} \frac{\rho^j}{\overline{D}(N_2)} & \frac{\partial \overline{D}(N_2)}{\partial \beta^j} \frac{\beta^j}{\overline{D}(N_2)} \\ \vdots & \vdots \\ \frac{\partial \overline{D}(N_i)}{\partial \rho^j} \frac{\rho^j}{\overline{D}(N_i)} & \frac{\partial \overline{D}(N_i)}{\partial \beta^j} \frac{\beta^j}{\overline{D}(N_i)} \end{bmatrix} \begin{bmatrix} \frac{\rho^{j+1}+\rho^j}{\rho^j} \\ \frac{\beta^{j+1}+\beta^j}{\beta^j} \end{bmatrix} = \begin{bmatrix} \frac{D(N_1)-\overline{D}(N_1)}{\overline{D}(N_1)} \\ \frac{D(N_2)-\overline{D}(N_2)}{\overline{D}(N_2)} \\ \vdots \\ \frac{D(N_i)-\overline{D}(N_i)}{\overline{D}(N_i)} \end{bmatrix} \tag{4}$$

where

$\overline{D}(N_i)$ = crack length at N_i, calculated using ρ^j and β^j,

$D(N_i)$ = measured crack length at N_i, and

The parameters ρ and β in the model were determined when the relative changes of adjusted parameters were minimized and so the elements in change matrix were less than 0.01.

The percent crack length at each of the pavement ages was used to develop the model parameters ρ and β in the reflection cracking model along with the system identification process. Table A10 presents an example for percent of reflective cracking development of all severity level of PetroGrid section in Amarillo and Waco. Table A11 shows the developed model parameters. Figure A7 and Figure A8 present the plots of calibrated model corresponding to the measured data for those two test sections. The results presented good data fitting along with satisfying the convergence criterion.

Table A10. Reflective Cracking Development of L+M+H for LTPP Test Sections.

Section No.	Maximum Crack Length (ft)	Number of Days after Overlay	% Crack Length
Amarillo-PetroGrid	658	0	0.00
		304	0.00
		670	0.00
		1035	1.98
		1341	6.69
		1583	10.64
		1765	24.77
Waco-PetroGrid	828	0	0.00
		731	11.96
		1096	21.62
		1308	25.48
		1522	28.26
		1673	36.35

Table A11. Calibrated Model Parameters of PetroGrid Sections.

Section ID	Overlay Type	Model Parameters (L+M+H)	
		β	ρ
PetroGrid - Amarillo	AC/AC	2.383	2036.85
PetroGrid - Waco	AC/Jointed Concrete	0.800	1881.81

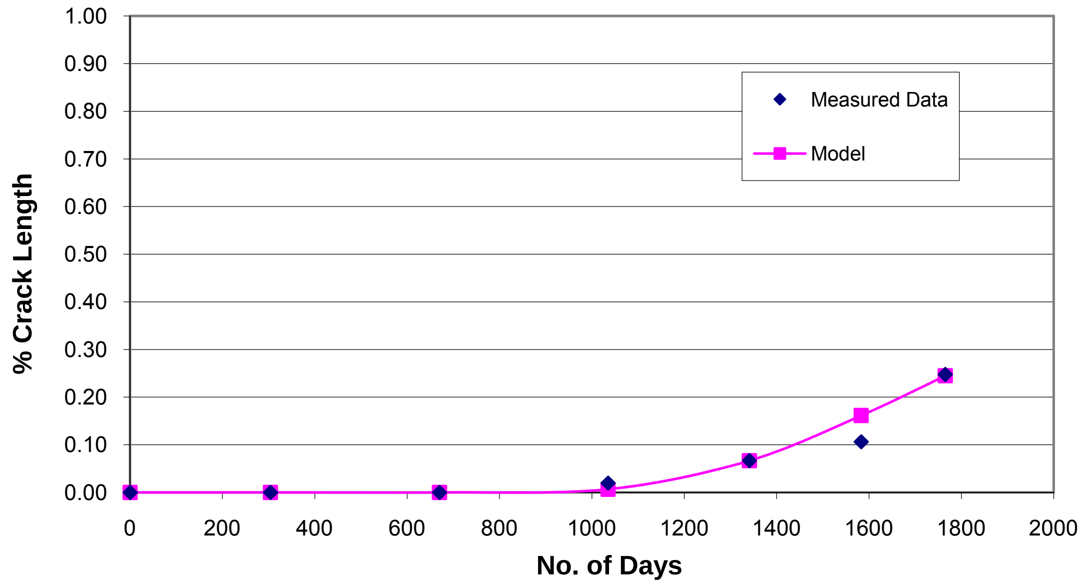


Figure A7. Calibrated Model on Measured Reflective Crack for PetroGrid Section in Amarillo.

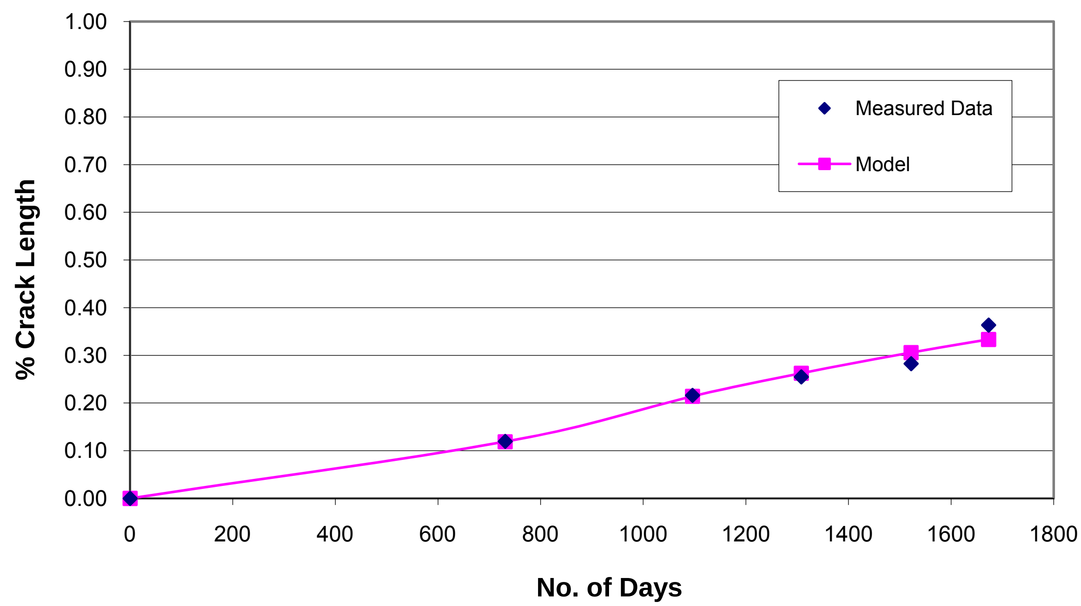


Figure A8. Calibrated Model on Measured Reflective Crack for PetroGrid Section in Waco.