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16. Abstract

Reflection cracking is a serious challenge associated with pavement rehabilitation. The primary objective of this study is to conduct an in-depth literature review of research projects on reflective cracking and a survey of the practices of highway agencies with regard to the types of cracking mitigation strategy used. Based on the results of the literature review and the survey questionnaire, a summarized assessment is presented for each reviewed treatment method. Further, a number of treatment methods were identified for further evaluation. For existing HMA pavements, crack sealing and overlay, chip seal and open-graded interlayers, full-depth reclamation, and cold-in place recycling are the most promising treatment methods. For existing PCC pavements, saw and seal, chip seal and open-graded interlayer systems, and rubblization are the most promising treatment methods. Based on the results of this study, the research team recommends that a follow-up study be conducted in order to evaluate the cost-effectiveness of the most promising treatment methods and to develop guidelines for the control of reflective cracking. The developed crack control guidelines will present recommended treatment methods for different classes of rehabilitated pavements in order to achieve adequate control of reflective cracking in a cost effective manner.

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Mitigation Strategies of Reflective Cracking in Pavements

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ABSTRACT

Reflection cracking is a serious challenge associated with pavement rehabilitation as it leads to premature failure of the overlay and allows water infiltration through the cracks, which causes stripping in HMA layers and weakening and deterioration in the base and/or subgrade. The primary objective of this study is to conduct an in-depth literature review of research projects on reflective cracking and a survey of the practices of highway agencies with regard to the types of cracking mitigation strategy used, selection criteria for the different strategies, construction methods employed to implement the strategies, experiences with the strategies and constructed systems, benefit/cost analysis performed, and guidelines for selecting appropriate strategies and constructing the chosen treatment system. This review will serve as a baseline for future research projects on this topic as identified by the results of the synthesis.

Based on the results of the literature review and the survey questionnaire, a summarized assessment is presented for each reviewed treatment method. Further, a number of treatment methods were identified for further evaluation. For existing HMA pavements, crack sealing and overlay, chip seal and open-graded interlayers, full-depth reclamation, and cold-in place recycling are the most promising treatment methods. For existing PCC pavements, saw and seal, chip seal and open-graded interlayer systems, and rubblization are the most promising treatment methods. However, one should consider that rubblization requires a thick overlay and may also necessitate guardrail adjustments and/or shoulder work.

Based on the results of this study, the research team recommends that a follow-up study be conducted in order to evaluate the cost-effectiveness of the most promising treatment methods and to develop guidelines for the control of reflective cracking. The developed crack control guidelines will present recommended treatment methods for different classes of rehabilitated pavements in order to achieve adequate control of reflective cracking in a cost effective manner. It is envisioned that a simple computer tool would be developed to allow the designer to enter information for a given project and with the computer program providing the recommended crack control treatment method along with cost saving estimates based on project conditions.

ACKNOWLEDGMENTS

The authors recognize the efforts of Doc Zhang and Kevin Gaspard of LTRC, who cooperated with the research team during this project. The U.S. Department of Transportation (USDOT), Federal Highway Administration (FHWA), and the Southern Transportation Consortium (STC) financially supported this research project.

IMPLEMENTATION STATEMENT

Based on the results of the literature review and the survey questionnaire, the following crack control treatment methods are recommended:

- **For existing HMA pavements, one of the following treatment methods may be selected:**
    - Crack sealing and overlay (pros: low cost and suitable for cracked asphalt pavements; cons: reflective cracking may still appear)
    - Chip seal interlayer (pros: low cost and adequate control of reflective cracking)
    - Full-depth reclamation (pros: prevent reflective cracking, suitable for heavily cracked pavements, environmentally-friendly; cons: cost)
    - Cold-in place Recycling (pros: prevent reflective cracking; cons: not suitable for heavily cracked pavements with fatigue cracking)
- **For existing PCC pavements, one of the following treatment methods may be selected:**
    - Saw and seal (pros: low cost and well-proven performance)
    - Chip seal and open-graded interlayer system (pros: low cost and adequate control of reflective cracking, can be used with weak subgrade)
    - Rubblization (pros: eliminates slab action, high probability of success; cons: only suitable in projects with suitable subgrade/base support, cost compared to conventional overlay)

To quantify performance and cost-efficiency, the research team recommends that a follow-up study be conducted in order to evaluate the cost-effectiveness of the most promising treatment methods and to develop guidelines for the control of reflective cracking. Details of this follow-up study are provided in Chapter VII of this report.

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CHAPTER I

INTRODUCTION

Hot-mix asphalt (HMA) overlays are commonly applied on existing flexible and rigid pavements when pavement conditions (structural and functional) have reached an unacceptable level of service. Overlays are designed to resist fatigue and/or rutting failure mechanisms *[1, 2]*; however, overlays may still show cracking patterns similar to the ones, which existed in the old pavement after a short period of time *[3]*. This distress is known as 'reflection cracking.' Reflection cracks are caused by discontinuities (cracks or joints) in underlying layers, which propagate through a HMA overlay due to continuous movement at the discontinuity prompted by thermal expansion and traffic loading. If the new overlay is bonded to the distressed layer, cracks and joints in the existing pavement almost always propagate to the surface within one to five years; as early as few months have sometimes been reported *[4]*. Seasonal temperature variations may also accelerate the reflection cracking process, especially when dealing with rehabilitated rigid pavements. Reflection cracking is a serious challenge associated with pavement rehabilitation as it leads to premature failure of the overlay and allows water infiltration through the cracks, which causes stripping in HMA layers and weakening and deterioration in the base and/or subgrade *[5]*.

Since the early 1930s, considerable resources and efforts have been spent to find new and relatively inexpensive techniques to delay reflective cracking *[6]*. Different methods, including the use of interlayer systems, have been suggested for enhancing pavement resistance to reflective cracking. Experimental investigations in the early 1980s showed that interlayer systems might be used to delay or to prevent the reflection of cracks through a new overlay placed over an old cracked pavement *[7]*. Later, Button and Lytton (1987) postulated that the use of interlayer systems to mitigate reflective cracking can be achieved by using two different mechanisms: reinforcing HMA with a stiff interlayer to provide a better distribution of the applied load over a larger area and to compensate for the lack of tensile strength of the HMA and dissipating strain energy in the vicinity of cracks through the use of a soft layer *[8]*.

Although it is generally recognized that each crack control treatment method should be used for a specific goal and that not all methods have a strengthening function, it is not well understood that, if used inappropriately, treatment methods actually can contribute negatively to pavement performance. This oversimplified view of the situation has led to a certain amount of mistrust and confusion among highway agencies regarding the benefits of crack control treatment methods. Contradictory opinions and experiences also have been reported in the literature. While some studies emphasized the surplus advantages, such as substantial savings in hot-mix asphalt (HMA) thickness, others found the use of treatment methods ineffective *[9, 10]*.

Repairing a deteriorated road using a conventional overlay is rarely a lasting solution. The original cracks and joints that move due to thermal and traffic loadings propagate to the new surface, causing reflection cracking *[11]*. Different crack control methods, including the use of interlayer systems, have been suggested. The general belief among pavement engineers is that, even when a technique to delay reflective cracking is successful, the cost is equivalent to the cost of repairing the cracks *[12]*. This opinion appears inaccurate if we consider the appearance of the reflection cracking a few months after application of the overlay, which is sometimes the case.

According to Lytton, the passing of a wheel load over a crack in the existing pavement causes three critical pulses, one maximum bending, and two maximum shear stresses *[13]*. As the movement of the crack increases, the propagation of the crack to the overlay occurs faster, Figure 1. A difference in temperature can also contribute to the crack propagation. Contraction and curling of the old pavement caused by temperature variation may result in the opening of the cracks, which may induce horizontal stresses in the HMA overlay.

Generally, loads can be applied on a pavement structure in a combination of three fracture modes, which represent the worst cases of loading *[14]*:

- **Mode 1** loading results from loads that are applied normally to the crack plane (thermal and traffic loading).
- **Mode 2** loading results from in-plane shear loading, which leads to crack faces sliding against each other normally to the leading edge of the crack (traffic loading).
- **Mode 3** loading (tearing mode) results from out-of-plane shear loading parallel to the crack leading edge. This mode of loading is negligible for pavements.

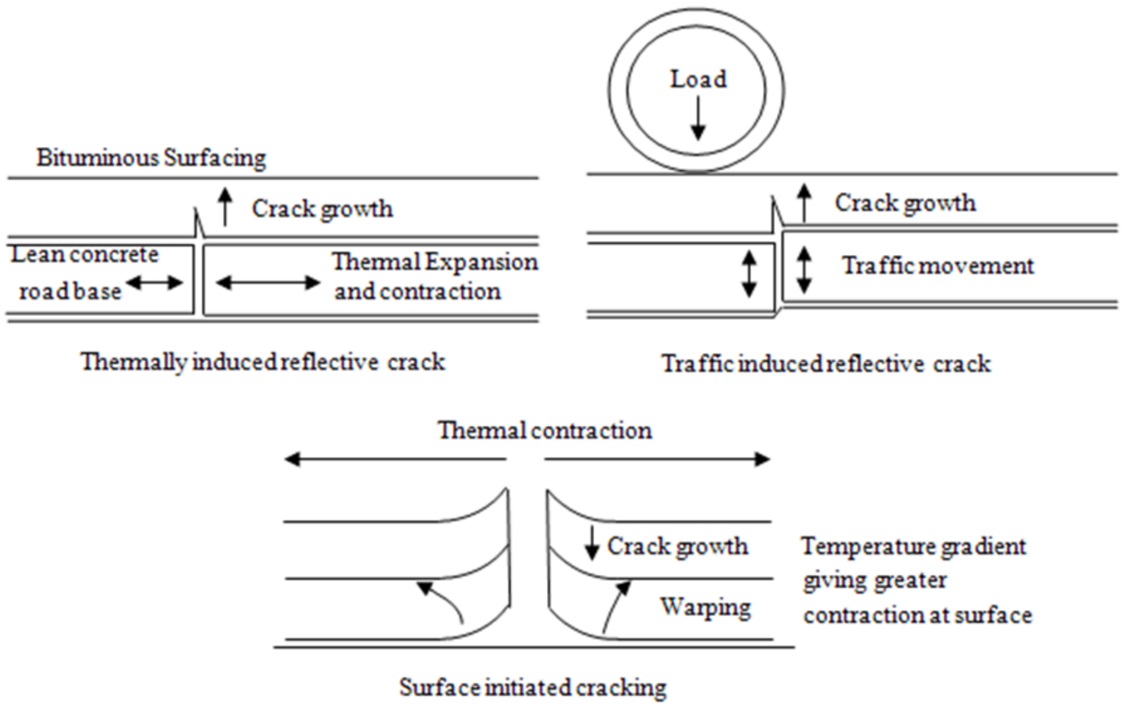
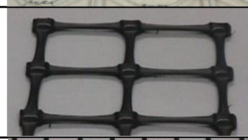
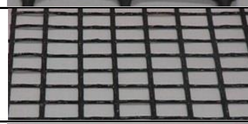
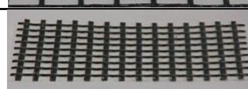
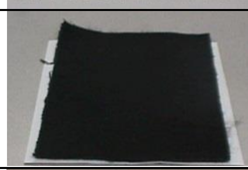


Figure 1
Mechanisms of reflective cracking *[15]*

Starting from the early 1960s, different treatment methods have been suggested to control reflective cracking including metallic grids, different types of geosynthetics, asphalt-based interlayers, and fractured-slab approaches. Fractured slab approaches including crack and seat, break and seat, and rubblization aim at reducing or eliminating the effective length of the original slab in order to prevent movement of the concrete layer, and in turn reflective cracking. Table 1 illustrates the major types of treatment methods that have been evaluated to control reflective cracking. The indicated price ranges are based on review of bid items and only represent an estimate. The following sections present a detailed presentation of each class of treatment methods.

Table 1

Major Types of Crack Control Treatment Methods

Treatment	Picture	Functions	Estimated Cost[1]
Galvanized Steel Netting		Reinforcement	3.00 – 5.00 $\$/yd^2$
Geogrid		Reinforcement	1.80 – 4.00 $\$/yd^2$
Geonet		Reinforcement	3.00 – 4.00 $\$/yd^2$
Glass-Grid		Reinforcement	4.00 – 7.00 $\$/yd^2$
Paving Fabric		Stress Relief	0.60 – 1.05 $\$/yd^2$
Geocomposite		Stress Relief	8.00 – 9.20 $\$/yd^2$
SAMI	 *[16]*	Stress Relief	
Rubblization[2]		Eliminates movement in concrete layer	5.00 – 6.00 $\$/yd^2$
NovaChip	 *[17]*	Stress Relief	3.00 – 4.00 $\$/yd^2$
Strata		Stress Relief	
Saw and Seal		Control reflective cracking by sawing overlay	1.00 - 2.00 $/ft.

[1] Only an estimate, actual cost may vary; [2] Rubblization cost does not include cost of heavy overlay.

OBJECTIVE

The primary objective of this study is to conduct an in-depth literature review of research projects on reflective cracking and a survey of the practices of highway agencies with regard to the types of cracking mitigation strategy used, selection criteria for the different strategies, construction methods employed to implement the strategies, experiences with the strategies and constructed systems, benefit/cost analysis performed, and guidelines for selecting appropriate strategies and constructing the chosen treatment system. This review will serve as a baseline for future research projects on this topic as identified by the results of the synthesis.

SCOPE

To achieve the aforementioned objectives, a comprehensive review of previous research studies was conducted to investigate the main types of crack control treatment methods used to delay/prevent reflective cracking. A questionnaire survey was conducted in order to identify current practices used by different states DOTs to combat reflective cracking. Collected information was used to conduct a comparative analysis that summarizes and compares each treatment method in terms of cost, effectiveness, and long-term performance. Based on the results of this synthesis, the research team identified the most promising treatment methods that should be considered for further evaluation and for quantification of their cost-effectiveness.

CHAPTER II

SURVEY OF STATE PRACTICES

A nationwide survey was conducted to collect information from highway agencies in the US and Canada on the current state of practices to address reflective cracking. Figure 2 shows the states that responded to the survey. In total, 35 responses were received from 25 states, Quebec Department of Transportation and Saskatchewan Ministry of Highway and Infrastructure (Canada). A list of respondents is provided in Appendix A.

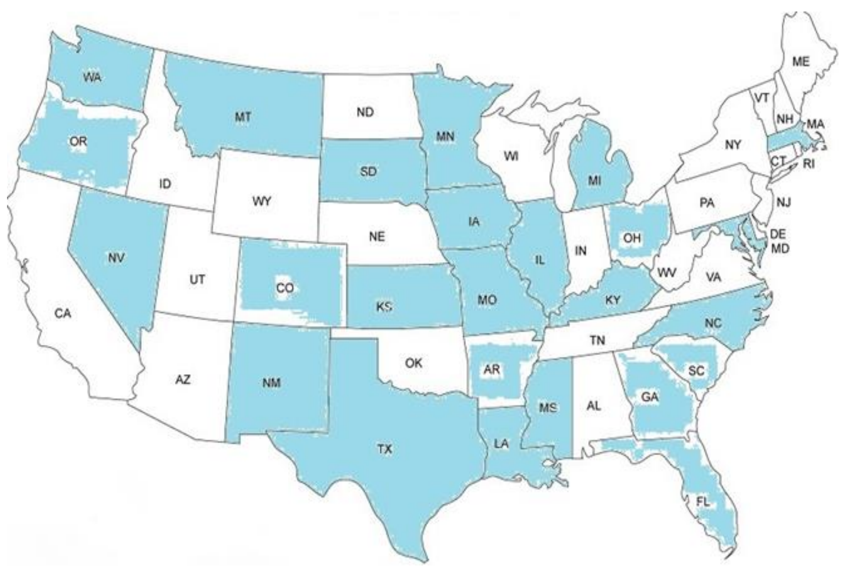


Figure 2
States Response to the Survey

The survey was posted online and was distributed through various list serves; it was also announced at related TRB committees. To expedite the response to the survey, the survey questionnaire was limited to nine main questions:

- What is the average service life in years of a regular 1.5 to 2in HMA overlay in your state against reflective cracking (i.e., time for the reflection of 50% of joints or cracks)?
- How severe do you consider the problem of reflective cracking in your state when applying an HMA overlay?

- Does your state take regular actions to address reflective cracking in HMA overlay?
- Which of the treatment methods are regularly used in your state to delay reflective cracking?
- Of the treatment methods, which have been evaluated on a trial basis in your state in the past ten years to delay reflective cracking?
- For the methods that you evaluated, was the overlay performance against reflective cracking improved, worsened, or was about the same?
- For the following asphalt mixtures, was the overlay performance against reflective cracking improved, worsened, or about the same?
- Does your state follow a systematic crack control policy to prevent or delay reflection cracking?
- What pre-construction repair activities do you recommend prior to HMA overlay application?

SURVEY RESULTS

Average Service Life of HMA Overlay against Reflective Cracking

Figure 3 presents the average service life of a 1.5 to 2.0 in HMA overlay against reflective cracking. The majority of the respondents (73%) indicated that average service life of a 1.5 to 2.0 in HMA overlay against reflective cracking is between 1 to 6 years, which is a very short service life. Only 12% reported that the average service life of the overlay against reflective cracking is between 6 to 10 years while 15% reported that they were unsure due to limitation in data collection. The high average service life of HMA overlay was observed in the states (e.g., GA, MD, FL, and MA), which take regular actions to address reflective cracking. These responses clearly indicate that in spite of the numerous studies conducted in the past 40 years in this topic, the majority of the states are still unable to control this failure mechanism. It was also noticed that for those states reporting a short service life (1-3 years), these states are located in the northern region of the US and Canada. This trend was expected due to the impacts of thermal movement on the fast propagation of reflective cracking.

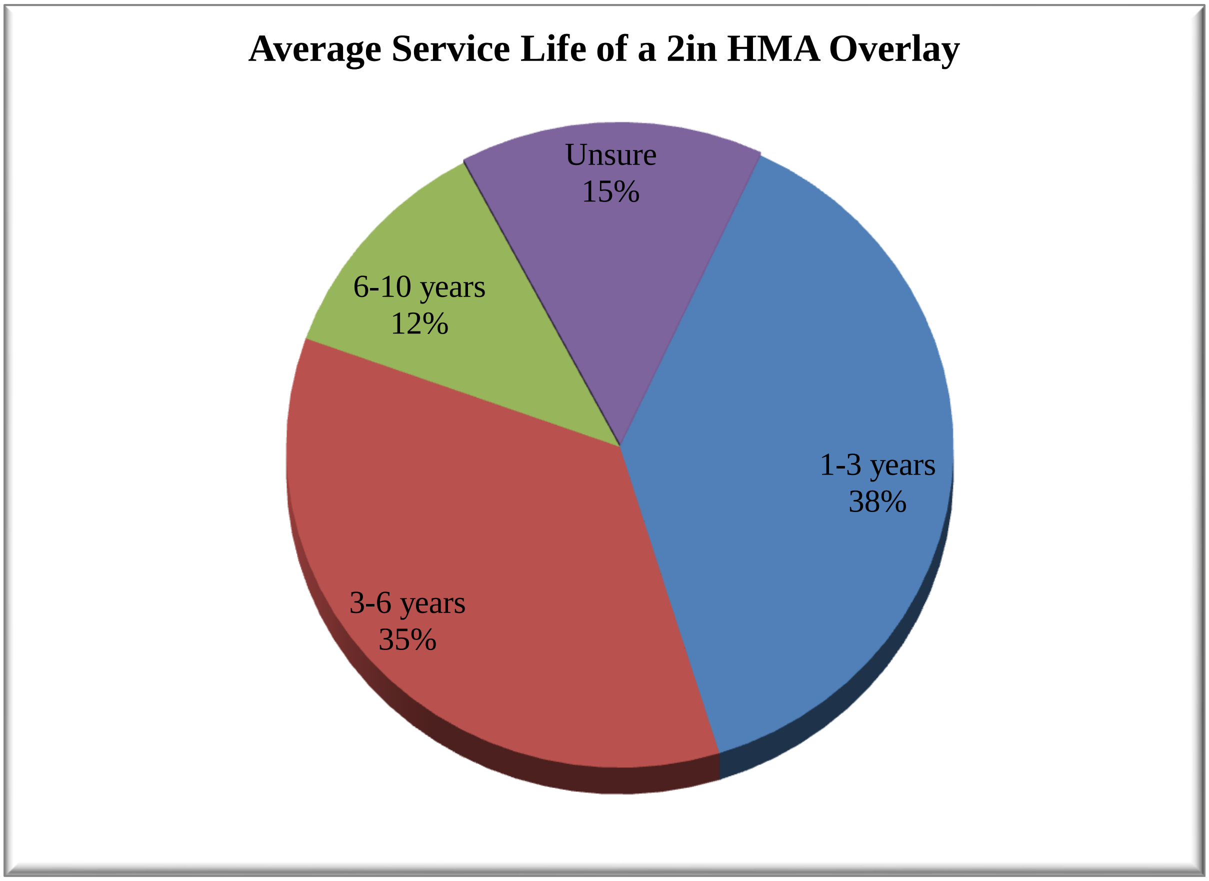


Figure 3
Average Service Life of a 1.5 to 2.0 in HMA Overlay against Reflective Cracking

Severity of the Problem

The second question in the survey gaged the importance of reflective cracking for highway agencies. The responses were collected on a scale from 1 to 5 as 1 being the lowest severity and 5 being the highest severity. Figure 4 presents the criticality of the reflective cracking problem for highway agencies. The majority of the respondents perceive the problem of reflective cracking as a medium to high level of severity. Given that not all roads would be subjected to reflective cracking, this response is indicative of a serious problem that should be addressed especially when dealing with rehabilitation of existing pavements.

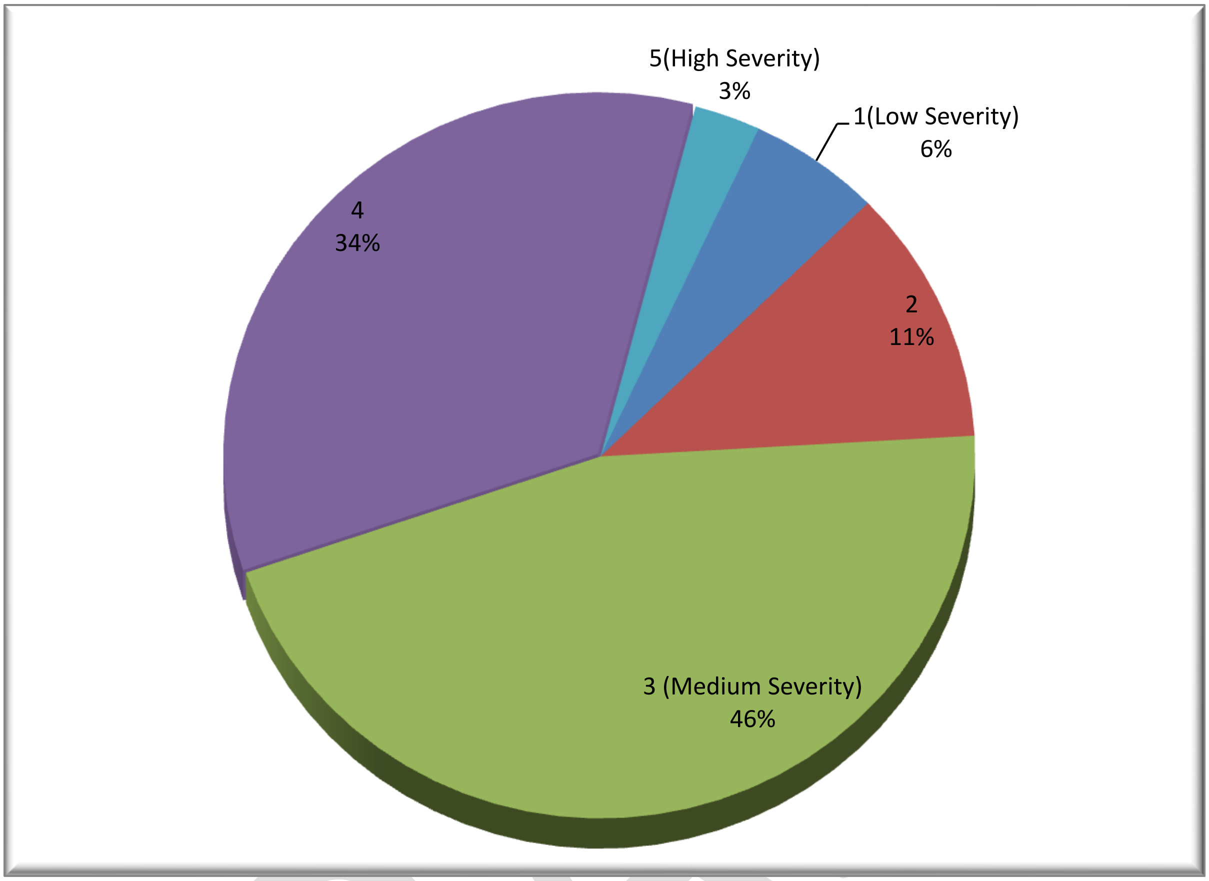


Figure 4
Severity of the Problem of Reflective Cracking

Actions to Address Reflective Cracking in HMA Overlay

The third question surveyed the current state of practices on whether regular actions are taken to address reflective cracking in HMA overlay. The survey results suggest that the majority of the states (63%) take regular actions to address reflective cracking in HMA overlay while 37% of highway agencies do not take regular actions to specifically address reflective cracking.

Treatment Methods Regularly used to Delay Reflective Cracking

Among the various treatment methods available to delay reflective cracking, the most common used method is crack sealing and overlay while there is no or minimal use of geocomposite material and steel mesh. Figure 5 presents a summary of the treatment methods that are regularly used to address reflective cracking in rehabilitated pavements. In the other category, respondent indicated that cold-in-place recycling (CIR), SMA, rubber seals, and open-graded crack relief interlayer are also used. From these results, one may conclude that saw and seal, chip seal, and rubblization are commonly used among state agencies to delay reflective cracking. The use of geosynthetics including paving fabric and fiber glass grid appears to be less common on a regular basis. A respondent indicated that with crack sealing, at least a year passes before overlaying to avoid rubber sealant expansion.

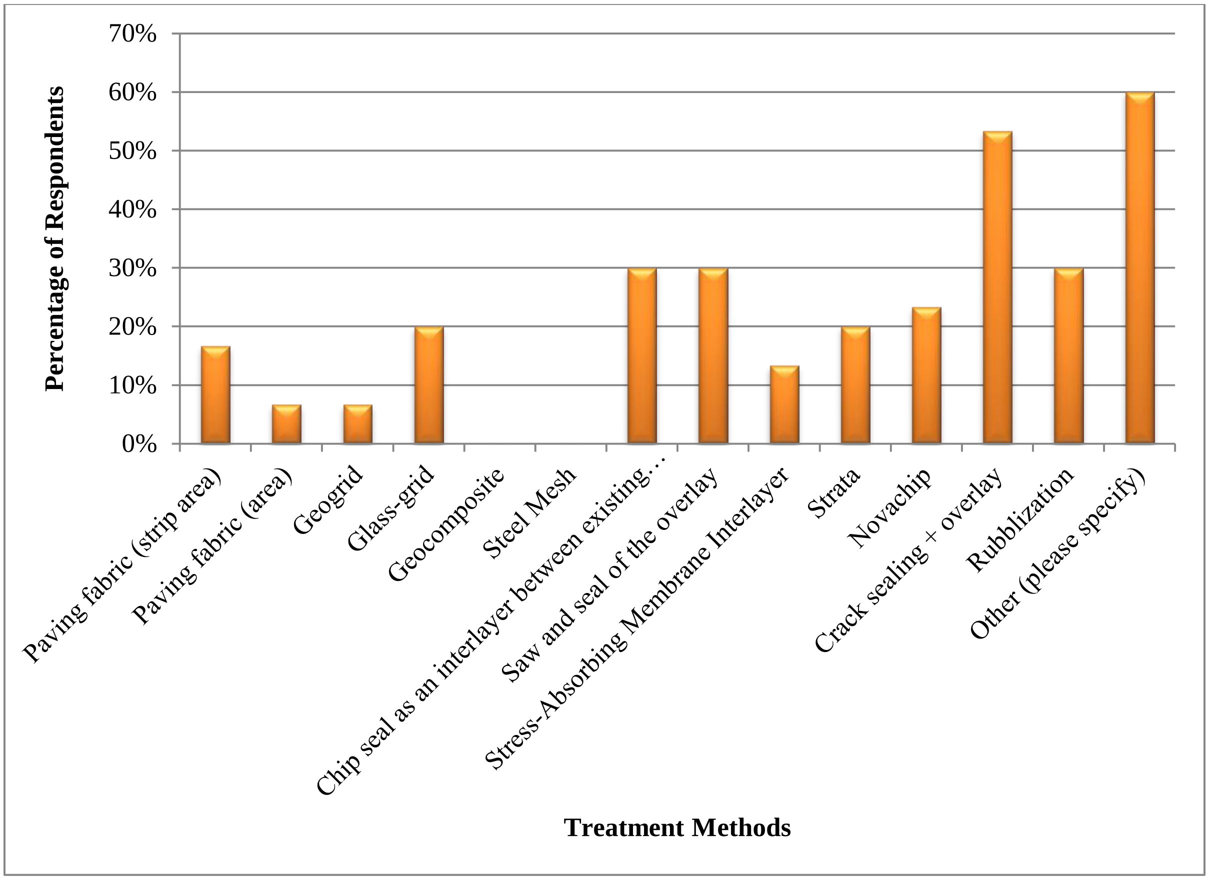


Figure 5
Treatment Methods Commonly Used to Delay reflective cracking

Evaluation of Treatment Methods

Almost all of the treatment methods available were found to have been evaluated on a trial basis by highway agencies, see Figure 6. However, one state did not evaluate any of these treatment methods in the past 10 years. The treatment methods in the “other” category include cold in place recycling, rubber seals, full-depth reclamation, open-graded interlayer, crack seat and overlay (CSOL), spray paver with polymer modified emulsion, crack relief layer, and ISAC. Georgia mentioned that the state is currently evaluating open-graded interlayer in a section at the NCAT test track.

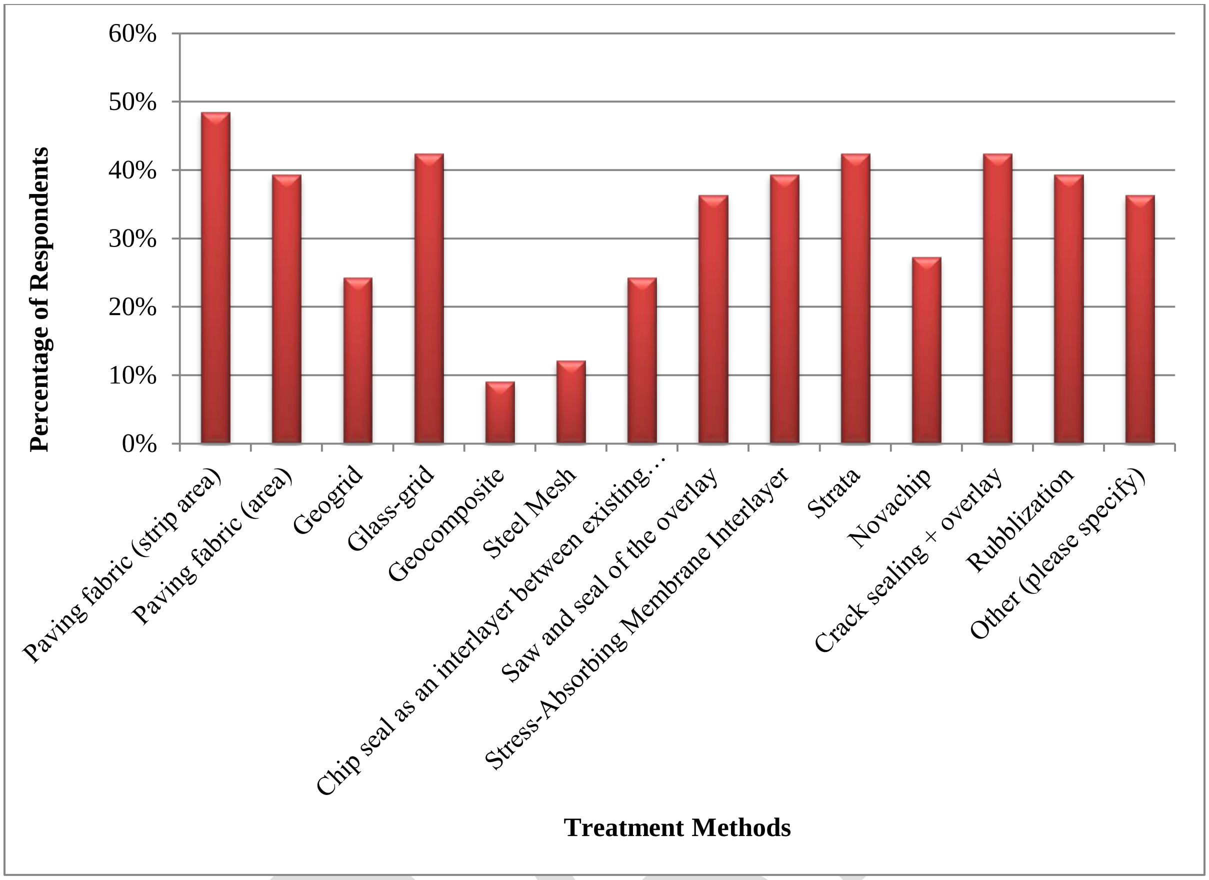


Figure 6
Evaluation of Treatment Methods

Performance of the Overlay for the Evaluated Treatment Methods

Figure 7 presents the percentage of respondents who reported an improvement for the different treatment methods evaluated in their state as compared to conventional overlay. As shown in this figure, rubblization and saw and seal appear to the most positively perceived method to address reflective cracking. However, one should acknowledge that rubblization is a long-term treatment that requires significant time and monetary investments and that is expected to significantly improve pavement performance. In contrast, the least beneficial treatments as reported by highway agencies were paving fabric and geogrid. Colorado indicated that fiber-glass grid and Strata are currently being evaluated. Further, Georgia indicated that open-graded interlayer appears promising in delaying reflective cracking. Two other agencies (Iowa and Quebec) indicated that CIR was the most effective in their states.

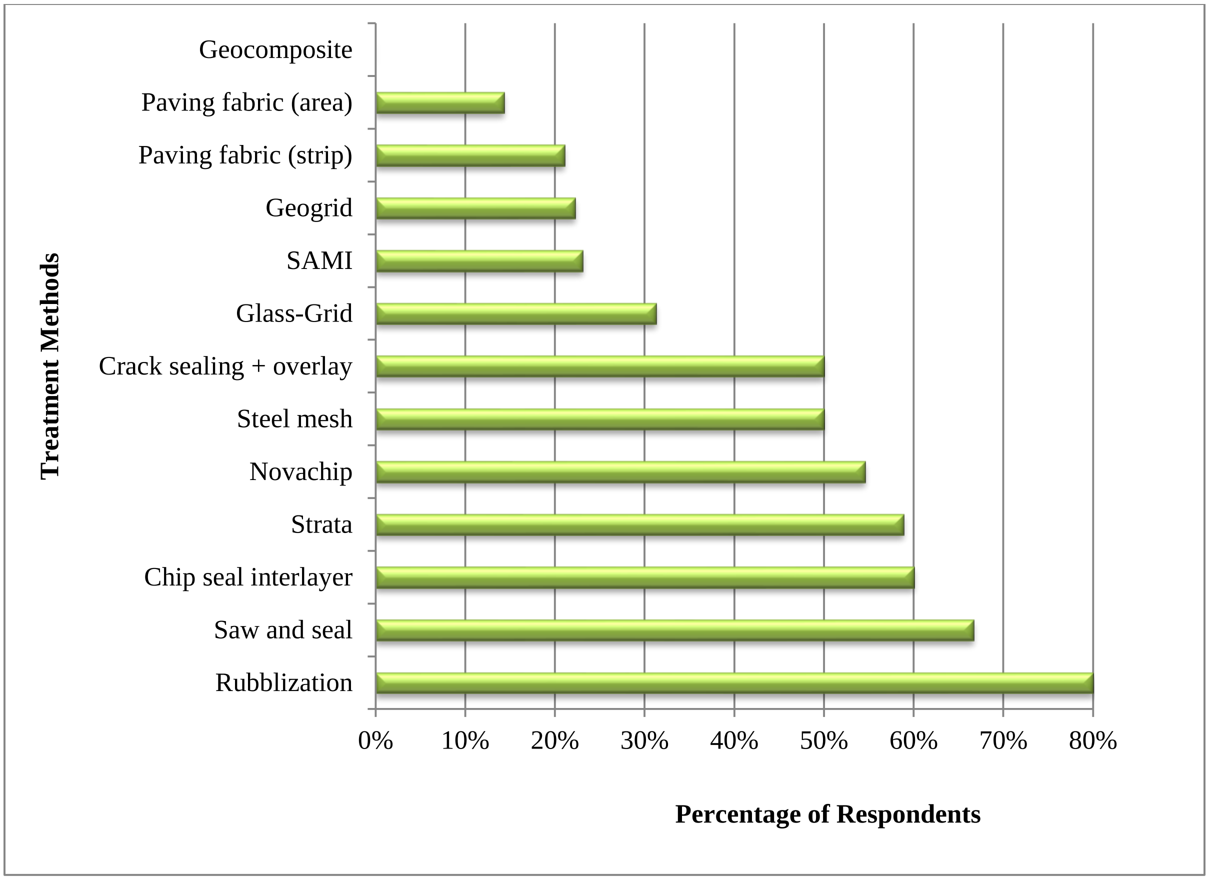


Figure 7
Treatment Methods that Positively Contribute to Delay Reflective Cracking

Performance of Different Asphalt Mixtures against Reflective Cracking

Figure 8 presents the percentage of respondents who reported an improvement for special purpose asphalt mixtures in their state as compared to conventional HMA overlays. As shown in this figure, SMA, Rubberized HMA, OGFC, and CIR have been found to be effective in addressing reflective cracking as compared to conventional HMA. As expected, mixes with high RAP/RAS were not reported to provide an improvement against reflective cracking. Missouri DOT, which is one of the leading states in using RAS, indicated that asphalt mixes with RAS holds up very well against rutting but are more prone to cracking because of their brittleness.

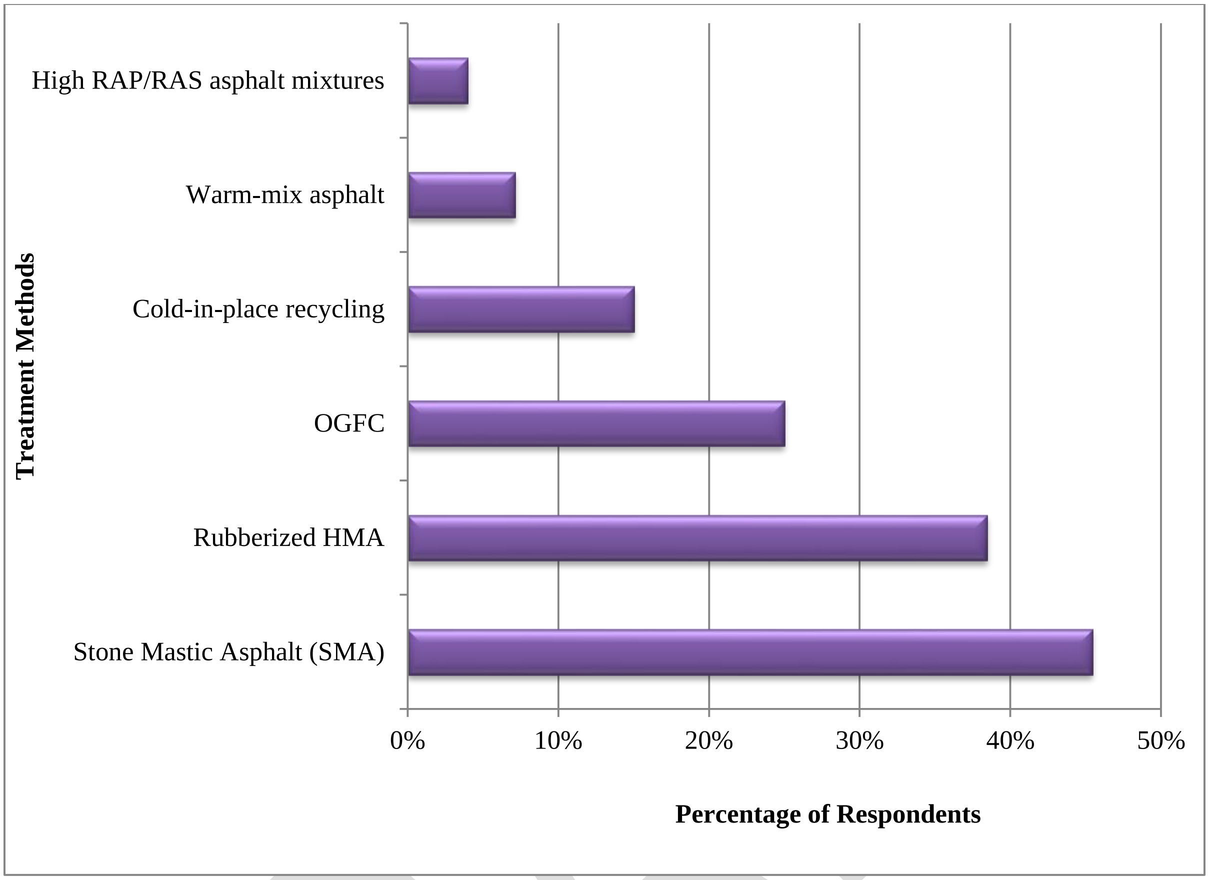


Figure 8
Asphalt Mixtures that Positively Contribute to Delay Reflective Cracking

Systematic Crack Control Procedure to Prevent Reflection Cracking

The survey results indicate that most of the states do not follow a systematic crack control procedure to prevent or delay reflective cracking. Figure 9 points that the majority of highway agencies do not have a systematic approach adopted to prevent reflective cracking in rehabilitated pavements. As reflective cracking is one of the major distresses in rehabilitated pavements, a systematic crack control procedure is needed to ensure that positively contributing treatment methods are regularly used.

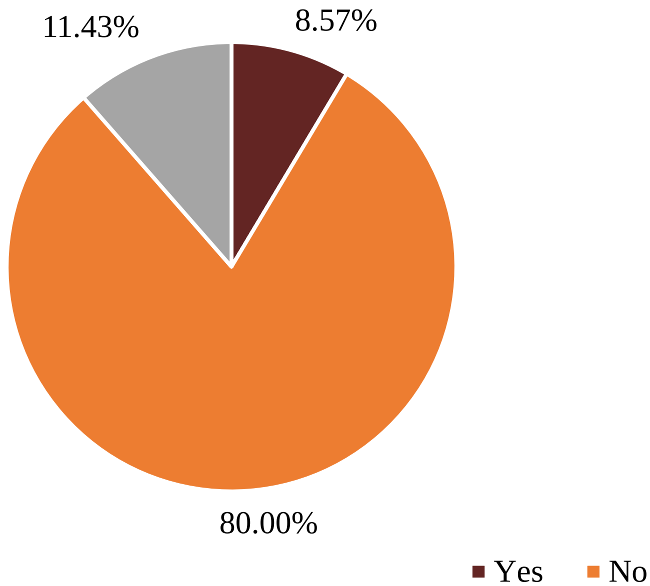


Figure 9
Use of a Crack Control Policy to Prevent Reflective Cracking

Pre-construction Repair Activities

Most of the respondents recommend patching, crack sealing, and joint repair as pre-construction repair activities prior to the overlay to control reflection cracking, see Figure 10. Void stabilization is less common than other repair activities possibly due to its cost (Figure 10). Joint repair and void stabilization are performed for PCC pavements while crack sealing and patching can be performed on either flexible or rigid pavements.

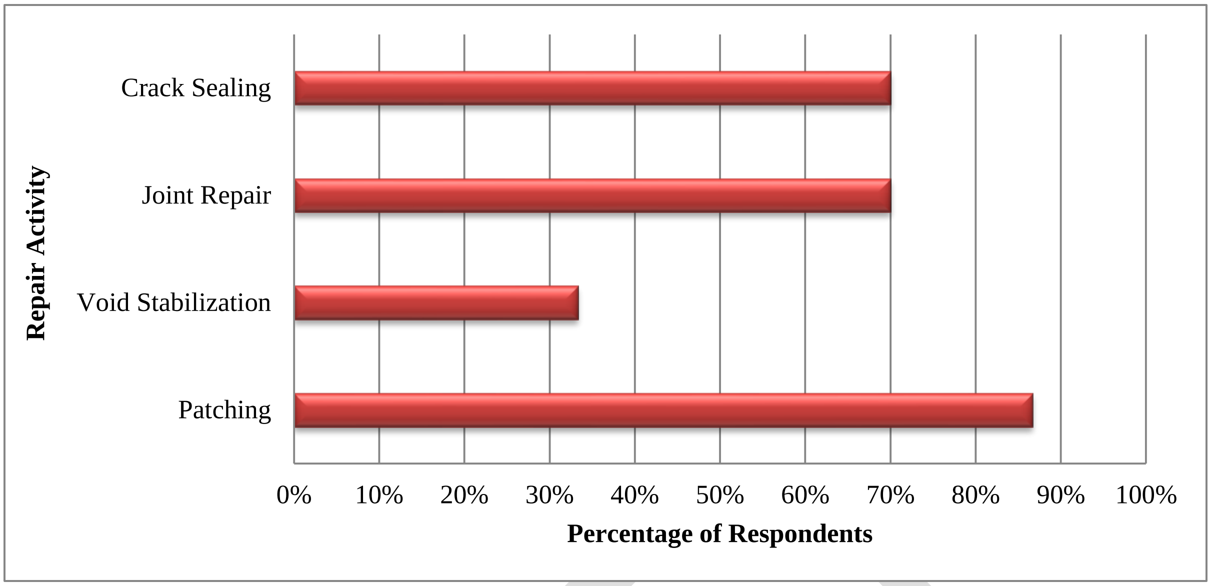


Figure 10
Pre-construction Repair Activities Prior to Overlay

CHAPTER III

LITERATURE REVIEW – GEOSYNTHETICS

"Geosynthetics" is the collective term applied to thin and flexible sheets of synthetic polymer material incorporated in soils, pavements, and bridge decks *[18]*. Geosynthetics are divided into seven major categories: geotextile, also known as paving fabric; geogrid; fiber-glass; geocell; geomembrane; geonet; and geocomposite. Geotextile, geogrid, fiber-glass, and geocomposite have been tested as reflective crack control treatments by acting as reinforcement or as a strain energy absorber, also known as stress relieving layer. The potential of these products as crack control treatments has been mostly mixed and depends on many factors including the installation procedure and conditions of the existing pavement *[19]*. For a geosynthetic product to outperform regular overlays, the existing pavement should not be severely deteriorated and may not experience excessive movements at the joints with a recommended load transfer efficiency of 80 percent or greater *[19]*. Product manufacturers recommend that a minimum overlay thickness of 1.5 in. should be used and that if the surface has been milled, a leveling course should be applied prior to installing the interlayer system *[20]*.

FIELD EVALUATION

Carey (1975) presented one of the first evaluations of paving fabrics in Louisiana *[21]*. Two paving fabrics (a nonwoven polypropylene fabric and a nylon fabric) were applied to highly distressed concrete pavements prior to the placement of HMA overlays to act as strain energy absorbers. A visual survey was conducted periodically for each test section to evaluate the effectiveness of the interlayer system in delaying reflective cracks. A comparison of treated vs. control sections indicated that paving fabrics were not effective in delaying or preventing reflective cracking. However, a long-term evaluation of the test sections was recommended to evaluate the potential of the fabrics to provide waterproofing benefits after reflective cracks have appeared.

McGhee (1975) presented Virginia's experience with reducing reflective cracking in asphalt overlay constructed over Portland cement concrete pavements *[22]*. The treatment methods evaluated were: (1) The use of sand as a bond breaker between Portland cement concrete (PCC) pavements and asphaltic overlays; (2) The use of a high tensile strength fabric as a stress relieving layer between an asphalt overlay and an existing concrete pavement on top of a weak subbase, and (3) the use of two types of fabric as a stress relieving layer between an asphalt overlay and a PCC pavement constructed on a strong subbase and subgrade layers. None of the methods were found to be effective in mitigating reflective cracking when vertical movement of slabs is predominant. Reflective cracking appeared early in the overlay service life when the differential movement of the slabs was greater than 0.002 inch. Both the asphalt impregnated polypropylene fabric (Petromat) and the nonwoven, spun-bonded nylon fabric (Chemstrand), were effective in delaying reflective cracking when placed in strip applications over the joints. The placement of the asphalt impregnated polypropylene fabric between the PCC pavement and the asphalt overlay prevented water infiltration and reduce pumping. Overall, it was observed that both asphalt impregnated polypropylene and nonwoven, spun-bonded nylon fabrics were effective in retarding reflective cracking in asphalt overlay. Tables 2 and 3 illustrate the relationship between reflective cracking and differential deflection and between reflective cracking and traffic volume.

Table 2
Reflective Cracking and Differential Deflection (Route 460) *[22]*

Differential Deflection (in.)	No. Joints Cracked		No. Joints un-cracked		% Joint Cracked	
	Fabric	Control	Fabric	Control	Fabric	Control
0	0	4	20	5	0	44
0.002	7	20	17	17	29	54
0.004	23	35	3	12	88	74
0.006	15	11	2	0	88	100
0.008	12	20	0	0	100	100

Table 3
Reflective Cracking and Traffic Volume *[22]*

Site	Truck Traffic	Total Traffic	Percentage Cracks Reflected		
			Petromat	Chemstrand	Control
3	270	19,000	41	0	0
4	3,050	42,500	52	68	100
5	3,050	42,500	0	0	90

Zapata et al. (1984) studied the performance of fabric-treated and untreated conventional repaired joints (control segments) to delay reflective cracking in asphalt overlay *[23]*. In the experiment, a 43 years old jointed concrete pavement was rehabilitated with an overlay while placing fabric reinforced grids over repaired joints (both longitudinal and transverse) and cracks. The comparative performance evaluation of six different fabrics (Protecto Wrap, Y-78, Pave Prep, Roadglass, Bituthene and Polyguard) was performed. The lowest reflection percentage of 11.5% (with an annual increase in crack reflection of 5%) of transverse joints was observed in the Roadglass-treated section. A reflection rate of 30 to 40% (with an annual increase in crack reflection of 16%) and of 22 to 26% (with an annual increase in crack reflection of 11%) was reported for the Polyguard and Protecto Wrap sections and for the Bituthene, Y-78, and Paveprep sections, respectively. A reflection rate of 41% (with an annual increase in crack reflection of 18%) was observed in the control sections. In case of longitudinal cracking, the rate of crack reflection ranged from 22 to 32% (with an annual increase in crack reflection of 12%) for the Polyguard, Protecto Wrap, and Pave Prep while the rate was about 6% (with an annual increase in crack reflection of 3%) for the Bituthene, Y-78, and Roadglass fabrics. A reflection rate of 46% (with an annual increase in crack reflection of 20%) was observed to reflect in the control sections. Overall, the researchers concluded that while paving fabrics do provide a level of resistance against reflective cracking, none of them completely prevented or greatly reduced reflective cracking.

Barnhart (1989) studied the performance of paving fabrics when used in strip applications to prevent reflective cracking in asphalt overlay *[24]*. Six different types of commercially-available fabric strips (Bituthene, Polyguard, Protecto Wrap, Y-78, Pave Prep, Roadglas, Mirafi 140) were compared to untreated sections to assess the effectiveness of the interlayer system. Cores were also examined from the treated sections to assess if the fabrics remained intact after installation. The fabrics covered the whole length of the longitudinal cracks and the whole width of the transverse cracks. After four years in service, except for the 'Protecto Wrap' fabric, paving fabrics showed similar performance against reflective cracking as the untreated sections. Barnhart noted that the fabrics were more effective in the longitudinal direction than in the transverse direction. Core samples were extracted from the areas where reflective cracking occurred and tested. It was observed that though the crack reflected, the fabrics were still effective in preventing moisture infiltration. The overall conclusion of the study was that paving fabrics delayed reflective cracking but not to a significant level. Further, it was recommended to check the specification requirement and to conduct quality checks prior to placing the paving fabrics.

Rollins et al. (1991) conducted a performance evaluation of three paving fabrics (paveprep, glassgrid and tapecoat) for a period of 4 years *[25]*. Treated and control sections were constructed with both sections consisting of eight transverse cracks. The existing pavement consisted of 6 in. cement-treated base, 5.5 in. asphalt concrete, and 0.5 in. friction course. The original cracks on the existing pavement had a width of 0.5 to 1 in. and a spacing of 100 to 150 feet. Problems were encountered during the installation of the fabrics due to improper bonding between the fabrics and the existing pavement. A 2 in. thick and 0.5 in. dense graded HMA overlay was applied on the sections. At the end of the evaluation period, statistical comparison was conducted between the treated and the control sections. Results showed no statistical difference between the treated and the control sections. Final inspection of the treated sections led to the conclusion that fabrics were not effective in retarding reflection cracking and should not be used in this application. Further, it was recommended to identify means to ensure proper bond between the fabrics and the milled pavement during installation. Tables 4 and 5 present a summary of the results of the field evaluation.

Table 4
Summary of Field Evaluation #1, April 11, 1989 *[25]*

Product	%Reflected by number	Observed Crack length	% Reflected by Total Length	Severity
Paveprep	100	371	76	Low
Glassgrid	87.5	291	60	Low
Tapecoat	100	300	63	Low
Control	100	409	85	Low

Table 5
Summary of product performance, Field Evaluation #2, May 29, 1991 *[25]*

Product	%Reflected by number	Observed Crack length	% Reflected by Total Length	Severity
Paveprep	100	413	98	Low – Medium
Glassgrid	100	454	97	Low – Medium
Tapecoat	100	444	94	Low – High
Control	100	477	99	Low – Medium

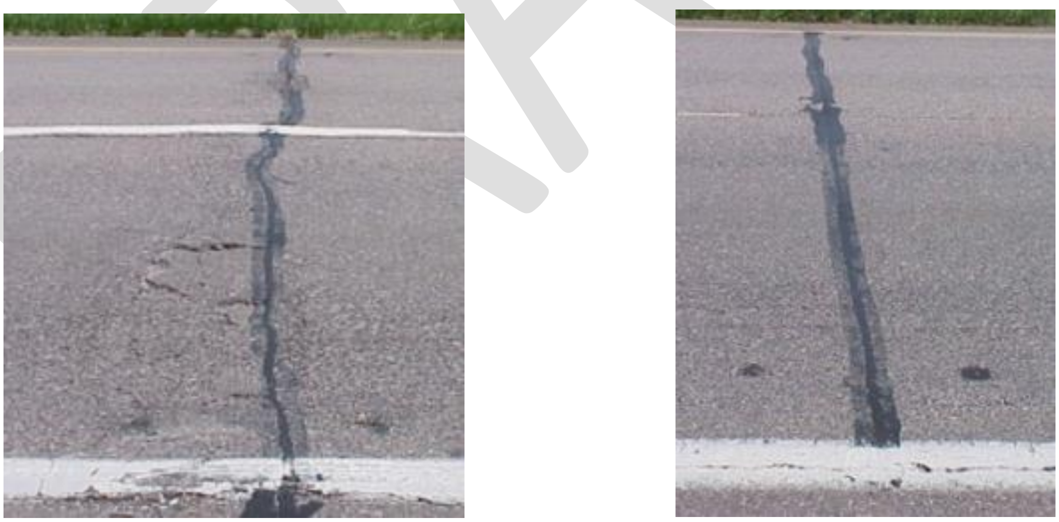
King (1992) reported on the construction of a section in Louisiana on Interstate 10 rehabilitated with a geogrid placed between two lifts of HMA overlay *[26]*. Prior to the HMA overlay, the existing PCC pavement was broken and seated. The first lift of HMA overlay was tack coated prior to the rolling of the geogrid interlayer. A total of five rolls of geogrid were placed over the entire two-lane span of the pavement. After one week of placement of the HMA overlay, the roadway began to ravel excessively and to spall. Due to heavy truck traffic, the grid was removed and discarded. In accordance with the manufacturers' recommendations, the grid was installed in east bound of the roadway and was secured with nails.

In a research study performed by Brooks and Countryman (1999), the potential use of geotextile and Glassgrid as a crack control treatment method was investigated *[27]*. Four sections were selected and were treated with either a fiber glass paving grid known as Glassgrid or a paving fabric known as polyguard NW-75 before placement of the overlay. The interlayer systems were placed between the existing pavement (7.0in thick PCC) and new asphalt overlay (2.0in thick). The Average Daily Traffic (ADT) on the roadway was reported to be 13,000 vehicles. The inspection was performed on a regular basis. During the early years after installation, only a few cracks were observed but the cracks started to reflect and become visible in the overlay four years after installation. The final inspection was performed on June 1998 after seven years in service and found that few and small reflective cracks appeared in both the treated and control sections. Therefore, the use of geosynthetics to retard the reflective cracking could not be verified from the results of this study.

Carmichael and Marienfeld (1999) synthesized the field performance of paving fabrics in delaying reflective cracking in 16 pavement sections located at 10 different sites *[28]*. The monitored sections made use of paving fabrics over existing PCC pavements as a stand-alone system. Seven of the sites were evaluated for five years while three other sites were evaluated for more than 10 years. In general, performance of paving fabric against reflective cracking was satisfactory. In one section, the overlay lasted more than ten years with only 10 percent reflection in the longitudinal joints and 20 percent reflection in the transverse joints. In another section, the percentage reflection after four years was 36.2 and 42.5 percent in the longitudinal and transverse directions, respectively. The authors pointed out that excessive movements at the joints may reduce the effectiveness of paving fabrics against reflective cracking. After laying down the fabric on the tacked surface without any folds or blisters, HMA overlay is placed on top of the interlayer and is carefully compacted using rollers.

Hughes and Somers (2000) evaluated the performance of three geosynthetics products (Petromat, a combined paving fabric heat bonded to a geogrid called 'Bit-U-Tex', and Glassgrid) *[29]*. Three treated sections and two control sections were used in the field evaluation. These sections consisted of an overlay with a thickness of 1.5 in over an existing concrete pavement. The Petromat and Bit-U-Tex were evaluated for three years. It was observed that Petromat and Bit-U-Tex did not prevent or delay reflection cracking. Similar performances were observed in the treated and the control sections. Fine hairline cracks were visible after one year of construction. At the end of the third year, significant amount of reflection cracking were observed in both the treated and control sections. Based on these results, Petromat and Bit-U-Tex were not recommended as a crack control treatment method. The evaluation of Glassgrid, which was scheduled for three years, was terminated after a period of two years as it showed poor performance against reflection cracking. Cracks began to open widely and spread, which was detrimental to road and public safety. Though longitudinal cracks did not reflect, almost all joints reflected through the overlay. Glassgrid did not resist the propagation of reflection cracking and only delayed them for six months. Therefore, Glassgrid was not recommended as a crack control treatment against reflection cracking.

Storsteen and Rumpca (2000) evaluated the performance of two types of geosynthetics in strip applications (Linq Tac-711N and Strata Grid-200) to retard reflective cracking in asphalt overlay constructed on top of an existing concrete pavement *[30]*. Twelve test sections (each sections consisting of 10 joints in the passing and driving lanes) were constructed and monitored for a period of three years. The parameters monitored included joint movement, reflective cracking, and shoulder cracking. Five inspections were performed during the period of three years. The researchers calculated the observed movement for each section by subtracting the narrowest joint width from the widest joint width. Further, the number of crack reflection in each section was calculated. Two types of rehabilitation strategy were followed: (1) Maximum rehabilitation involves full-depth repair of the concrete joints prior to the overlay; (2) Minimum rehabilitation consisted of only repairing small cracks at the joints. Some of the joints were sawed after placement of the overlay while others were left unsawed. In general, most the unsawed joints reflected through the overlay regardless of whether a fabric was used. Based on an economic analysis, the most cost effective repair strategy was the one with minimum rehabilitation, with no fabric, and in which joints were sawed. When the joints were not sawed, reflective cracks appeared in an irregular shape, making sealing the cracks more challenging, Figure 11. The researchers summarized the number of cracks and movement of slabs in the different sections, see Table 6. As shown in this table, the size of the field experiment was limited.



(a) (b)

Figure 11

Comparison of Reflective Cracks in (a) Unsawed Joints and (b) Sawed Joints *[30]*

Steen (2004) investigated the use of paving fabrics to reduce reflective cracking originating from cement-treated bases *[31]*. The author indicated that the use of cement-treated or lime-treated bases is widely used in pavement construction over weak subgrades. This base type provides a strong foundation for the pavement and helps reducing rutting. It is also a common practice to pre-crack the base in order to reduce thermal movements into this layer. However, even with pre-cracking, this type of base is likely to crack due to its rigidity. In this case, paving fabrics may be used as a stress reliever in order to extend the pavement service life against reflective cracking originating from the base layer. The author discussed some successful applications of this methodology. In one project, a pre-crack cement-treated base was used to increase the pavement structure capacity. However, reflection cracking appeared right after the construction of the first lift of HMA overlay. The use of a tack-coat saturated paving fabric was successful. Two similar projects were also described.

Table 6
Number of Reflective Cracking in the 12 Test Sections *[30]*

Joints	Material	Rehabilitation	Asphalt-Joint Treatment	Number of cracks that reflected through Asphalt Overlay Adjacent to Joint	
				Driving	Passing
615-624	Strata Grid-200	Max	Sawed	2	0
625-634	Linq Tac-711N	Max	Sawed	0	0
635-644	None	Max	Sawed	0	1
645-654	Strata Grid-200	Max	Unsawed	5	0
655-664	Linq Tac-711N	Max	Unsawed	2	2
665-674	None	Max	Unsawed	3	0
675-684	Strata Grid-200	Min	Unsawed	1	1
685-694	Linq Tac-711N	Min	Unsawed	2	0
695-704	None	Min	Unsawed	2	0
705-714	Strata Grid-200	Min	Sawed	2	0
715-724	Linq Tac-711N	Min	Sawed	2	0
725-734	None	Min	Sawed	1	0

Based on field experience, Steen recommended that the paving fabric be installed between the two lowest layers of asphalt overlay and not directly on top of the cement-treated base *[31]*. This provides a uniform platform for tack-coat application. Even with the use of fabrics, pre-cracking is recommended as it reduces thermal movement and is inexpensive. Pre-cracking is usually conducted during construction prior to setting of the stabilized material. The use of paving fabrics offers the advantage of obtaining stress-relieving benefits as well as water proofing capabilities. Based on field experience, the use of a paving fabric is comparable to the cost of 0.5 in of HMA overlay. According to the author, this is cost effective compared to the use of a thick overlay to combat reflective cracking.

Shuler and Harmelink (2004) reported on a field study conducted to evaluate the performance of geotextiles to retard reflective cracking *[32]*. Eighteen test sections were constructed in which eight treatment methods were evaluated for five years: 90-pound Petromat (A), 120-pound Petromat (B), Petrotac (C), ProGuard (D), two types of crack sealers (ASTM D3405 and polymer-modified) without routing (F and H), and with routing (E and G). Two experimental sections were constructed. In the first section, 1 in. of old pavement was milled in the passing lane and 1.5 in. in the driving lane. Then, 4 and 5 in. thick overlays were applied in the passing and the driving lanes, respectively. In the second section, the entire pavement width was milled and a 4 in. overlay was applied to both lanes. ESALs of 20 million in 20 years were reported by Colorado DOT. Reflective cracks were not observed in any of the test sections during the first and the second year after construction. It was observed that treatments A, B, C, F, G and H performed better than the control section in the first section and treatments B, C, D, E and H performed better than the control section in the second section after five years. However, no section with geotextile performed better than the control section in the passing lanes; see Figure 12. Results from the economic analysis indicated that the construction and repair costs were the least for the control section. Among the treatment methods test in the driving lane, the highest cost was associated with the 90-pound and 120-pound Petromat and the lowest cost was associated with the Petrotac and the crack sealers without routing.

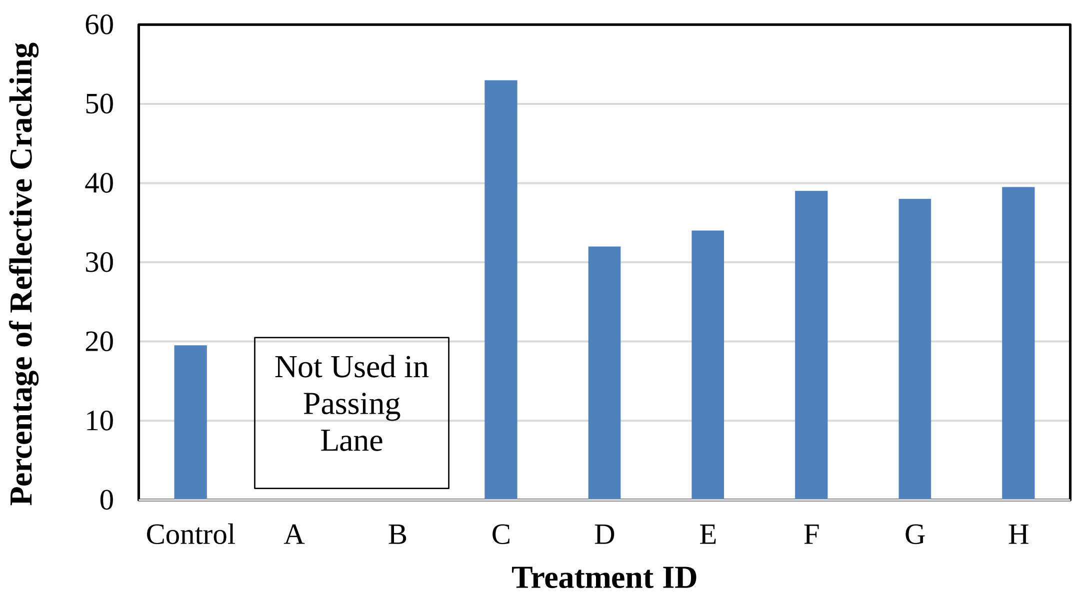


Figure 12
Total Cost of Treatments after 5 Years for Passing Lane *[32]*

Bush and Brooks (2007) conducted a field study to compare the effectiveness of different geosynthetics used to delay reflective cracking in asphalt overlay *[33]*. Five different types of geosynthetics were applied over 98 transvers cracks; crack filling was applied on 22 transverse cracks and 20 transverse cracks were selected as control sections. Six treated sections and one control section were constructed with the treated sections located in extreme conditions of temperature and precipitation. An average daily traffic of 4,899 was recorded in the test sections. The average depth of the existing pavement was around 11.0 in with six consecutive pavement lifts. The five different types of geosynthetics were: Glassgrid 8502®, GeoTac®, PavePrep SA®, Polyguard Cold Flex 2000 SA®, and Polyguard 665™. Year-to-year inspection for a period of eight years was performed to measure the length and severity of reflective cracking. Results showed that 17 (out of 22) cracks with 73% of original crack length reappeared in the crack fill only sections. None of the geotextiles reduced the total number of reflective cracks, see Figure 13. However, the use of geosynthetics reduced the high severity of cracks by 80%. Among the five geosynthetics used, the best performer in reducing crack severity was Glassgrid 8502®. Though all 20 cracks reflected in the section using Glassgrid 8502®, 95% of these cracks were low severity cracks with short length.

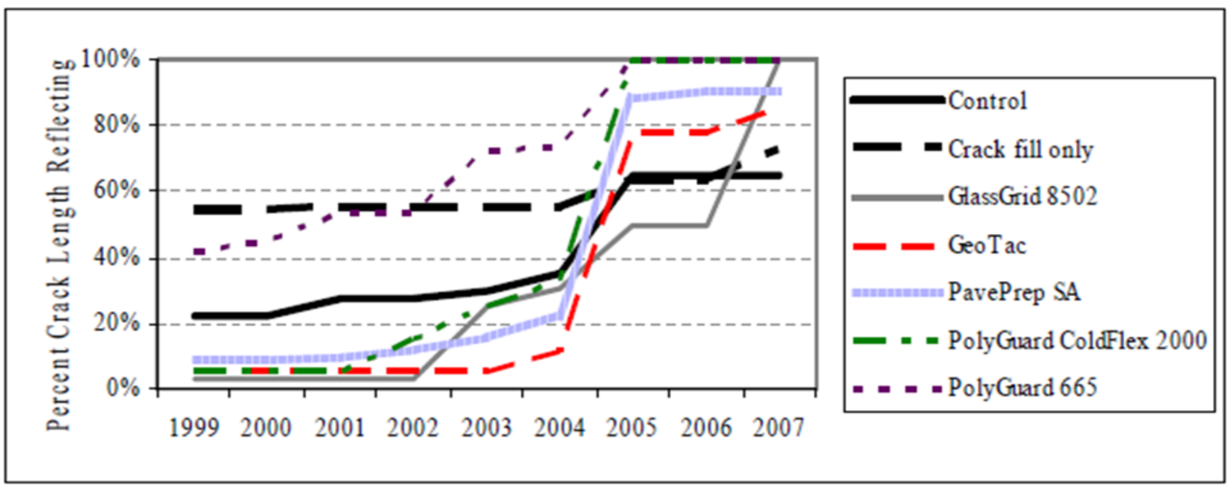


Figure 13
Performance of Different Types of Geosynthetics from 1999 to 2007 *[33]*

Bondt (2009) conducted a comprehensive review of the use of grid (fiberglass, geogrid, etc.) in Europe to retard reflective cracking in semi-rigid pavements *[34]*. The author observed that the performance of the grid can range from positive to negative depending upon the application, characteristics of the project, and the quality of the installation. The designers and the concerned authorities should ensure the suitability of a particular grid for a particular site condition. It was postulated that grid reinforcement has outperformed regular overlay against reflective cracking in semi-rigid pavement. A long-term evaluation of grid performance in the Netherlands is presented in Figure 14. The author noted that further research should be carried out to determine the adhesive property, design procedures, mechanical and durability properties, and cost effectiveness of the grid in semi-rigid pavements.

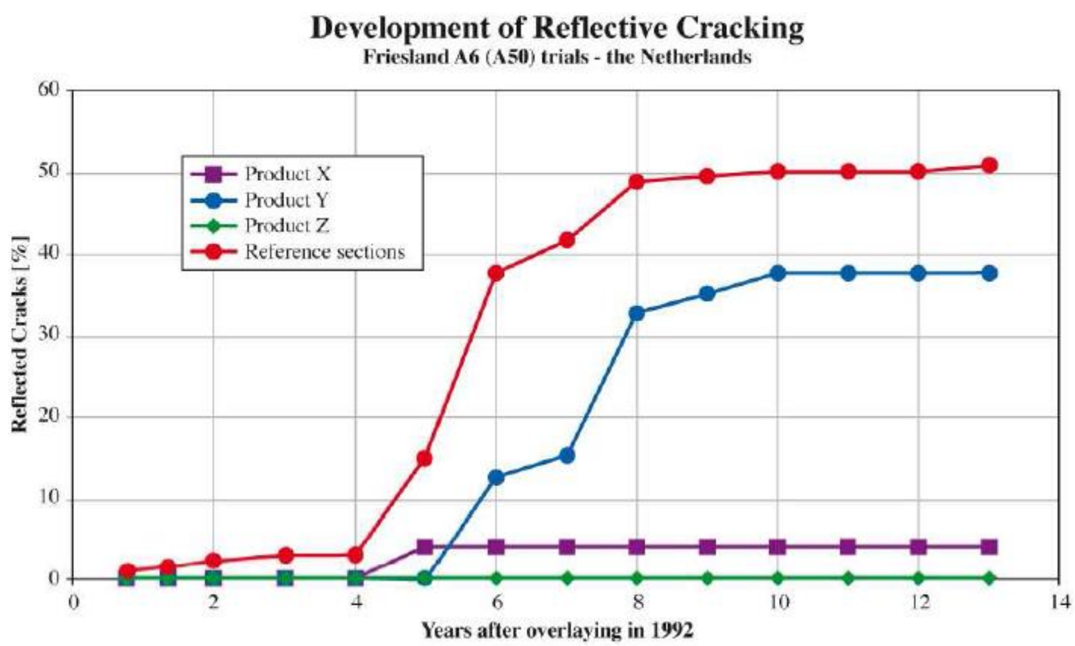


Figure 14
Long-Term Performance of Grid in Semi-Rigid Pavements in the Netherlands *[34]*

Abernathy (2013) conducted an experiment to evaluate the effectiveness of paving fabric to retard reflection cracking *[35]*. Four geosynthetics (TruePave Engineering paving mat, Pave-prep Geocomposite membrane, Glasspave 25 waterproofing paving mat, and Glassgrid 8512) were evaluated. Eight sections were selected with each section being approximately 300 ft. in length. The interlayer systems were installed in September 2008 and the final evaluation was conducted in April 2013. A tack coat was applied on each section before the installation of the geosynthetics. The installation was performed under extreme temperatures and excessive freeze and thaw cycles, which could have increased the potential of cracks development. Frequent site visits were conducted on a regular basis to study the modes and areas of crack formation. It was concluded that the treatment methods applied did not delay reflection cracking in comparison to the control section.

Andrews (2013) synthesized the effectiveness of grid (Geogrid and Glassgrid) as a reinforcement to asphalt pavement *[36]*. Based on a review of laboratory and field data for sites that have been in service for many years, the author evaluated the effectiveness of grid to enhance resistance to reflective and fatigue cracking. Laboratory testing conducted between 1981 and 1985 at the University of Nottingham showed that the life of the pavement could be extended by a factor of 10 through the use of grid; however, the cost aspect of the interlayer system was not discussed. This was attributed to the mechanical stabilization property of the grid through an interlock mechanism. Field evaluation included the monitoring of numerous sites constructed with a wide range of geosynthetics. Field performance result of the grid was found to be excellent. Geogrid was found to increase pavement life, decrease the thickness of the asphalt layer, and to maintain the structural integrity of the pavement in most of the cases. Figure 15 presents the comparative performance of different grids as tested in a site in the Netherlands.

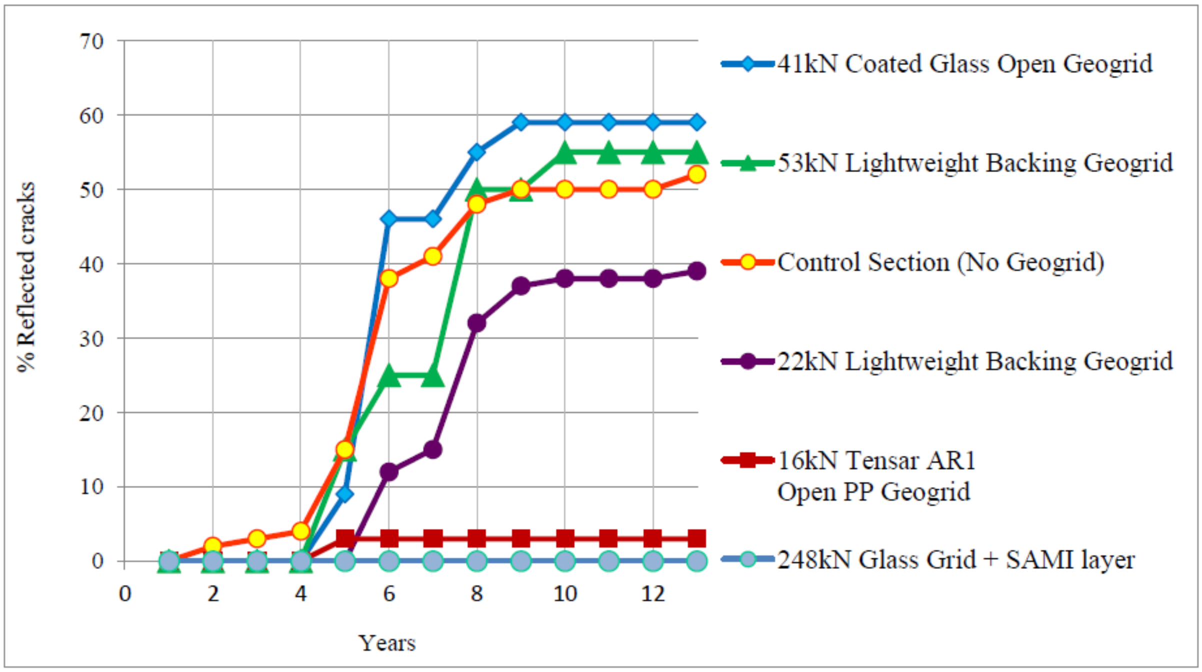


Figure 15
Field Evaluation of Different Grid Products *[36]*

LABORATORY EVALUATION

Zhengqi and Dengliang (2000) conducted laboratory tests to determine the reflective cracking resistance of geonet reinforcement *[37]*. A full-scale fatigue system, which consisted of a concrete slab overlaid with an asphalt layer, was used to evaluate the effectiveness of geonet to retard reflective cracks in the overlay. During testing, a horizontal load was applied to the concrete slab to simulate joint opening and closing. Test results showed that the specimens with geonet had greater fatigue life than those without the reinforcement. The increased fatigue life of the overlay with geonet validated the effectiveness of the geonet to retard reflective cracking. Results from full-scale fatigue testing performed at room temperature showed that the crack in the unreinforced specimens started to develop after seven load applications and propagated extensively after 83 applications while the values were 132 and 730 for the reinforced specimens. These results proved the effectiveness of geonet to retard the growth and propagation of reflective cracks. Similar results were observed when the tests were conducted at varying temperatures. Field testing was conducted to confirm the results from laboratory investigation. A 100 meters long test site was constructed with the overlay consisting of 3cm-Ac-16 (I) concrete as surface and 4cm-asphalt macadam. Transverse cracks at interval of 30-50 meters were observed in the unreinforced road sections while the reinforced road section showed no sign of reflective cracking.

Cleveland and co-workers (2004) evaluated the laboratory performance of six different types of geosynthetics (two fiberglass grid composite, two polyester grid composite, one fiber glass grid, and one polypropylene nonwoven fabric) *[38]*. Laboratory testing was performed on HMA beams using the TTI overlay tester and a computer program was developed for the analysis. Three major findings were reached from the study: 1) Pavement performance with geosynthetics can range from successful to disastrous with the cost-effectiveness of geosynthetics mostly marginal; 2) the use of geosynthetics increased the number of cycles to failure in the overlay tester; and 3) the use of a leveling course (0.75 to 1.0 in) before placing the interlayer can provide a better performance against reflective cracking. Whether geosynthetics are used or not, the use of a light tack coat application increases the number of cycles to failure making the overlay more resistant to reflective cracking. This is a significant finding that should be evaluated further even with regular overlays given the low cost of tack coat. The researchers developed a guideline for the use of geosynthetics in asphalt overlays based on laboratory test results. They also developed a computer program for the design of overlay with geosynthetics. It was recommended that the geosynthetics should not be used with emulsified tack coat unless sufficient time is allowed for breaking and curing. When a self-adhesive fiberglass grid is used, a tack coat should be applied on top of the grid with the same PG grade as the one used in the asphalt overlay.

Montestruque et al. (2004) conducted a laboratory evaluation of polyester geogrid using dynamic fatigue tests in prismatic beams loaded in bending and shearing modes *[39]*. Sixteen laboratory beams with dimensions of 460 x 150 x 75 mm and with pre-cracks with openings of 3, 6, and 9 mm were tested. The geogrid was placed on top of the crack tip. Laboratory test results showed an increase in fatigue life with the use of geogrid; further, the cracking mechanism changed from a single dominating crack to several low severity micro cracks. The use of geogrid delayed crack propagation and stopped it at a certain length after that. The movement of the micro cracks in random direction also helped stop its subsequent growth. Geogrid improved the fatigue life by a factor ranging from 4.45 to 6.14. Laboratory test results and contributing mechanisms were also verified and explained using Finite Element (FE) simulation.

Laboratory and numerical investigations were conducted to determine the crack resistance characteristics of geogrid. Field conditions were simulated to examine the response of asphalt overlays placed on top of an existing concrete pavement and to evaluate the effects of construction techniques and position of geogrid on the resistance to reflective cracking. The researchers analyzed the fatigue life and induced stresses, which are the major factors contributing to the occurrence of the reflective cracking. It was found that placing the geogrid deeper into the new overlay can improve the interlayer performance. However, the geogrid did not perform well if the cohesive bond between the layers was not strong enough. Further, the grid performed better with thick overlays than with thin overlays.

Sobhan et al. (2004) conducted a laboratory investigation to study the growth and propagation of reflective cracks when geogrid is placed over an existing concrete pavement as a reinforcing layer *[40]*. The overall effects of the grid location on the propagation and mitigation of cracks were investigated. Two types of geogrids (Tensar Biaxial Geogrid (BX 1500) and Amoco PetroGrid 4582) were considered in the experimental investigation. Static tests were conducted on unreinforced specimens to determine the static load bearing capacity and to simulate the growth and propagation of cracks. Cyclic tests were then conducted for both unreinforced and reinforced specimens to analyze the crack propagation, develop the failure criterion, and to assess the effectiveness of geogrid to mitigate reflective cracks. Fabric Effectiveness Factor (ratio of number of cycles to crack for reinforced specimen to number of cycles to crack for unreinforced specimen) was calculated to quantify the performance of geogrids. Embedment Factor (the ratio of grid location from bottom of the overlay with height of the overlay) was calculated to observe the effects of geogrid location on crack propagation. It was observed that at the same load ratio, the reinforced specimen with geogrid embedded at the bottom of overlay was more effective than the specimen with geogrid simply placed at the bottom with tack coat. The specimens with geogrid embedded at the middle were found to be more effective than the specimens with geogrid placed at the bottom. It was also observed that the fabric effectiveness factor increased with the increase in embedment factor (Z) for a range of $0 \leq Z \leq 5$. For all the specimens and under varying loading conditions, the reinforced specimens outperformed the unreinforced specimens to provide the best resistance to reflective cracking.

Khodaii and Fallah (2009) conducted a laboratory experiment to determine the effectiveness of geogrid to mitigate reflective cracking and permanent deformation in asphalt overlays *[41]*. The field conditions of an asphalt layer overlaid on top of a crack in concrete or asphalt pavement was simulated in the laboratory. To this end, an asphalt mixture specimen was placed over two discontinuous concrete or asphalt concrete blocks with a height of 100mm. Four specimens were prepared and tested: 1) Control specimen with no geogrid, 2) Specimen with geogrid embedded in the concrete or asphalt concrete block, 3) Specimen with geogrid placed at a depth of one-third from the bottom of the concrete or asphalt concrete block and 4) Specimen with geogrid placed at mid-depth. The four specimens were placed on a rubber foundation and a repetitive loading using hydraulic dynamic loading frame was applied. The initiation and propagation of reflective cracking was monitored for each specimen. It was observed that the geogrid was effective in controlling reflective cracking and improving pavement performance. The best performance was obtained in case of Specimen 3 where the geogrid was placed at a depth of one-third from the bottom. The authors also observed that top-down cracking on the overlay depended upon the geogrid position and relative stiffness of the overlay with existing pavements. Figure 16 presents the permanent deformation of different specimens under repeated loading for an asphalt overlay on top of a concrete pavement.

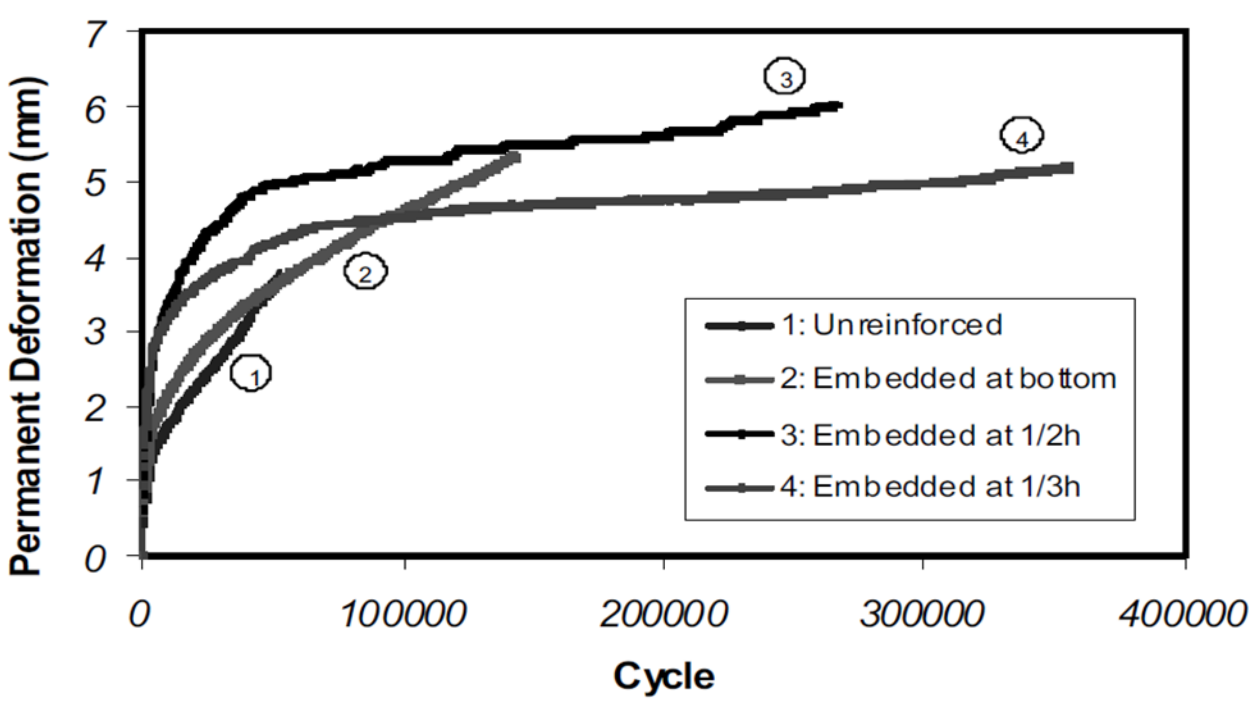


Figure 16

Permanent Deformation for Overlays on Top of a concrete block and with a 10mm Gap at 20°C *[41]*

Zamora-Barraza and co-workers (2010) conducted a laboratory study to evaluate the performance of an anti-reflective system consisting of a geogrid, geotextile or a Stress Absorbing Membrane Interlayer (SMAI) as a reflective cracking retarding medium *[42]*. The researchers adopted the laboratory set-up shown in Figure 17. As shown in this figure, the load is applied to the test specimen through a prismatic steel element; further, a rubber layer is used to support the lower part of the test specimen and to propagate the cracks. The experimental program evaluated six different anti-reflective systems as well as a number of tack coat application rates. The most effective treatment was identified based on the average number of cycles before failure. Results identified the geogrid to be the best performer in the laboratory. The geogrid was observed to have the potential to withstand a load cycle of three to six times the one for the control sample. Increasing the modulus and stiffness of the geogrid increased the resistance to cracking. The authors recommended proper installation in the field to ensure similar performance is achieved.

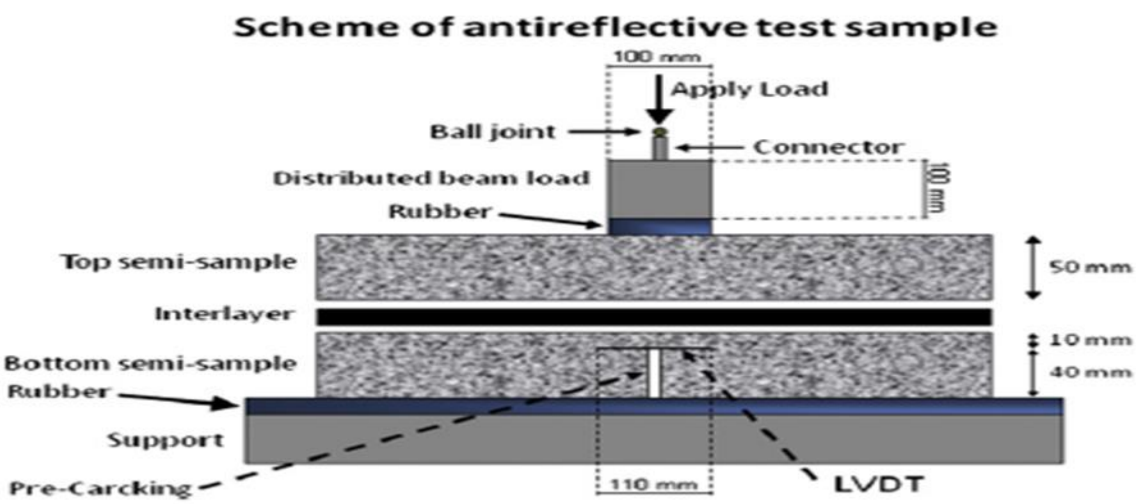


Figure 17
Anti-Reflective Cracking Test Piece Schematic *[42]*

Solaimanian (2013) studied the effect of a geocomposite consisting of a high-modulus geogrid and a lightweight, non-woven geotextile on reflective cracking in asphalt overlays *[43]*. The experimental program evaluated the performance of an asphalt overlay placed on top of a concrete layer with and without geocomposite. Further, a composite system consisting of asphalt concrete for the bottom and top layers was evaluated. Test specimens consisted of a 2-in asphalt overlay on top of the concrete or asphaltic layer. A MMLS3 test system was employed for accelerated loading of the overlay. Results of the experimental program did not show bottom-up reflective cracking in any of the test specimens. However, the geocomposite significantly enhanced the top-down cracking resistance of the overlay.

The specimen without geocomposite showed top-down cracking after 20,000 cycles while the specimen with geocomposite resisted top-down cracking for 150,000 cycles. For the asphalt over asphalt configuration, a test was performed for the specimens without geocomposite. In this test, no reflective cracks were observed in the overlay for 465,000 cycles. Therefore, no further test was performed.

<u>Theoretical Evaluation</u>

In a study by Kuo and Hsu (2003), a parametric analysis was conducted using Three-Dimensional (3D) Finite Element (FE) to evaluate the effectiveness of geogrid in delaying reflective cracking *[44]*. Eighteen cases were analyzed by varying geogrid position, geogrid strength, temperature, and overlay thickness. The cracking path was studied comparing to the fatigue life of the model parts. Three types of reflective cracking mechanisms were identified from the results of analysis. Mostly, the cracks appeared from the bottom of the asphalt layer, top-down cracking was observed in case of soft overlay stiffness or very thick overlay. In most cases, the cracks would initiate from the interface when debonding starts to occur. The service life of the pavement was improved when the geogrid is placed at one-third depth of the asphalt overlay. In addition, the strength of the geogrid had no significant impact on the interlayer performance but it could have an effect if the joints/cracks of the PCC have very low load transfer efficiency.

Amini (2005) synthesized past literatures and conducted a survey in the state of Mississippi to analyze the possibility of using paving fabrics as a reflective control treatment technique *[45]*. Various factors such as temperature, underlying joint/crack movements, thickness, spacing of cracks, and subgrade condition may affect the performance of paving fabrics. Amini observed that paving fabric can function as an effective technique to absorb the normal stress generated by underlying cracks, hence, leading to the control of reflection cracking. Paving fabrics were also observed to be beneficial in preventing the intrusion of the water and moisture in the pavement. The study found that paving fabrics have been successful in enhancing pavement performance in most of the projects. However, paving fabrics may not be beneficial with thin overlays. Further, fabrics did not perform well to reduce thermal cracking but were effective in relieving load-related fatigue distresses. Paving fabrics were observed to be most effective in warm climate conditions. The author recommended further evaluation and testing of the potential of paving fabrics to mitigate reflective cracking.

Elseifi and Al-Qadi (2005) evaluated the potential of a specially designed geocomposite membrane to delay the reflection of cracks in rehabilitated pavements through strain energy dissipation *[46]*. The geocomposite membrane consisted of a 0.07-in. thick low-modulus polyvinyl chloride (PVC) backed on both sides with 0.028 lb./ft^2 of polyester nonwoven geotextile. Results of this analysis showed that the placement of a soft interlayer creates a protective shield around the crack tip, separating the criticality of the stress field in the cracked region from the bottom of the overlay. This study also indicated that a strain energy absorber would only be effective in the crack propagation phase if the crack does not pass through the interlayer and propagates horizontally at the interlayer-existing pavement interface. Monismith and Coetzee referred to this mechanism as “a crack arrest” phenomenon *[47]*. Therefore, the installation of this interlayer is crucial in dictating its performance. If damage or tearing of the interlayer occurs, the effectiveness of the strain energy absorber membrane would be altered.

Cost-Effectiveness

Maurer and Malashekie (1989) evaluated the performance of six treatment methods (four paving fabrics, one fiberized-asphalt, and one fiber-reinforced asphaltic concrete) to retard reflective cracking in asphalt overlay *[48]*. The treated sections were compared against each other as well as against a control section. Construction monitoring indicated that the fiber-reinforced asphalt concrete was the least expensive and the easiest to install whereas the paving fabrics were the most expensive and the most difficult to install. Crack control treatment methods were monitored after 8, 26, and 44 months of placement. All treatment methods were observed to delay reflective cracking. Based on the performance of treatment methods, the construction costs, and the current and future crack sealing costs, none of the treatment methods evaluated was observed to be cost effective. Fabric costs were at $1.79 to $2.39/$m^2$ and sealing cost was at $0.95/m. These treatment techniques were not recommended for future use.

Buttlar et al. (2007) studied the cost-effectiveness of nonwoven paving fabrics placed over a PCC pavement to delay the reflective cracking in the overlay *[49]*. They conducted a survey in Illinois to establish a database for the projects using paving fabrics (test projects) and not using paving fabrics (control projects). The performance and life cycle cost of the paving fabrics were evaluated. The fabrics were observed to delay the reflection of longitudinal cracks but the transvers cracks reflected at a similar rate for treated and untreated sections. Overall, the strip and area treatment methods increased the life span of the overlay by 1.1 and 3.6 years, respectively. The fabrics were observed to reduce the permeability of the pavement even in the case of reflective cracking. Two cases were considered in the Life-Cycle Cost Analysis (LCCA) of the fabrics. The maintenance and milling costs were neglected in Case 1 and were included in Case 2. Other costs in the analysis included the cost of materials and construction, cost of the overlay, and reflection cracking control cost.

The authors found no significant statistical difference in the life-cycle cost of treated and untreated projects in Illinois.

FIBER-GLASS GRID

Field Evaluation

Marks (1990) presented the performance of Glasgrid in delaying reflective cracking in four test sections in Iowa *[50]*. Glasgrid consists of a series of fiberglass stands joined together into a mesh and coated with an elastomeric polymer. The Glasgrid was installed on I-35 in which two 1.5-in lifts of binder course were placed followed by a 1.5-in wearing surface. Performance was monitored annually for five years by determining the number of cracks that reflected through the layer and by comparing the reinforced sections to the control segments. In one section, the Glasgrid was placed directly on top of the concrete pavement while in the three other sections; it was placed between lifts of asphalt mixture. Results of the monitoring showed that the best performer was the section in which the Glasgrid was placed directly on top of the concrete pavement, with 43% of the joints reflecting after five years. The poorest performer was one section with Glasgrid placed between lifts of asphalt concrete with 80% of the joints reflecting after five years. Conclusion of this study indicated that the use of Glassgrid yields a small reduction in reflective cracking but it did not justify the cost of the interlayer system.

Bischoff and Topel (2003) evaluated the performance of GlasGrid, a glass fiber mesh pavement reinforcement geotextile, in delaying and mitigating the formation of reflective cracking in overlay *[51]*. In 1990, two test sections were established on STH 57 in Sheboygan County with the sections evaluating a single strand grid and a double strand grid. After the existing PCC pavements (originally built in 1957) were cleaned and repaired, an asphaltic concrete overlay of 1½ in thick was placed. GlasGrid was then installed in the test sections in 5-foot widths across the transverse joints and cracks in the underlying JPCP and the final overlay of 1½ in thickness was placed over the GlasGrid. Reflective cracking became visible within six months after construction. By the end of the fourth year, the percentage of reflective cracking in the test section using double strand gird exceeded the percentage in the control section, which had no GlassGrid. Type 3 (banded) cracks and Type 1 (less than ½ in in width and less severe than Type 3) cracks appeared in the test and control sections. Regular annual crack surveys were performed for a period of five years and after ten years and then the final survey was conducted in 2002 reported that neither single strand grid nor double strand grid were effective in addressing reflective cracking. It was recommended from this study that WisDOT should stop applying GlasGrid as reinforcement or as a mitigation technique for reflective cracking in asphalt overlays. The average percentage of reflective cracking in each section is presented in Table 7.

Table 7
Average % Reflective Cracking per Test Section *[51]*

Average % Reflective Cracking per Test Section						
Section	Years After Construction					
	1	2	3	4	5	10
Double Strand	53	69	76	91	91	108
Single Strand	55	61	68	83	83	106
Control	59	73	86	87	87	105

Chen and co-workers (2003) reported on the field performance of various rehabilitation techniques used in Texas including fiber-glass grid reinforcement *[52]*. In one section located on IH 45 (ESALs of 42.2x106), the grid was installed between 2.0 in. of leveling course and 2.0 in. of wearing course. The grid was placed only on top of the joints in strip application. The performance of the grid was inadequate as the section failed prematurely and had to be replaced after one year. Observed distresses included alligator cracking and moisture accumulation at the interface between the overlay and the grid as evident from a Ground Penetrating Radar (GPR) survey. A control section on the same road segment that did not use the reinforcement system performed relatively well. The authors attributed the poor performance of the grid to debonding between the interlayer and the surrounding HMA layers as evident from extracted cores. In another test section in which full-width application of the grid was used, delamination occurred between the grid and the upper HMA overlay. This section had to be replaced one week after placement.

The field performance of Glasgrid (Grid 8501 and 8502) was investigated in two different climatic zones; Zone I (wet, no freeze) and Zone VI (hard freeze, spring thaw) *[53]*. The performance of the grids was evaluated in light of various design approaches and remedial techniques. The performance was evaluated for a period of 6 years for two sites in Zone I and for a 2 ½ years for one site in Zone VI. Results showed that Glasgrid extended the overlay service life against reflective cracking in the evaluated sites by a factor of 2 to 3. The performance of the grid on Site 3 located in Zone VI was improved when the existing pavement was milled before placement. While all cracks reflected in the control section, only 1 or no cracks reflected in the reinforced sections. The performance of Glasgrid for the two sites in Zone I is presented in Table 8. The researchers concluded that a Glasgrid with low elongation at its ultimate strength provided a significant improvement against reflective cracking.

Bush et al. reported on an experiment conducted by the Oregon Department of Transportation (ODOT) to evaluate five different geosynthetics types including Glasgrid *[54]*. The test section was located on US 97 (AADT of 4,899) and consisted of a flexible pavement that suffered from transverse cracking. Prior to rehabilitation, the location and severity of existing cracks was noted; the severity of the cracks ranged from medium to high. Only strip application of the interlayer was considered in this study by placing it on top of the existing cracks; a 2.0-in. overlay was used on all sections. Performance was monitored annually using visual surveys for the period from 1999 to 2007. Results of this study showed that none of the geosynthetics prevented the cracks from reflecting; however, they reduced its severity. Of the five geosynthetics, Glasgrid was the only interlayer that performed well against high severity cracks. However, the least reflective cracking occurred in the crack fill only test section.

Table 8
Performance of Glasgrid in Two Sites in Zone I *[53]*

Site ID	Grid 8501 Section	Control Section	Grid 8501 PCC Section
Site 1			
Existing crack length	87.1m (Tran. Cracks), 115m (Long. Cracks)	22.8m (Trans. Cracks), 44.5m (long. Cracks)	1229.6m (Tran. Cracks), 285m (long. cracks)
Overall % reflection	4.5%	38.0%	12.0%
Cracking per 1000m^2 road	7.94m	46.9m	75.93m
Site 2			
Existing cracks	376.9m (Tran. Cracks), 596.8m (Long. Cracks)	186.1m (Tran. Cracks), 263m long. cracks	
Overall % reflection	10.2%	27.8%	
Cracking per 1000m^2 of road	29.1m	73.1m	

Hanek (2009) studied the effectiveness of Glasgrid to prevent reflective cracking in rehabilitated pavements. Two test sections with three subsections were established *[55]*. Within each section, cell A was pretreated with a crack sealer; cell B was treated with crack sealer and Glasgrid, and cell C was untreated and used as a control section. Periodic crack surveys were performed for six years to monitor area, length, and orientation of the cracks. The existing pavement was heavily cracked, mostly with thermal cracking, and carried an

ADT between 150 and 900. Based on monitoring for six years, Glasgrid 8502 was effective in comparison to the control section in controlling reflective cracking. The other type of Glasgrid (Glasgrid 8501) was less effective due to the presence of other pavement distresses. Figures 18 and 19 present the overall performance of the test and control sections.

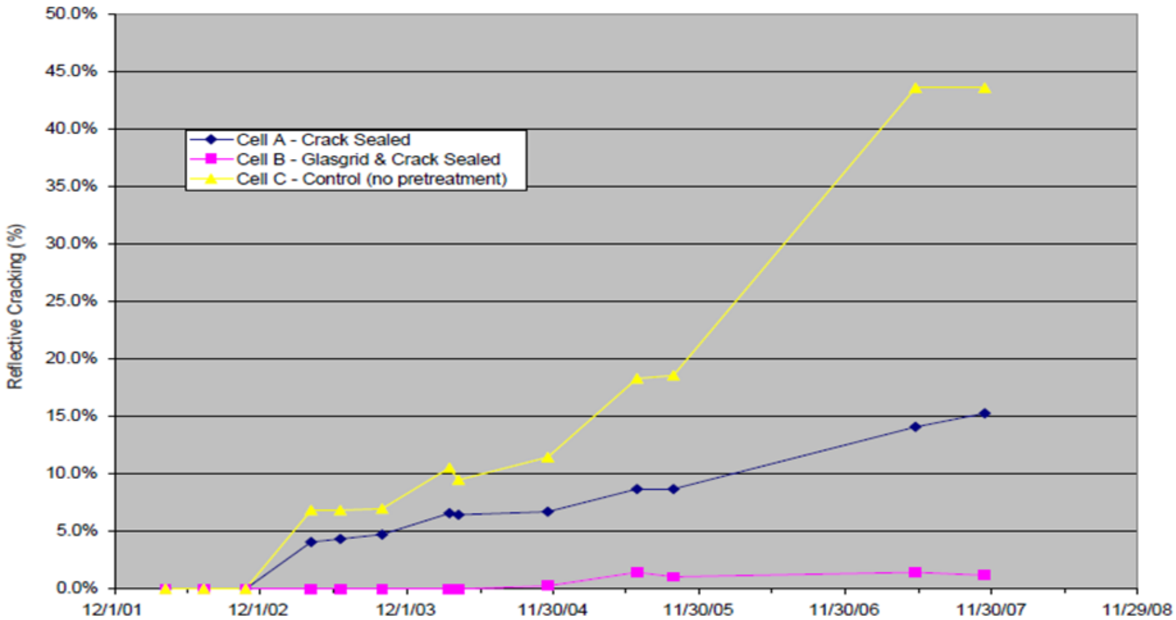


Figure 18
Test Section no. 1 *[55]*

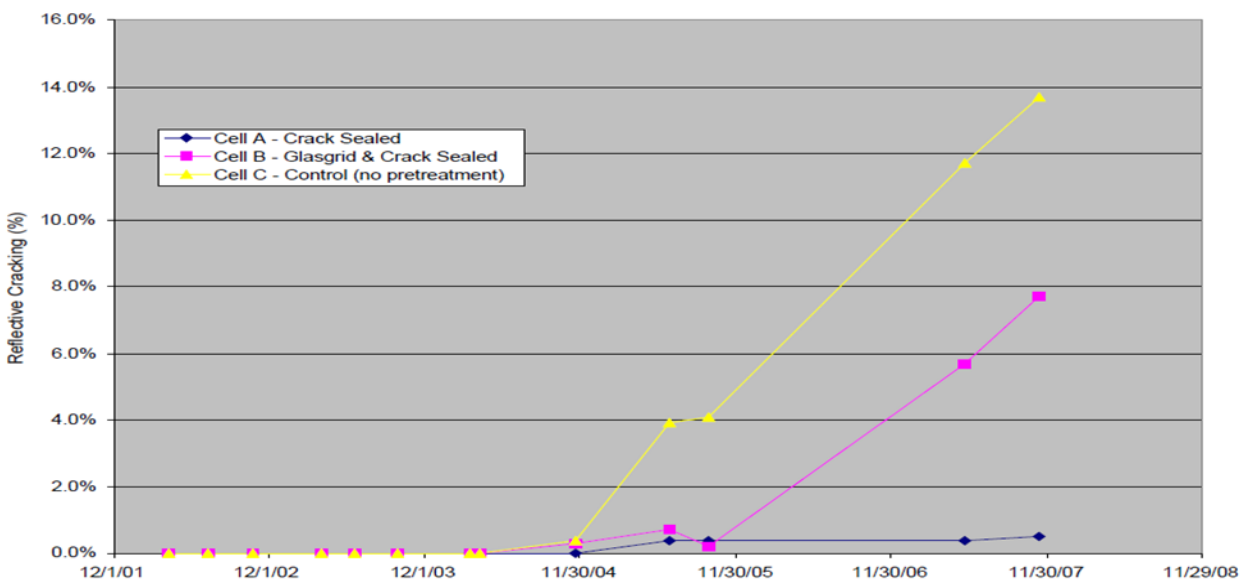


Figure 19
Test Section no. 2 *[55]*

Laboratory Evaluation

Nguyen et al. (2013) presented a review of the performance of fiber-glass grid based on a literature review as well as based on the results of accelerated testing conducted at IFSTTAR in France [*56]*. Based on their review, the authors found that fiber-glass grid has shown mixed performance, especially in the field. This was attributed to poor bonding between the grid and the asphalt material. The authors also presented the results of two full-scale fatigue experiments conducted at the IFSTTAR accelerated pavement research facility. The experiment was carried out to compare the performance of a reinforced section with fiber-glass grid (Section C) and an unreinforced section (Section D). The grid was placed in the lower part of the asphalt layer, 20mm above the interface with the granular subbase. The test results showed that the fiber-glass grid placed at the bottom of the asphalt layer improves the fatigue life of the pavement provided good bonding is achieved with the grid. A significant increase in crack resistance was observed in the section with fiber-glass grid as presented in Figure 20. However, the levels of pavement deflection and rutting were similar in the reinforced and unreinforced sections.

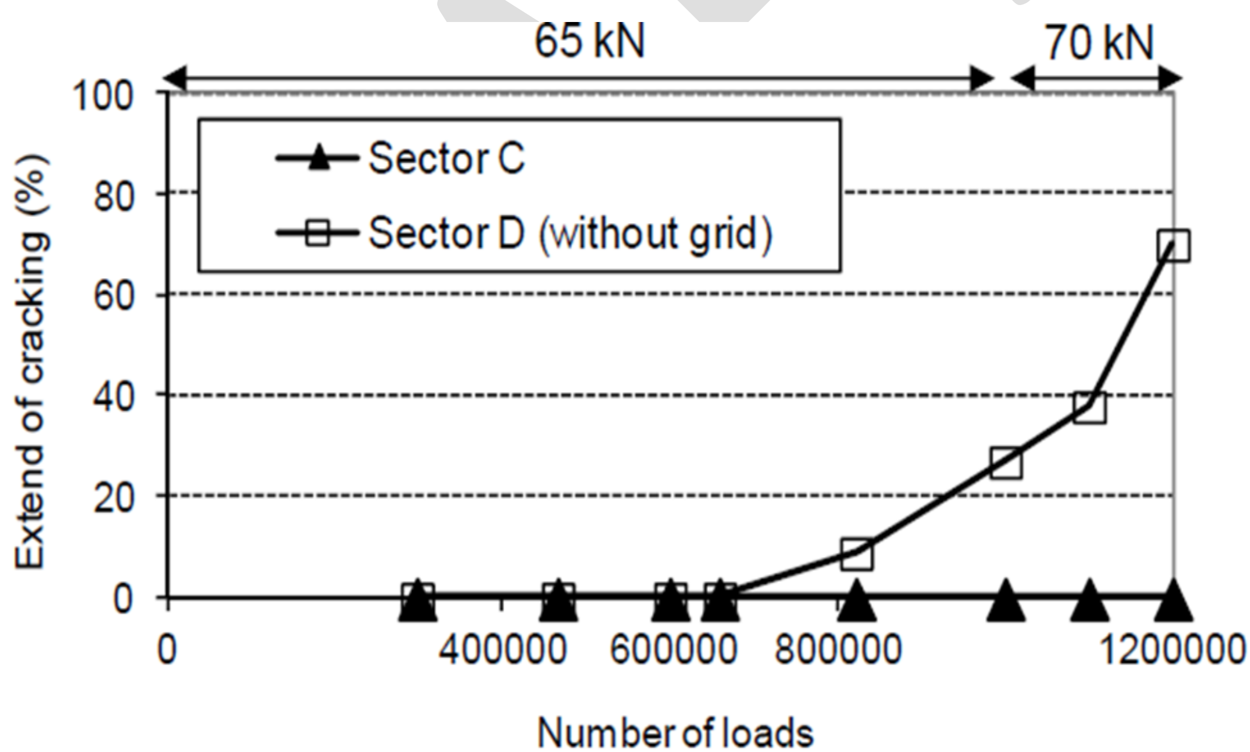


Figure 20
Extent of cracking in percent, on the 2 sections *[56]*

Chazallon et al. (2013) conducted a laboratory fatigue experiment and a finite element analysis to determine the effectiveness of a fiber glass grid in delaying the initiation and propagation of fatigue cracking *[57]*. Four specimen beams were prepared; two with a standard overlay asphalt mixture (BB1, BB2) and two reinforced with fiber glass grid (RBB2wy, RBB3wy). These beams were tested in fatigue using a four point bending test (4PB) mode at 10°C and 25Hz. The Four Point Bending Test (4PB) was selected as it has the configuration to form the cracks in the central part of the specimen where tension and compression stresses are uniform. Results presented in Figure 21 show the evolution of the ratio between the measured force and the initial force for the reinforced and unreinforced beams. Analysis of the test results showed that the use of fiber-glass grid increased the fatigue life by a factor ranging from 35.2 to 65.5%. Based on these results, the authors recommended the consideration of grid reinforcement in the pavement design.

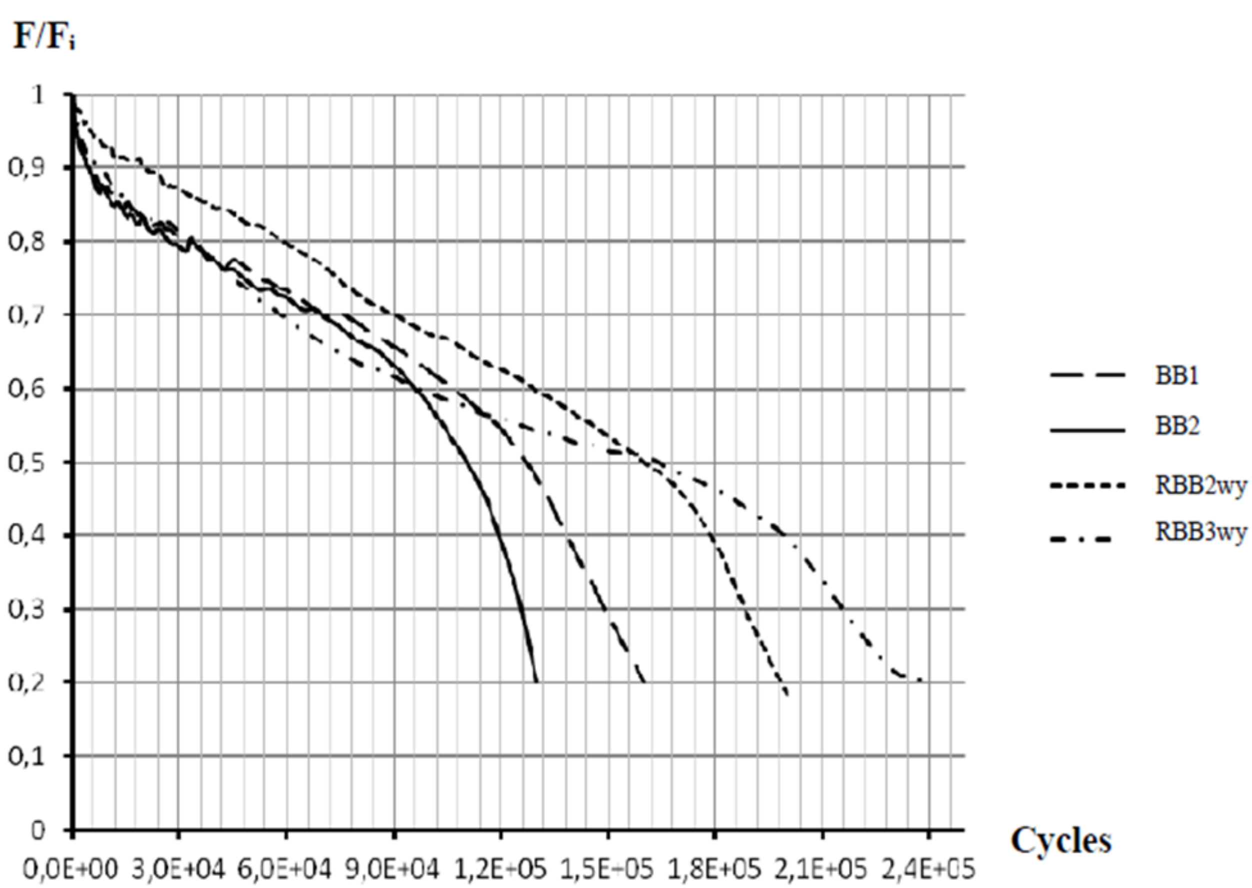


Figure 21
Evolution of the force during four fatigue tests *[57]*

Cost-Effectiveness

Bush and Brooks (2007) analyzed the cost benefit of using Glasgrid to retard reflective cracking *[54]*. Since Glasgrid 8502 is not self-adhesive, it required tack coat to be applied. The application of tack coat resulted in an increase in labor and equipment cost for Glasgrid

8502 compared to other treatment methods. However, based on the performance of Glasgrid 8502 against reflective cracking, the researchers concluded that it is a cost-effective treatment method when only reflective cracking is considered. After a period of 8 years, it was observed that the section using Glasgrid 8502 showed minimum or no reflective cracking while the other sections required repaving due to appearance of severe transverse cracks. Overall, it was concluded that geosynthetics could be cost-effective in roadway in which transverse cracking is the sole distress.

Hanek (2009) calculated the material and installation costs of Glasgrid 8501 (560 lb. /in across length) and 8502 (1,120 lb. /in across length) to determine the cost effectiveness of the products *[55]*. Glasgrid 8502 was observed to provide a significant life cycle cost savings, given its effectiveness in mitigating medium to high severity transverse and longitudinal cracks. Based on the results of the cost analysis that was conducted in 2008, the author found that the use of 33% coverage Glasgrid 8502 is equivalent to a 0.75in asphalt thickness assuming a cost of asphalt of $60/ton, see Figure 22.

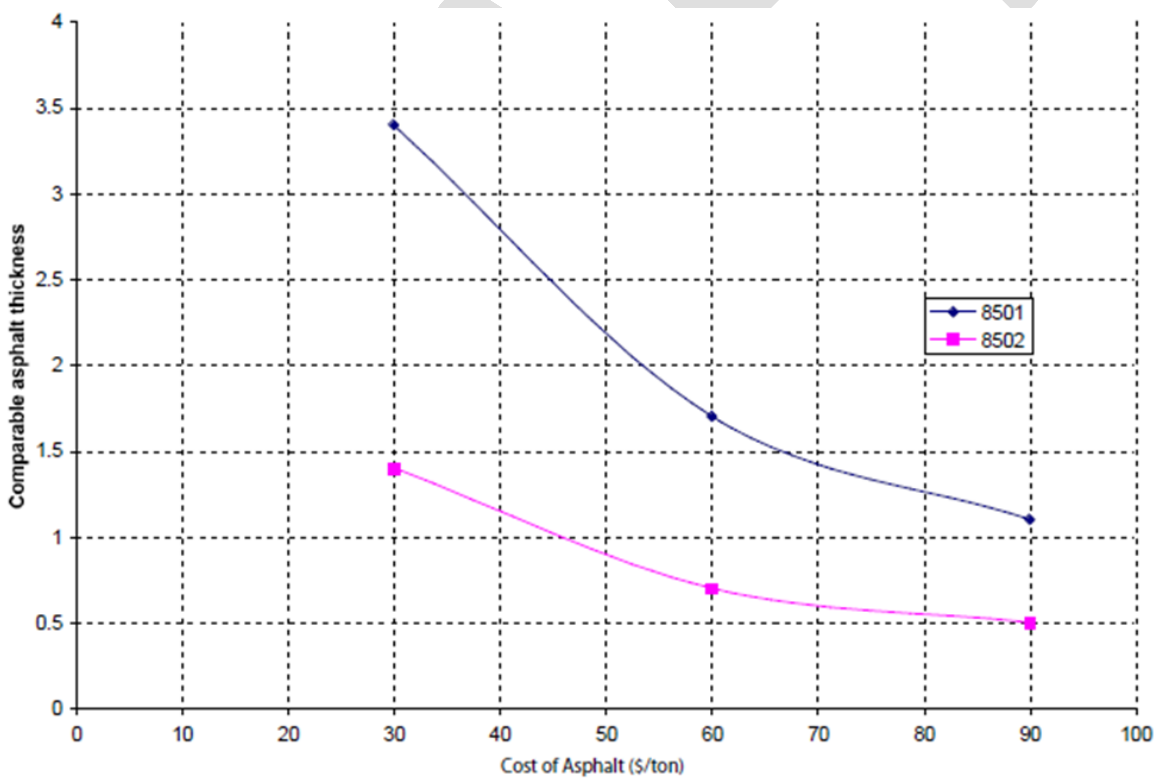
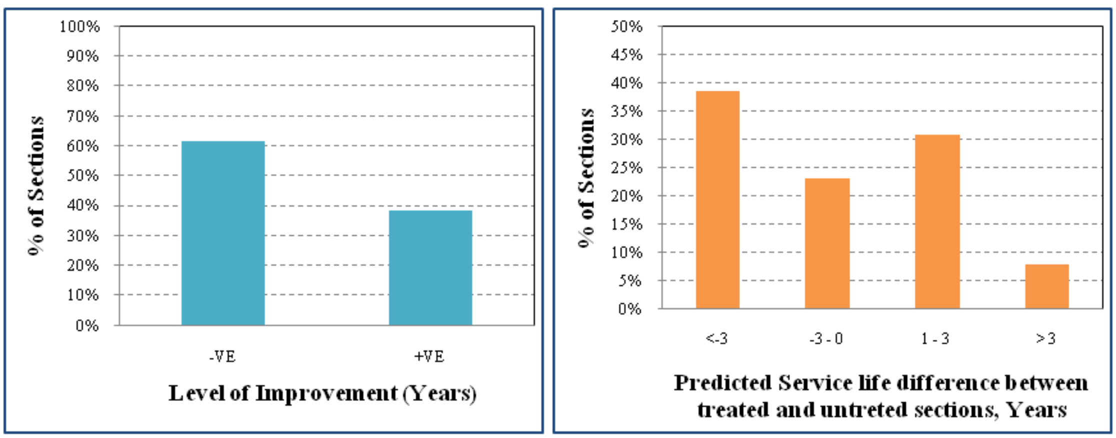


Figure 22

Comparison of the Cost of Glasgrid to the Cost of Asphalt *[55]*

Elseifi and Bandaru (2011) evaluated the cost-effectiveness of fiber-glass grid in delaying reflective cracking based on the analysis of 13 in-service rehabilitated pavements in

Louisiana *[5]*. Fiber-glass grid may be placed as either a complete road system (area application) or at particular locations in the pavement (strip application). This analysis considered pavement sections in which fiber-glass grid was used as a complete road system. Based on the analysis of field performance data collected from the Louisiana Pavement Management System (PMS), Figure 23 presents the level of improvement or reduction in performance due to the use of fiber-glass grid. In this figure, individual sites were grouped into classes that exhibited similar levels of contribution from fiber-glass grid. As these results showed, 62% of the sites reflect a negative impact in which the untreated sections outperformed the treated sections by a range of 0 to 7 years, while the remaining 38% of the sites showed a positive contribution ranging from 1 to 6 years.



(a) **(b)**

Figure 23
Contribution of fiber-glass grid to predicted pavement service lives

Cost data for the fiber-glass grid as well as HMA overlays were obtained from actual bid items for each project. Figure 24 presents the percentage increase in the cost of the HMA overlay, due to the fiber-glass grid treatment. The increase in cost ranged from 1.6 to 128% averaging 48% of the HMA overlay cost.

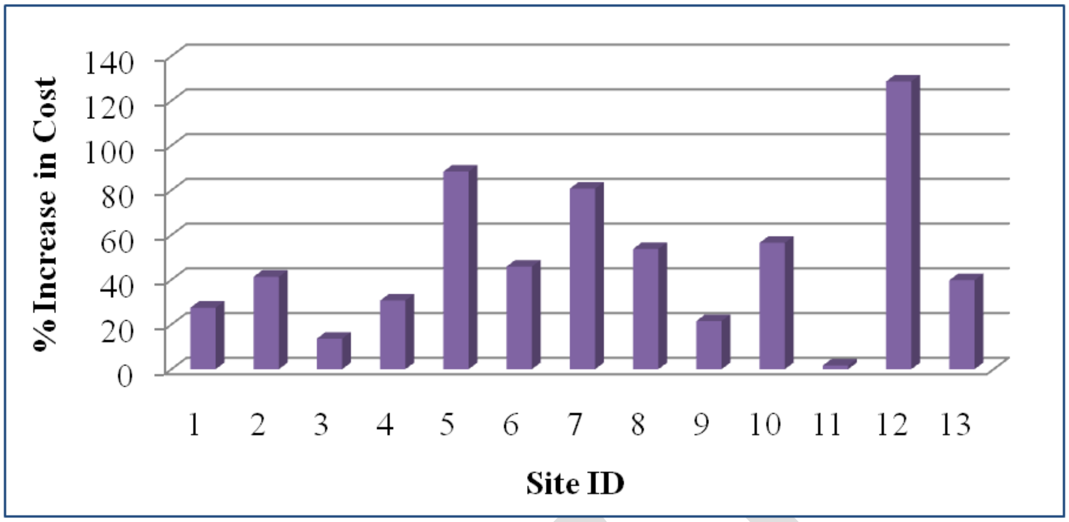


Figure 24
Increase in cost of the HMA overlay due to fiber-glass grid

Figure 25 compares the cost of reinforced HMA overlays to the cost of regular HMA overlays. In this figure, a positive cost difference indicates that the use of fiber-glass grid is economical, while a negative cost difference indicates that the interlayer is not cost-effective when compared to regular HMA overlays. As shown in this figure, the majority of the sections (92%) indicate that fiber-glass grid is not cost-effective when compared to regular HMA overlays. Based on these results, the use of this interlayer will be more costly to highway agencies than economical as shown by the majority of sections in which the reinforcement was not cost-effective.

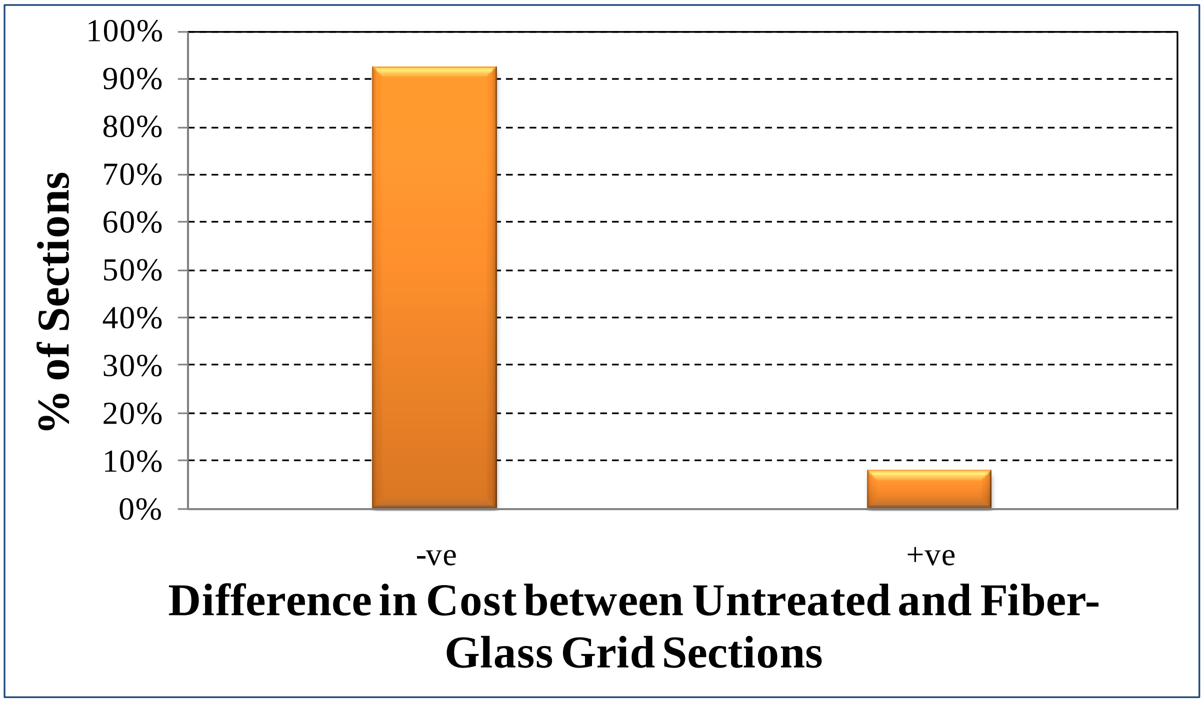


Figure 25
Cost effectiveness of fiber-glass grid treatment method

CHAPTER IV

FRACTURED SLAB APPROACHES

Fractured slab approaches are methods that aim at reducing or eliminating the effective length of the original slab in order to prevent movement of the concrete layer, and in turn reflective cracking *[58]*. Fractured slab approaches include crack and seat, break and seat, and rubblization. The difference between these approaches is mainly related to the level of destruction applied to the concrete layer. In crack and seat, existing asphalt overlays are removed; then, the concrete layer is cracked using a pavement breakers and seated back onto the subbase by applying 2 to 3 passes of 35 to 50 ton rubber tire roller. In this case, the concrete is broken down into 18 to 24 in pieces that still provide a level of aggregate interlock while reducing movement due to thermal expansion and contraction. The seating step is important to ensure stability of the broken concrete layer and to reduce voids in the fractured material. Crack and seat is mainly used for jointed plain concrete pavement (JPCP) with or without dowel bars *[59]*. It is more suitable for concrete pavements that have not been completely damaged to a point where aggregate interlock may be lost during cracking. Further, the selection of a suitable slab size during cracking is critical for the success of this rehabilitation technique and to ensure that reflective cracking does not occur after construction. While reducing slab size reduces movement and the potential for reflective cracking, it decreases the slab stiffness and its ability to carry heavy loads. California usually recommends a transverse strike every 4 to 6ft; however, other states such as North Dakota and Minnesota specify a transverse strike every 3 ft. A suitable overly thickness ranging from 4 to 6 in is also needed to prevent reflective cracking. Choubane and Nazef (2001) recommended the use of an asphalt-rubber membrane interlayer prior to the overlay to reduce reflective cracking *60]*. Break and seat is similar to crack and seat but it is mainly used with jointed reinforced concrete pavement (JRCP). In this case, the bond between steel reinforcement and concrete should be completely eliminated by reducing the effective length of the original slab. While the cost of crack/break and seat can be significant, it was shown that it may not completely control reflective cracking and may only delay it for a period of 3 to 5 years *61]*.

Rubblization, which is the most promising fracturing slab techniques, has been used with all types of concrete pavements. It consists of completely destroying slab action by transforming the concrete layer into an aggregate base *[58]*. The size of the broken concrete pieces usually ranges from 2 to 6in and therefore, this process results in a significant loss of concrete strength, see Figure 26. A study reported that the resulting rubblized layer has a strength that is 1.5 to 3 times greater than high quality dense-graded crushed stone base *62]*. However, rubblization may not be effective if the existing concrete pavement is deteriorated due to poor subgrade support and with saturated soil conditions. The rubblization process is critical in ensuring satisfactory long-term performance of the overlay. It can be achieved using two types of equipment: resonant breaker and multiple-heat breaker. The resonant pavement breaker (RPB) employs vibrating hammers to destroy the concrete layer as well as to break the bond between the concrete and steel reinforcement. This approach has been less favored in recent years given that it may require numerous passes to completely destroy the concrete layer, which may not be feasible if the subgrade conditions are not adequate. The second approach, based on the multiple head breaker (MHB), allows rubblization to be completed in one pass. It employs a series of 12 to 16 102 to 123 lbs. hammers to crush a concrete width ranging from 2 to 12.5 ft. with a production rate of 0.75 to 1.0 lane-mile/day.

Figure 26
Rubblized Concrete Pavement *[63]*

PERFORMANCE OF RUBBLIZATION

Field Evaluation

Timm and Warren (2004) studied the effectiveness of rubblization in Alabama in JPCP and CRCP *[58]*. In this study, nine projects that were in service for a period ranging from 2.5 to 11 years and that applied rubblization were evaluated. The average thicknesses of the concrete layer and the asphalt concrete overlay in the rubblized sections were 9.3 and 10.5 in, respectively. Two main findings were observed in the analysis. First, the number of cracks was more in the truck lane and second, the number of cracks increased with the age of the rubblized sections. Graphical and statistical analysis (using MINITAB software package) of the data showed that rubblization had improved pavement performance. However, higher levels of distress were observed in the CRCP sections possibly due to incomplete debonding between the concrete and steel reinforcement. Therefore, precautions should be taken before rubblizing these sections. Further, the authors recommended continuous monitoring of the sections to establish the long-term benefits of rubblization.

Sebasta and Scullion (2007) evaluated the performance of rubblization as a rehabilitation technique for concrete pavements in Texas *[64]*. Through a series of field investigation, projects were evaluated prior to and after construction using non-destructive test (NDT, i.e., ground penetrating radar [GPR], falling weight deflectometer [FWD], and dynamic cone penetrometer [DCP]). GPR surveys were used to identify areas of moisture accumulation the subgrade, which may impact the rubblization process, as well as section breaks in the supporting structure. DCP data were used to assess the support beneath the slab as well as support at larger depths beneath the slab. The support at large depth is important to avoid shear failures with the resonant breaker. The Illinois DOT rubblization selection chart was used in assessing the section suitability for rubblization, see Figure 27.

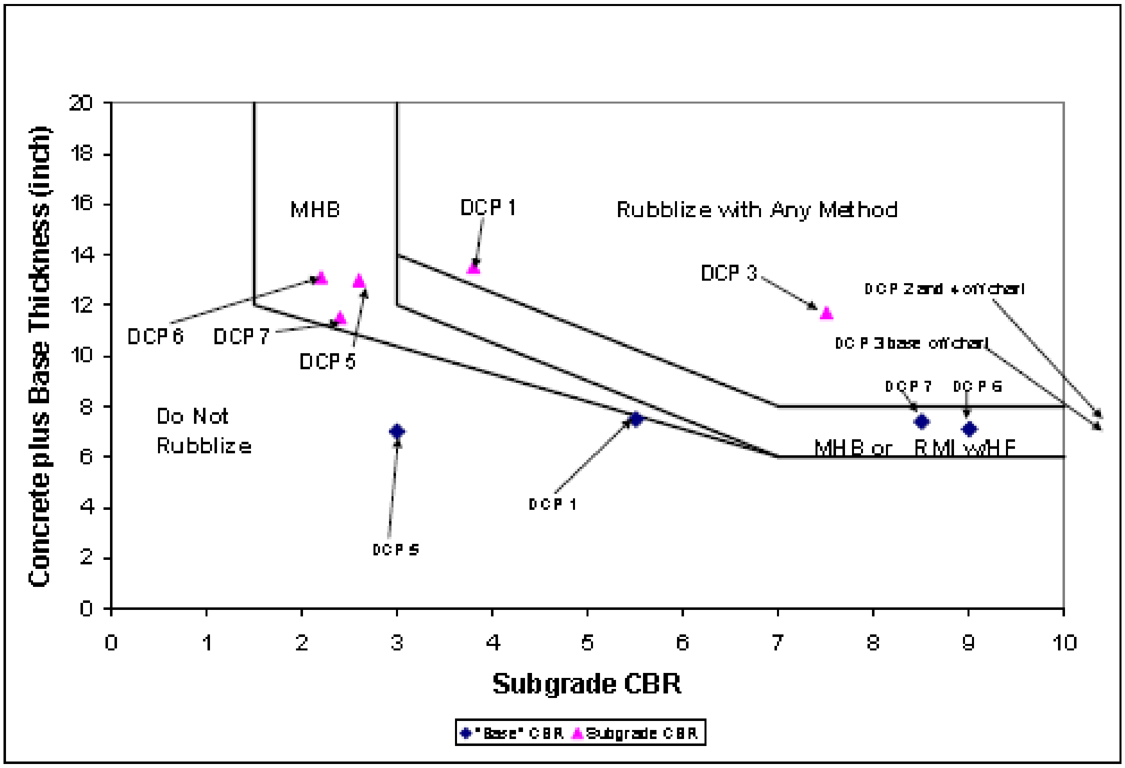


Figure 27
IDOT Rubblization Selection Chart

The first project consisted of a 7-in JCP over a subgrade with joint spacing of 40 ft. and cracks spacing of 6 to 7 ft. Based on the test results from NDT, the authors recommended not to rubblize the section as the subgrade beneath the slab did not provide strong support due to the presence of voids beneath the slabs. The second project consisted of approximately 7 to 8 in. of JCP over a subgrade. Based on the test results from NDT, the majority of the JCPs were marginally suitable for the rubblization. The third project consisted of a 9 in Continuously Placed Contraction Design (CPCD) concrete with asphalt-treated base and 17 in thick embankment. Rubblization was recommended for this project as strong support was provided by the subgrade. The fourth project consisted of a 1 to 2 in of HMA over 10 in of JCP pavement. NDT test results suggested that the pavement is suitable for rubblization. The next project had been rubblized and its performance was monitored four years after construction. The rubblized section performed well despite heavy rains in the area. It was noted that modulus of the rubblized layer increases with age from 114 ksi to 323 ksi. The authors recommended evaluating this trend in other field projects. In summary, the authors stated that drainage and support beneath the slab are the two main issues for success of the rubblization process *[64]*. In addition, estimating the modulus of the rubblized layer at 5% of the concrete modulus prior to rubblization appears reasonable.

Rajagopal (2011) conducted a study to evaluate the effectiveness of rubblization in concrete pavement to enhance the performance of asphalt overlay *[65]*. The researcher evaluated the performance of rubblization in past projects in Ohio, analyzed the effectiveness of rubblization in different states, and conducted a field demonstration to demonstrate the capabilities of pavement breakers. Pavement Condition Rating (PCR) and FWD data were obtained from past projects and used in evaluation. An average performance period of 11.7 years for the rubblized and rolled (R/R) pavements was estimated from analysis of PCR data. Further, the use of preventive maintenance would extend the performance period of rubblized pavements to a period of 20 years or more. Fifteen states, which routinely use rubblization, reported good to excellent performance. The author acknowledges that current QA practices in Ohio should be reviewed especially with respect to the recommended fragment size and shape as it is not consistently applied on all projects.

Laboratory Evaluation

Lee et al. (2010) stated that the use of rubblization typically results in the upper layer to be rubblized to 1.5 to 2.8 in. in size while the lower part of the concrete remains at larger size of 11.8 in. or more *[66]*. To this end, the authors conducted a laboratory simulation to determine the minimum depth of 40-70mm size rubblization required to prevent reflective cracking in asphalt overlay. The initiation of reflective cracks due to bending and shear failures was simulated in the experiment. These modes of failure were tested for rubblized depths of 0, 4, and 8in. A vertical dynamic load was applied to simulate the shear strain due to traffic loading in the pavement. Repeated loading was applied and the crack initiation and propagation was analyzed for different depths of rubblization. A vertical load of 1212 lb. was applied to simulate a tire pressure of 100 psi and to determine the required depth against shear failure. The test was carried out until the cracks propagated through the entire depth of the specimen. To check the depth of rubblization against bending failure, a repeated moving load was applied and the growth and propagation of reflective cracks was monitored for every 500th loading, see Figure 28. It was observed that for both modes of failure, no reflective cracks were observed for a rubblization depth of 4in. or more.

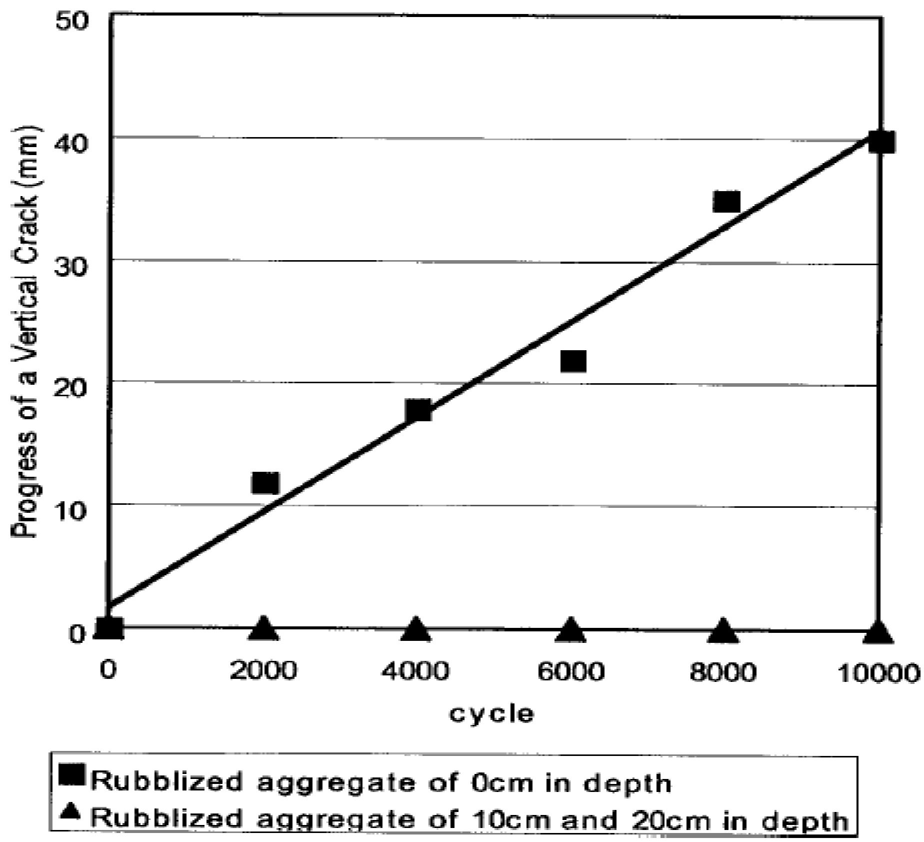


Figure 28
Vertical Crack Propagation in Shear Failure Test *[66]*

Theoretical Evaluation

Dave and Buttlar (2009) performed a finite element-based pavement simulation to understand the mechanism of thermal reflective cracking and to study the effects of joint spacing and rubblization on the overlay performance against reflective cracking *[67]*. Superpave low-temperature performance grades of -22, -28, and -34 were studied in three asphalt mixtures. Asphalt mixtures with superior Superpave low temperature performance grades (i.e., -34°C) were observed to better resist thermal reflective cracking. The curling of the PCC slabs due to the difference in temperature and joint opening due to pavement cooling were found to be the major contributors for the initiation of thermal reflective cracking. To this end, PCC pavements with large joint spacing would exhibit more thermal reflective cracking due to the larger effect of slab curling. Cracking due to curling and cooling was generally minimized in rubblized pavements. The simulation results that compared rubblized and intact slabs found that rubblization prior to the overlay could reduce thermal reflective cracking in the overlay. Further, bottom-up cracking was observed in intact slabs whereas top-down thermal cracking were observed in rubblized PCC pavements.

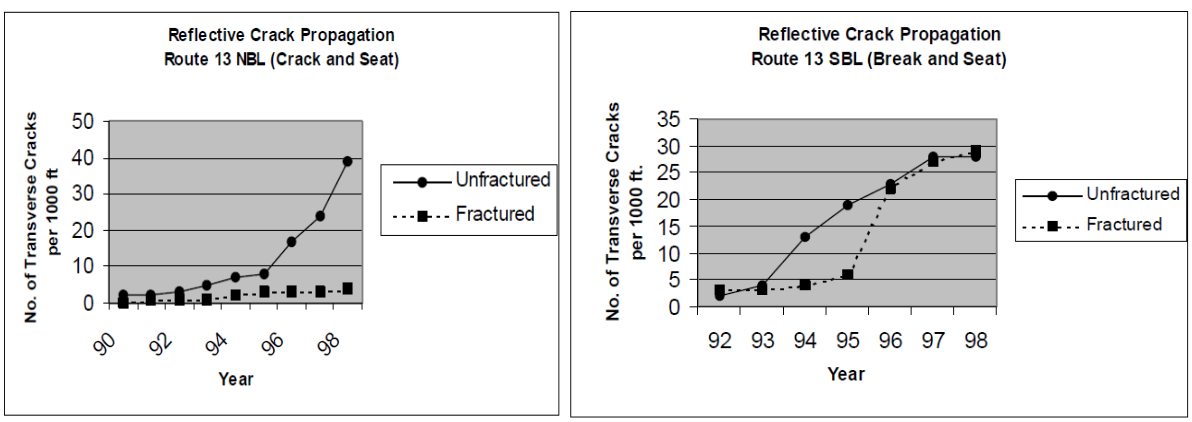
PERFORMANCE OF CRACK AND SEAT

Field Evaluation

Schutzbach (1988) conducted a study to evaluate the effectiveness of crack and seat as a pavement rehabilitation technique for concrete pavements in Illinois *[68]*. The performance of crack and seat was evaluated in six projects for a period of five years. Crack and seat was applied by cracking the concrete into 1.5 to 2.0 ft. sized pieces and was followed by an overlay of thickness ranging from 3 to 7½ in. Since the cracking was not destructive, traffic was allowed on the cracked concrete and after seating. A noted limitation of the study is that only one site had a control section and traffic was relatively low on the evaluated roads. In the project built with a control section, reflective cracking appeared in both the crack and seat and the control sections; however, crack and seat appeared to delay reflective cracking for 3 years. Therefore, the author could not establish the cost effectiveness of crack and seat. Further, the use of crack and seat with JRCP was not recommended as a large number of reflection cracks were observed in the overlay over this type of pavements. This was due to the stress development as the steel holds the concrete firmly during the temperature variations. Thick overlays with edge bars are more suitable than crack and seat method for JRCP's. The performance of crack and seat method is also dependent upon the design of the overlay thickness.

Choubane et al. (2000) evaluated the performance of crack and seat technique to retard reflective cracking in 14 tow-lane sections of I-10 in Florida *[69]*. Further, the evaluation of asphalt rubber interlayer membrane (ARMI) was conducted. Data were collected for seven years from the time of construction and were analyzed in terms of distresses namely rideability, rutting, and cracking. It was observed that the pavement provided good ride characteristics during the monitoring period. Rutting performance was also reported to be effective with less than 6-mm of rutting. In terms of cracking, reflective cracking was insignificant as detailed in the visual surveys. Overall, the effectiveness of crack and seat was excellent. The use of ARMI also played an important role in enhancing field performance. Overall, researchers gave a high rating to the performance of crack and seat when used in conjunction with an ARMI as an effective treatment method to delay and mitigate reflective cracking.

Freeman (2002) conducted a research study to evaluate concrete fracturing and seating techniques to arrest or delay reflective cracking in asphalt overlay placed over severely distressed JPCP and JRCP *[70]*. Five projects (two JPCP projects and three JRCP projects) were evaluated for a period of eight years. Prior to rehabilitation, vertical displacements ranging from ¼ to ¾ in. were measured across the transverse joints; further, patched slabs representing 8 to 15% of the total number of slabs were recorded in the test and control sections. The test sections were fractured with a guillotine drop hammer and then seated with a 50-ton pneumatic tire roller. Detailed crack survey was performed in each year and the number of cracks formed in the test and control sections were compared to determine the effectiveness of the crack and seat technique. In case of JPCP, crack and seat was effective in reducing the formation of reflective cracking, Figure 29a. In the case of JRCP, this technique was less effective as it only delayed reflective cracking for three years, Figure 29b. After three years, the performance was found to be similar as the control sections. Based on these findings, it was concluded that slab fracturing and sealing is an effective technique to delay reflective cracking in asphalt overlay given the nominal cost of crack and seating operation.



(a) **(b)**

Figure 29

Reflective Cracking over Time for Site 1 (JPCP) and Site 4 (JRCP) *[70]*

A six years evaluation of pre-cracking as a technique to retract reflective cracking in semi-rigid pavement was performed in the UK *[71]*. Twelve sections including eight pre-cracked sections and four control sections were constructed as full-scale trial sections. The cement-bound material (CBM) pavement were pre-cracked using four different techniques namely the vibrating plate, OLIVIA, CRAFT and a guillotine. Pre-cracks were induced in the transverse direction with a longitudinal spacing of 3m. Visual condition surveys, core analysis, Falling Weight Deflectometer (FWD) and High-speed Survey Vehicle (HSV) were employed to evaluate the performance of the experimental sections. Visual surveys showed the reduction in the number and length of reflective cracking compared to the respective control sections. Reflective cracking was observed to be severe and notably progressive in the control sections while their presence was minimal in the pre-cracked sections. The guillotine technique of pre-cracking was observed to perform well in most of the sections. Results from the FWD tests indicated the no reduction of stiffness occurred in the pre-cracked sections as compared to the control sections.

CHAPTER V

OTHER TREATMENT METHODS

NOVACHIP

NovaChip is a two-steps treatment method consisting of applying a polymer-modified asphalt emulsion, known as NovaBond®, followed by an ultra-thin gap-graded AC layer. This product, which was originally developed in France, is manufactured and distributed by SemMaterials in the US. It was originally introduced as a surface treatment for weathered and cracked pavements in order to address the rough texture and the potential for flying chips encountered with chip seal. The application of NovaChip® requires the use of specially designed equipment that places both the Novabond® and the NovaChip® in a single pass. North Carolina has significant experience with the use of NovaChip on high traffic Interstates. Through communication with North Carolina DOT, the authors learned that it is frequently used on jointed concrete pavement and provides a service life of 10 years or more, even with high traffic and high truck percentage. It is favored in North Carolina because it does not require adjusting the grading of the existing pavement or adjustment to supporting structures such as guardrails.

Cooper and Mohammad (2004) reported Louisiana's first experience with NovaChip® *[72]*. A test section (SP 407-04-0034) with moderate traffic with an average daily traffic (ADT) of 4,776 was constructed in 1997 in Lafourche Parish on LA 308. Prior to the project, the existing surface was a plant mix seal that was constructed in 1978 on top of 7 in. of HMA. Three sections were constructed and evaluated. In the first section, constructed in 1998, 2.0 in. of the existing HMA was milled with 3.5 in. of overlay placed on top of the milled surface. In the second section, constructed in 1997, a NovaChip with a thickness of 0.75 in. was installed. In the third section, constructed in 1998, 1.5 in. of the existing HMA was milled with a 3.5-in. overlay placed on top of the milled surface. After six years in service, the NovaChip was performing satisfactorily with respect to rutting, international roughness index (IRI), longitudinal, random, and transverse cracking. Based on this evaluation, Cooper and Mohammad recommended evaluating the technology in concrete pavements as it may result in cost savings for LADOTD.

In a report published by National Center for Asphalt Technology (NCAT), Douglas stated that projects in Bucks County and Montgomery County of Pennsylvania reported minor reflective cracks on the surface of the roadway where NovaChip was used *[73]*. Similar conclusions were made from projects with NovaChip in Alabama. Pretreatment of existing joints before application of NovaChip is strongly recommended. Any cracks greater than 0.25 in. should be cleaned routed and sealed.

A field study was performed by Russel et al. (2008) to evaluate the prospective use of NovaChip as a substitute for HMA Class G (fine graded dense asphalt) that is normally specified for asphalt pavements in city roads *[74]*. The major cracks before the application of NovaChip were transverse cracks, longitudinal cracks, and alligator cracks. Though the frequency of reflective cracking increased over time, the cracks remained less severe. NovaChip was observed to reduce medium and high severity cracks. The low severe cracks were visible soon after placement of the overlay but there was a reduction in the level of cracks after three years of installation. The rideability of the roads remained constant after four years of the installation and the rutting was also reduced. However, NovaChip use on roads with high traffic volume like interstates and high volume arterials is limited. In the case of city roads, Novachip was found to be an effective treatment method to address reflective cracking and can be used as a substitute for HMA Class G. Overall, the authors stated that NovaChip can perform well for a period of approximately 6 years.

Russel et al. also evaluated the cost-effectiveness of NovaChip as compared to HMA Class G based on the prices in 2001 *[74]*. Washington DOT commonly places an 1-in. HMA Class G on top of chip seal, known as BST, to reduce noise and roughness problems. The use of NovaChip was evaluated for low volume roads since its performance on high-traffic roads is unknown. The cost of NovaChip ranges from $3.00 to $4.00 per square yard. Table 8 compares the life-cycle costs of various rehabilitation treatments as reported by the authors. In order to find the cost-effectiveness of NovaChip, it was important to estimate the service life of NovaChip. Based on pavement performance data collected on one project, researchers predicted that the service life of NovaChip would be between eight to nine years. Results presented in Table 9 indicate that the cost of NovaChip is comparable to HMA Class G. However, when only the construction cost is considered, the base cost of NovaChip was twice that of HMA Class G.

Table 9
Annual worth of various rehabilitation treatments *[74]*

Rehabilitation Type	Estimated Time Between Treatments (yrs.)	Annual Worth ($/Lane Mile)	Annual Worth ($/Square Yard)
BST	6	2,700	0.28
HMA Class G	7	8,300	0.89
NovaChip	8 to 9	7,800 - 8,600	0.83 - 0.92
HMA Class A or ½ in Superpave	10	11,100	1.18

SAW AND SEAL

The saw and seal method is a treatment used to prevent random propagation of reflection cracking from underlying Portland Cement Concrete (PCC) joints to the top of an HMA overlay. The saw and seal method consists of sawing the HMA overlay to create transverse and longitudinal joints at the exact locations of the PCC joints followed by sealing of the constructed joints. Saw and seal operation should be performed promptly after placement of the overlay but at least 48 hours after paving *[75]*. Success of the saw and seal method depends on applying the treatment at the exact locations of the joints *[76]*. Prior to the overlay, existing joints on the concrete pavement are located and marked. Joints are then reestablished with a chalk after the overlay. These joints are dry cut using a rideable concrete saw. The cuts are cleaned prior to placing the sealant. The cleaning process involves usage of hot compressed air to get rid of all the dust particles, loose debris, and most importantly, moisture that clings to the walls of the groove. For cleaner joints, a sand blaster may be used to remove any remaining debris. The final step is to seal the joints with a low-modulus rubberized sealant *[77]*. Most of the grooves are overfilled from bottom up and then followed by squeegeeing to flush the applied sealant with the pavement surface. It was observed that sealant cools and contracts quickly once the squeegeeing process is completed. Sealing the created joints prevents the infiltration of water and incompressible materials from getting into the underlying layers. Since water infiltration and the possible stripping of HMA accelerate pavement deterioration, sealing the overlay joints properly plays an instrumental role in extending pavement service life *[78]*.

Field performance of the saw and seal method in composite pavements was evaluated by various investigators. A seven year field evaluation of crack control treatments (saw and seal method, fabrics, membranes, and fiber glass laminates) was conducted in New York *[79]*. In this controlled experiment, sections with two joint spacings were built on top of concrete pavements and were monitored for seven years. Field evaluation included visual surveys, deflection testing, coring, and materials testing. Performance was assessed in terms of crack extent and severity as well as load transfer efficiency across the cracks. Results of the evaluation determined that the saw and seal method was the best performer of all the considered treatment methods. In addition, this study concluded that a joint spacing of 15 ft. reduces the severity of reflection cracking as compared to a joint spacing of 20 ft.

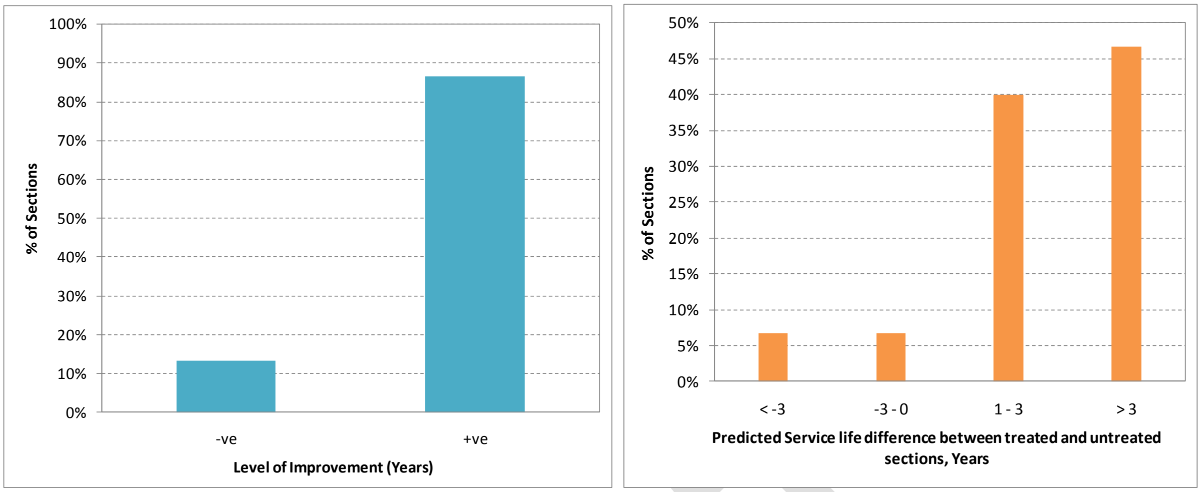
An experimental study conducted in North Dakota monitored the performance of 54 sawed and sealed joints after a 4in. overlay was placed on top of an existing PCC pavement *[76]*. Coring conducted in the sawed and sealed joints indicated that the constructed joints converged with the overlying pre-sawed PCC joints. After seven years in service, the test section was performing satisfactorily with only a few spalls in the driving lane. However, it was observed that longitudinal cracks developed between the joints in the shoulder area. Based on these results, this study recommended that this treatment method be considered in the rehabilitation of existing PCC pavements as it provides low maintenance cost and good riding quality.

The field performance of 10 projects constructed with HMA overlays treated with the saw and seal method was evaluated *[80]*. These sites, which were located in six states, were evaluated through condition surveys, roughness measurements, and deflection testing. Selected sites had been in service for a period ranging from 2 to 10 years and with an overlay thickness ranging from 2 to 4.5 in. Based on the results presented in this study, it was concluded that the saw and seal method reduces pavement roughness by 20% and transverse reflection cracking by as much as 64%. However, it was noted that a saw cut more than 1 in. away from the joint would result in secondary cracking.

Researchers at LTRC investigated the effectiveness of several water proofing membranes, sawing, and sealing of joints and use of latex modified asphalt concrete against reflective cracking *[81, 82]*. During installation of the membrane, the HMA overlay appeared to shove during compaction and 6- to 8-in. humps were noticed along the joints. Performance evaluations for the crack control measures were conducted biannually for three years or until extensive reflective cracking occurred. These evaluations included measurements or estimates of crack mapping, rutting (none detected), ride quality, and raveling. Results of the evaluation showed that sawing and sealing over existing transverse joints in a new overlay appears to be the most effective in controlling reflective cracking. In addition, latex-modified HMA was able to control reflective cracking better than conventional HMA.

Janisch and Turgeon (1996) conducted a review of the effectiveness of saw and seal to mitigate reflective cracking in Minnesota *[83]*. They reviewed about 50 test sections where saw and seal was applied. It was observed that saw and seal performed effectively in 75% of the sections. Sections in which saw and seal was unsuccessful were those in which the sawing was not made through the entire thickness of the overlay or used a reservoir only. One of the test sections where the existing cracks were straight and where saw and seal was directly applied over the cracks had an effectiveness of 100% for a service life of five years. Based on the results of the study, the authors recommended not using saw and seal in the case of a concrete pavement with badly deteriorated joints and with extensive patching at or near the joints. In case of HMA overlay over an existing asphalt pavement, the practice of sawing the joints at uniform intervals without giving attention to the crack location made it ineffective to control reflective cracking. Further, saw and seal shall not be used in case of severe load-related distresses such as alligator cracking, potholes, or severe stripping.

Elseifi et al. (2011) evaluated the performance of saw and seal in the pavements with Hot-Mix Asphalt overlaid on existing PCCP *[84]*. The evaluation was conducted for a period of six to 14 years. Based on the analysis of 15 pavement sections, the authors concluded that 87% of the test sections showed positive improvement in performance for a service life of 1 to 12 years while 13% showed negative results. As shown in Figure 30, the evaluated sections performed well with a majority (47%) showing an improvement in service life ranging from 4 to 12 years. Based on the analysis, an average improvement of 4 years was estimated. Video crack survey was conducted to examine the cracking pattern at joints and to determine the presence of secondary cracking near the sawed joints. It was determined that the percentage of secondary cracks in the sites in which the saw and seal method did not perform well or similar to the untreated sections was 0.6%. This low level of secondary cracks in the evaluated sites indicates that the approach adopted in Louisiana to locate the joints after placement of the overlay is effective in minimizing secondary cracks. Theoretical investigation conducted using 2 dimensional FE analysis indicated that the use of saw and seal method significantly reduced the strains levels at the PCC joints. This will result in the control of crack initiation at bottom of overlay and propagation with repetition of loads. The saw and seal dissipated the energy due to wheel loading and expansion and contraction of the concrete and allows the movement of the slabs underlying the HMA without formation of the cracks.



(a) **(b)**

Figure 30

Contribution of the Saw and Seal method to the Predicted Pavement Service lives *[84]*

Elseifi et al. (2011) also evaluated the cost effectiveness of saw and seal in pavements with an overlay on top of an existing concrete pavement *[84]*. The evaluation was conducted for a period of six to fourteen years. The cost effectiveness was determined by comparing the inflated Total Annual Cost (TAC) of the treated and untreated sections. Of the fifteen sections evaluated, 80% of the sections showed positive results in terms of cost effectiveness especially in the sections with low to medium traffic volumes. One possible reason for this trend is that the increase in traffic loading may result in minor rutting in the wheel paths, which may cause the sealant to come off with time and, therefore, gradually decrease the serviceability of the pavement structure. Figure 31 presents the cost of treated and untreated sections based on the concept of TAC.

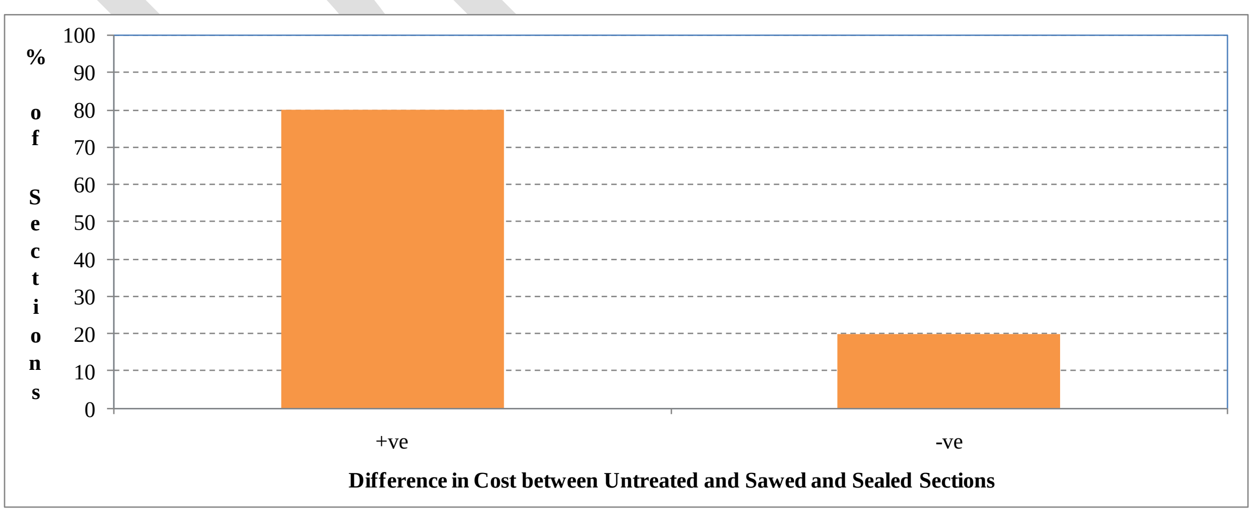


Figure 31

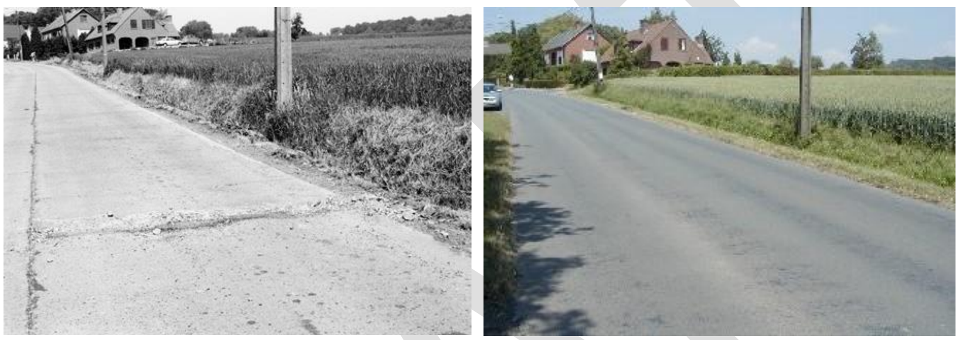
Cost Effectiveness of the Saw and Seal Treatment Method *[84]*

STEEL REINFORCING MESH

One of the oldest interlayer systems used in flexible pavement is steel reinforcement. The idea, which appeared in the early 1950s, was based on the general concept that if HMA is strong in compression and weak in tension, then reinforcement could be used to provide needed resistance to tensile stresses *85]*. However, the concept of using steel reinforcement in HMA materials was abandoned in the early 1970s after tremendous installation difficulties were encountered. The idea reappeared in Europe in the early 1980s with the development of a new class of steel reinforcement products. Many of the problems encountered earlier appeared to have been solved, and satisfactory experiences with the new class of steel reinforcement were reported. The current steel mesh product consists of a double-twist, hexagonal mesh with variable dimensions, which is transversally reinforced at regular intervals with steel wires (either circular or torsioned flat-shaped) inserted in the double twist, as shown in Figure 32. No welding is used in the new generation of steel reinforcement. This eliminates installation difficulties and any variation in HMA densities caused earlier by welded reinforced steel.

Figure 32
Steel Reinforcing Mesh *[85]*

Evaluation of the new class of steel reinforcement showed that the performance of the overlay was enhanced if slab-fracturing techniques were used to reduce vertical movements at the joints prior to placement of the overlay *[85]*. It was also concluded that overlay thickness still remains the major factor controlling pavement performance. Among the evaluated test sites was a project in Mont-Saint-Aubert. This site consisted of a highly deteriorated rigid pavement structure with a traffic pattern classified as light to medium; see Figure 33. In 1989, steel reinforcement was installed after minor repairs to the existing pavement structure. A 3-in. overlay was then applied on top of the steel netting. Figure 33(b) illustrates the same road after 11 years of service (2000). After 10 years of service, inspections of this site showed a reflective cracking occurrence of only 1%. To date, the new class of steel reinforcement has only been installed in the US in a limited number of experimental sections starting with the Virginia Smart Road in 1999 and several test sites in Pennsylvania, Delaware, and Maryland. Pioneer work conducted in the evaluation of the new class of steel reinforcement in the US has been conducted by Al-Qadi and co-workers *[85, 86]*.



(a) **(b)**

Figure 33
Comparison between a road in Belgium: before repair and 11 years after repair *[85]*

Hughes and Al-Qadi (2001) reported on the installation of steel nettings in Pennsylvania *87]*. The authors recommended that a standard methodology need to be developed for the installation of steel netting. This includes factors such as nailing pattern, use of overlap, and application of micro-surfacing after the steel mesh. In addition, the steel netting needs to be fabricated from domestic steel.

A theoretical study was performed by Elseifi and Al-Qadi to study the behavior and benefits of steel reinforcing interlayer in delaying reflective cracking *[88]*. The effects of traffic and thermal loading in the HMA overlay over rigid pavements were considered and simulated using three-dimensional finite element analysis. In general, traffic loadings cause the propagation of discontinuities through the opening mode (Mode I) and the sliding mode (Mode II). In contrast, thermal expansion and contraction may only cause the propagation of discontinuities through Mode I. Results of the heat transfer analysis indicated that the temperature variation in a concrete slab is minimal when overlaid. In addition, a positive temperature gradient was noted at all time between the top and bottom surfaces of the overlaid concrete slab. Considering the effects of thermal and vehicular loading in overlaid rigid pavements, the use of steel reinforcement was judged effective in delaying the reflection of cracks at the joint location. It was found that the use of steel netting could reduce transverse and longitudinal strains at the bottom of overlay by as much as 20% hence reducing the rate of crack propagation. Overall, steel reinforcing netting was effective in retarding reflective cracking due to vehicular and thermal loading.

A design project was conducted by Baek and Wang (2007) to evaluate steel netting as a long-lasting rehabilitation technique to mitigate reflective cracking in airfield pavements *[89]*. They performed a FE analysis to demonstrate the performance of steel mesh installed at the bottom of a 3-in asphalt overlay on top of an existing concrete pavement, see Figure 34. One gear loading of Boeing 747-400, one of the heaviest aircrafts, was applied on the pavement structure. However, they did not consider temperature and moisture variation in the pavement in the FE analysis. Results showed that steel reinforcing netting was able to reduce reflective cracks due to underlying transverse and longitudinal cracks by factors of 8.4 and 1.4, respectively. The authors recommended that pavement conditions, temperature and moisture variations, and the design parameters for overlay and existing slab such as size, depth, thickness, etc. should be carefully examined before rehabilitating the pavement with steel netting.

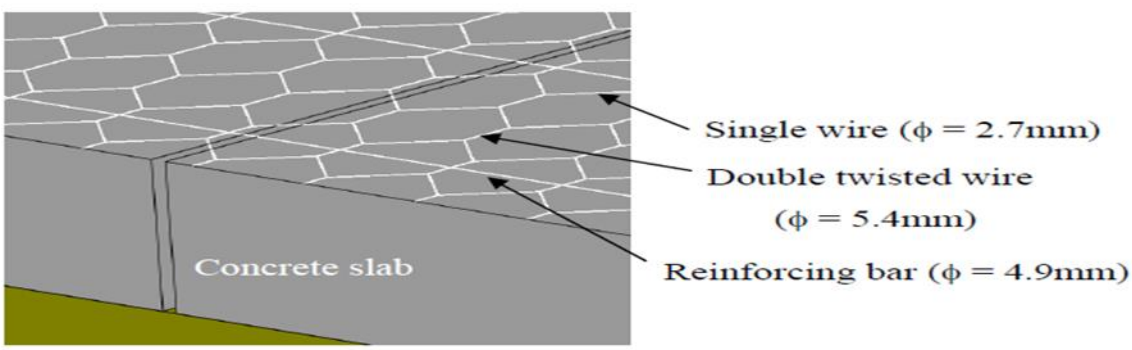


Figure 34
Steel Reinforcement Netting Configuration and Placement in Concrete Slab *[89]*

STRESS ABSORBING MEMBRANE INTERLAYER (SAMI)

SAMI is constructed by placing a seal coat made of rubber asphalt binder (80% asphalt cement and 20% ground tire rubber) on the surface of the old pavement and then rolling in coarse aggregate chips. This layer may be used as a stress-relief interlayer. The main role of the SAMI is to retard crack propagation and improve the tensile strength at the bottom of the overlay due to the presence of the rubber asphalt binder. It is thought that this interlayer will cause the overlay to behave independently from the underlying structure. If this hypothesis is correct, higher tensile strains will occur in the overlay, but no reflective cracking will take place.

Way (1979) summarized a study involving the evaluation of 18 selected roadway test sections performed by Arizona Department of Transportation *[90]*. All 18 sections were constructed on Interstate 40 with different types of crack control treatment methods to delay reflective cracking and with an adjacent control section. Treatment methods included a wide range of methods including fiber-glass grid, paving fabrics, SAMI, and asbestos fortified AC mix. Reflective cracking was monitored for each section for six years with an estimated traffic of 1 million ESALs. Of the 18 treatment methods, the following five treatments were effective in delaying reflective cracking in the overlay:

- Asphalt rubber membrane seal coat;
- Asbestos plus 3% asphalt, which would not be considered nowadays after the health risks of asbestos have been identified;
- Heater scarification with reciamite (surface recycling);
- Asphalt rubber membrane flushed into asphaltic concrete overlay; and
- 200/300 penetration asphalt.

It was recommended that these treatment methods be applied in conjunction with thin overlays (4 in. or less). The asphalt rubber membrane should be used with chips to transfer the vertical loads and the heater scarification depth should not be less than 3/4 in. Table 10 presents the performance of the recommended treatment methods against reflective cracking as well as the control section.

Table 10
Percentage reflected cracks under various treatment techniques *[90]*

Section	Treatment techniques	% reflected cracks	
		1975	1978
3 and 4	Asphalt rubber membrane seal coat under ACFC	4	2.1
5	Asbestos plus 3% asphalt	13	5.9
18A	Heater scarification with reciamite (surface recycling)	6	7.4
1	Asphalt rubber membrane flushed into asphaltic concrete overlay	19	12.8
10	200/300 penetration asphalt	8	16.1
	Control section without patching	17	27

Scofield (1989) evaluated the history, effectiveness, and development of asphalt rubber by analyzing past projects from historical database and by examining the ongoing performance of eight projects with 47 test sections *[91]*. ADOT has been using asphalt-rubber since 1968; over the years, ADOT established its own specifications and construction techniques. It was observed that over the past two decades, 90% of the sections with SAMI had been used in mitigating reflection cracking. ADOT's current philosophy is to use asphalt rubber as a binder in open graded and dense graded asphalt concrete. These treatments are utilized for overlaying rigid and flexible pavements and are typically placed in 1 in. and 1.5 to 2 in. thicknesses for open graded and dense graded mixtures, respectively. Results show that the average service life of SAMI is approximately five and ten years on the interstate and state routes while it was eight years on US routes, respectively. Results from this study led to the conclusion that asphalt rubber has been successful in controlling pavement distortion due to expansive soils and reducing reflection cracking in overlays placed in both rigid and flexible pavements.

Way presented ADOT's experience in using asphalt rubber (AR) to delay reflective cracking *[92]*. Since the late 1980s, asphalt rubber has been used in open-graded or gap-graded mixes that are ½ to 1 in. thick and 1 in. to 2 in. thick, respectively. The percentage of AR binder in open graded mixes ranges from 9 to 10% and in gap graded mixes; it ranges from 7.5 to 8.5%. In one project constructed in 1988, a 1-in. open-graded asphalt rubber layer was placed on interstate 19. The mix contained 10% asphalt rubber by weight the mix and was placed on top of a JPCP. No cracks reflected until 1996 and only a few transverse cracks appeared at the joints. Since this first project, dozens of projects were constructed using a similar approach. Figure 35 compares the performance of a project built with AR and a control section built with a conventional overlay. The grade of asphalt binder used as a base to make AR is a PG 58-22 (AC-10), in contrast to typically stiffer grade of PG 64-16 (AC-20) used in the mountains. In the desert, the AR base asphalt grade is PG 64-16 (AC-20) compared to PG 70-10 (AC-40) typically used for dense grade mixes. AR can be graded from a PG 70-22 to a PG 82-28 using the Superpave specification system.

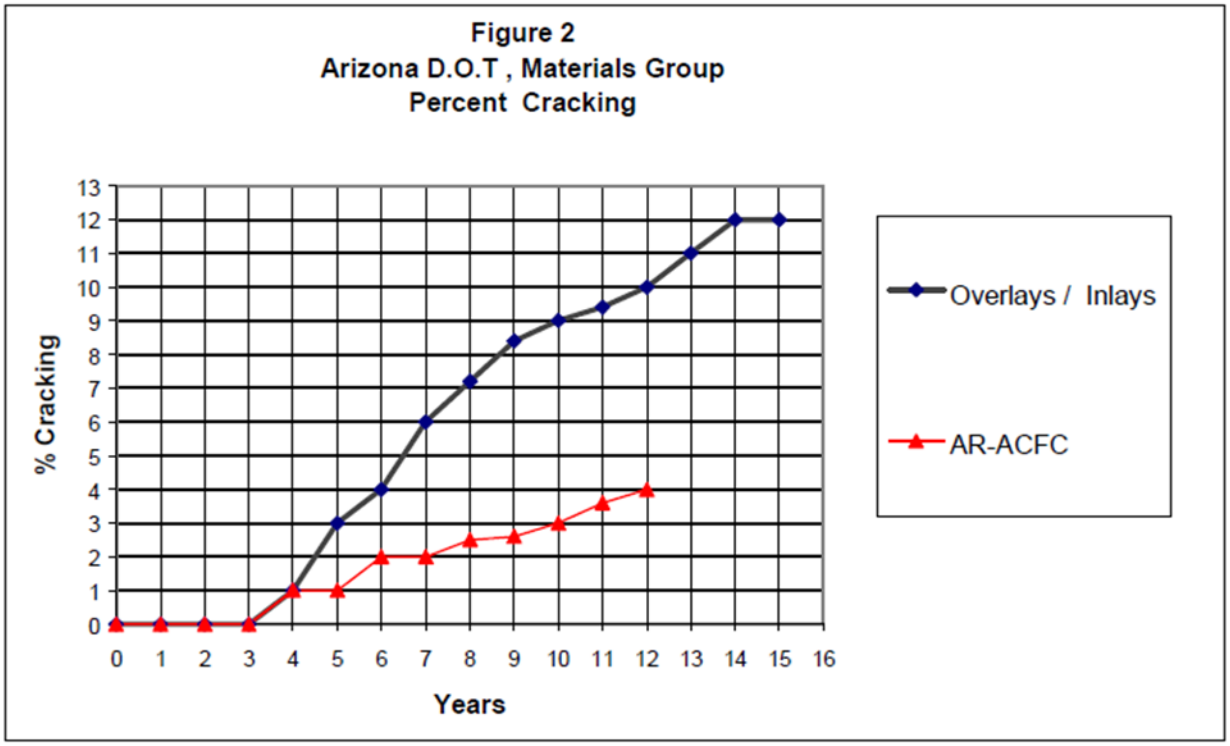


Figure 35

Comparison of the Performance of AR Mixes to Conventional Overlays *[90]*

Makowski et al. (2005) evaluated the effectiveness of fine aggregate, asphalt-rich, polymer-modified asphalt mix interlayer to absorb joint movement, delay reflective cracking, and protect the existing pavement *[93]*. Reflection cracking was a major challenge in Wisconsin as the crack reflected within a year or two. The researchers evaluated four projects in Wisconsin to determine the effectiveness of asphalt mix interlayer. The first project, which was constructed in 1996 showed no improvements in delaying reflective cracking for a period of three years. In the other three projects, however, performance-related design tests led to an improved overlay mix to complement the asphalt mix interlayer. These projects showed a significant improvement and were observed to delay reflective cracks by 42% as compared to the control sections. Extracted core samples showed that even when the overlay cracked, the interlayer mix did not, thus protecting the underlying structure. The authors also identified large movements in the concrete pavement as a factor that may hinder the performance of the interlayer system.

Gordy and Whittington (2008) evaluated a new interlayer system, known as Distress Resistant Membrane (DRM) developed by the Mississippi Department of Transportation (MDOT) to mitigate reflective cracking *[94]*. DRM consists of a three-part system that includes a sealant, an emulsion, and small aggregate. A sealant, consisting of high grade base asphalt modified with elastomeric polymers, is placed first, followed by an emulsion. Small aggregates are then placed on top of the emulsion. A 4-in overlay was then placed on top of the interlayer system in two lifts. A control section and a section in which milling was performed but was allowed to remain in place were also constructed. The researchers analyzed IRI and PCR data along with video images to identify pavement distresses. The data collected in 2006, three years after construction, showed no sign of reflective cracking in the DRM section, whereas a few cracks appeared in the control section. In 2008, reflective cracks were observed in the DRM section as well. It was concluded that DRM did not fully mitigate reflective cracking but only delayed the time of occurrence. It was also mentioned that with a cost of $2.03 per square yard, the DRM system does not appear to be cost effective as it only delayed reflective cracking for 20 months. The distresses observed after three and five years of placement are summarized in Table 11.

Table 11
Average Transverse and Average Longitudinal Cracking *[94]*

Segments	Average Transverse Cracking Per Sample (Feet)		Average Longitudinal Cracking Per Sample (Feet)	
	2006	2008	2006	2008
DRM	0	45.9	0	69.9
Control	14.7	124.8	5.9	77.3
Milling	27	66	0	0

Zaghloul et al. reported on the performance of two types of stress absorbing membrane interlayers in California *[95]*. SAMI-R and SAMI-F, which stands for rubberized stress absorbing membrane interlayer and fabric stress absorbing interlayer, respectively, were tested. SAMI-R was designed to provide structural strength to the pavement besides retarding reflective cracks when used with rubberized asphaltic concrete *[95]*.

The construction procedure for SAMI-R involves the placement of asphalt rubber binder followed by the application of aggregates that are pre-coated with paving asphalt. SAMI-F is placed under dense graded asphaltic concrete. However, there are some factors, which may limit the performance of SAMI if it is not properly constructed. In a hot environment, SAMI should be used carefully as it prevents evaporation of moisture from the subgrade, which would eventually weaken the substructure of the pavement. Stripping of HMA from aggregates would occur if moisture is trapped within the asphalt concrete; this can be prevented by treating the aggregates prior to construction. SAMI-F may become dry and lose its ability to retard reflective cracking if it is used directly on a coarse surface like chip seal or open graded asphalt concrete. SAMI-F should not be used with a high temperature asphalt mix as it would melt the fabric. Improved performance was reported when the fabric is saturated with asphalt *[96]*. In the comparison study performed by Zaghloul et al., SAMI-R and SAMI-F performed similarly in terms of predicted service life and rehabilitation stages; however, SAMI-R outperformed SAMI-F in roughness performance *[95]*.

A study performed by Morian et al. (2005) in Pennsylvania evaluated the performance and cost-effectiveness of cold-in-place recycling and SAMI in 49 sections. Results showed that the use of SAMI and cold in-place recycling improved pavement service life when compared to normal milling and leveling rehabilitation procedures *[97]*. While cold-in-place recycling extended the overlay service life by four to five years, the use of SAMI increased pavement service life by two years and proved to be cost-effective when compared to conventional leveling and milling procedures *[97]*. Further, the application of the overlay when the pavement is in fair condition proved to be more cost-effective as compared to its application when the pavement reaches a poor condition. Table 12 presents the cost comparisons of the four treatment methods evaluated in this study.

Table 12
Net Present Value Comparisons for Four Treatment Methods

Treatment	Initial Cost ($)	2nd Cycle Cost ($)	PVF	Salvage Value ($)	PVF	PNV ($)	Rank
Leveling	63,712	59,840	0.68	0	0.46	104,138	4
Milling	60,192	59,840	0.68	0	0.46	100,618	3
SAMI	61,600	59,840	0.62	19,947	0.46	89,872	2
Cold Recycled	41,677	33,229	0.58	18,988	0.46	52,200	1

Note: 4% discount rate is used with 20-year analysis period. PNV= present net value; PVF=present value factor for calculation of PNV

Shatnawi et al. (2012) reviewed the performance of Asphalt Rubber Aggregate Membrane Interlayer (ARAMI) chip seals and asphalt rubber absorbing membrane interlayers (SAMI-R) against reflective cracking in the field, the laboratory, and using two-dimensional FEA *[98]*. Field performance in California and Arizona was reviewed and showed the significant benefits of these interlayers in delaying reflective cracking. This was attributed to the elastic properties of the interlayer as well as its superior aging characteristics that allow it to sustain five times greater strain than conventional asphalt binder. A laboratory study was conducted to simulate reflective cracking using the Hamburg wheel tracking test. Among the different interlayer systems evaluated, SAMI-R showed superior performance against reflective cracking. Two-dimensional FEA was conducted to study the influence of a number of factors on the performance of rehabilitated pavements against reflective cracking with and without SAMI-R. Results showed that SAMI-R can reduce critical stress and strain by a factor ranging from 92 to 98%.

Chowdhury and Button (20074) conducted a laboratory evaluation of a SAMI known as FiberMat Type B to delay reflective cracking in asphalt overlays *[99]*. Laboratory evaluation was conducted using the TTI overlay testers on specimens consisting of the FiberMat sandwiched between two HMA layers. After placement of a tack coat on the bottom layer, chopped glass fibers were spread onto the specimen top surface. Cover stone was then applied and then rolled to ensure bonding between the tack coat and the loose stone. The researchers observed two modes of crack propagation: 1) The crack starting from the existing pavement move up to the interface and propagates trough the new overlay; and 2) The crack moves up to the interlayer and turns its direction right and move horizontally along the interlayer. Mode 2 was the predominant cracking mode observed in small and large specimens prepared with FiberMat. Results also showed that the specimens containing FiberMat lasted 3 to 4 times more than the corresponding control samples.

Greene et al. (2012) studied the performance of Asphalt Rubber Membrane Interlayer (ARMI) – a type of SAMI constructed with a single application of a No. 6 stone – as a reflection cracking mitigation technique in Florida *[100]*. According to the authors, the performance of ARMI in Florida has been mixed and concerns were expressed that the interlayer may result in an increase in rutting in the overlay. Accelerated Pavement Testing (APT) and long-term field performance of experimental projects were used to study the performance of the interlayer. Field evaluation of constructed projects showed that ARMI did not effectively delay reflective cracking. Five test lanes were designed and constructed to evaluate the impact of ARMI on rutting performance. The APT study results show that an ARMI resulted in an increase in rutting when subjected to a combination of slow moving loads and high temperatures. A laboratory test method known as Composite Specimen Interface Cracking (CSIC) that was developed at the University of Florida was used to assess the possibility of using ARMI as a reflection cracking control technique. Three sections with and without ARMI were tested with CSIC with the same peak load for each tests. The sections without ARMI provided a better performance than the section with ARMI, see Figure 36. This study provided the base for Florida Department of Transportation to not to consider ARMI as a primary treatment method for mitigating reflective cracking and attempt to identify a more effective treatment method.

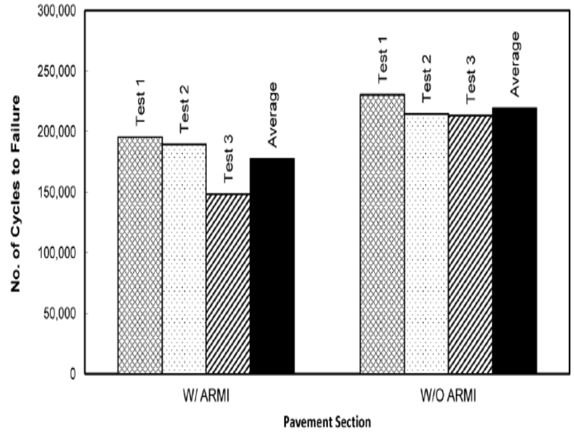


Figure 36

Number of Cycles to Failure for Pavement Sections with and without ARMI *[100]*

Ogundipe et al. (2013) conducted a theoretical study the behavior of SAMI against reflective cracking *[101101]*. Three-dimensional FE models were developed to simulate a wheel tracking test consisting of an overlay on top of an existing pavement. Results of the analysis show that when SAMI was used, greater displacements were observed in the model. Further, greater strain concentration occurred around the crack region when SAMI was used. However, lower strain was observed at the bottom of the overlay when SAMI was used, which may be beneficial.

COMPOSITE SYSTEM

Composite system is a multi-purpose system consisting of two or more types of treatment methods used to achieve more than one function in the pavement system (e.g. water prevention and stress-relief). Elseifi and Al-Qadi (2005) evaluated the potential of a specially designed geocomposite membrane to delay the reflection of cracks in rehabilitated pavements through strain energy dissipation *[102]*. The geocomposite membrane consisted of a 0.07-in. thick low-modulus polyvinyl chloride (PVC) backed on both sides with 0.028 lb/ft^2 of polyester nonwoven geotextile. Results of this analysis showed that the placement of a soft interlayer creates a protective shield around the crack tip, separating the criticality of the stress field in the cracked region from the bottom of the overlay. This study also indicated that a strain energy absorber would only be effective in the crack propagation phase if the crack does not pass through the interlayer and propagates horizontally at the interlayer-existing pavement interface. Monismith and Coetzee referred to this mechanism as "a crack arrest" phenomenon *[103]*. Therefore, the installation of this interlayer is crucial in dictating its performance. If damage or tearing of the interlayer occurs, the effectiveness of the strain energy absorber membrane would be altered. Further, when a strain-energy absorber layer is used, fatigue of the overlay should not be neglected and should be adequately controlled through the proper design of the overlay thickness and materials. The increase in deflections may be least critical when a low modulus interlayer is placed on top of an existing rigid pavement, where fatigue of the overlay is usually not a concern.

Deuren and Esnouf (1996) presented the performance of a system consisting of a chip seal reinforced with a geotextile membrane to treat severely cracked asphalt pavements *[104]*. The system consists of an ultra-thin overlay on top of a chip seal reinforced with a paving fabric. This system, which is widely used in Australia, consists of a paving geotextile saturated with bitumen and covered with either a single or double bituminous chip seal. A thin overlay (about 0.5 in.) is then applied. The advantage of the described treatment is that it prevents water infiltration into the pavement layers and allows for vertical movement at the cracks due to its high flexibility. This system has been used successfully for over 10 years in over 200 locations in Australia. The authors indicated that the average service life of this system is at least 10 years. A case study of the Monash Freeway is presented. The described treatment has been used on this heavily trafficked freeway. Until the end of the evaluation, there were no signs of cracking for the past five years.

Dempsey developed a composite interlayer system, known as the Interlayer Stress Absorbing Composite (ISAC), which consists of a low stiffness geotextile at the bottom, a viscoelastic membrane at the center, and a high stiffness geotextile at the top *[105]*. A detailed analysis of the causes of reflective cracking indicated that neither a stress-absorbing membrane interlayer (SAMI) nor a geotextile can completely control this distress when used separately. Through the ISAC system, the low-stiffness geotextile fully adheres to the existing pavement and accommodates large deformation at the joint without breaking its bond with the slab. The viscoelastic membrane layer acts similar to a SAMI by allowing relative movement between the top and bottom geotextile and between the overlay and the existing pavement. The high modulus geotextile, which forms the upper layer of ISAC, provides reinforcement to the overlay. The ISAC system has been evaluated in the laboratory. The laboratory setup consisted of an HMA overlay placed on top of a jointed PCC slab. A hydraulic actuator was used to simulate thermal loading by opening and closing the joint in the slab. The performance of the ISAC system was compared to an unreinforced overlay and to two interlayer products. Testing was conducted in an environmental chamber set at a temperature of $-1.1^{o}C$. Field performance of the ISAC system was also evaluated in six pavement sections.

Laboratory results indicated that the control section and the overlays reinforced with two typical interlayer products failed after less than 10 cycles of joint movement of 0.07 in. In contrast, the overlay incorporating the ISAC system only cracked at a joint movement of 0.2 in. and did not exhibit any cracking at smaller joint movements with cycles. Field performance of the ISAC system indicates that it is effective in retarding reflective cracking. In one test site (IL 38), while the control sections showed 16 and 18 full-width reflective cracks after less than a year, the section reinforced with ISAC only showed five reflective cracks after six years in service. At another location, while the control section experienced 45 to 50 reflective cracks per kilometer, the ISAC section only indicated three reflective cracks.

Vespa (2005) evaluated the performance of ISAC against reflective cracking in five projects constructed between 1997 and 2000 *[106]*. No pre-overlay distress survey was conducted in the first project (JRCP, ADTT 850, no milling); however, no significant amount of cracks formation was noticed. The use of ISAC delayed reflective cracking for a period of one to two years in the second project (JPCP, ADTT 500, no milling). In the third project (JPCP, ADTT 650, milled); the ISAC section was compared to an adjacent section constructed with a Sand Anti-Fracture (SAF) layer. The ISAC section was found effective in delaying reflective cracking compared to SAF section. Reflective cracking was also delayed in the fourth project (JRCP, ADTT 7600, milled) for two years compared to the untreated section despite heavy traffic volume. In the fifth project (JPCP, ADTT 200, no milling), ISAC was able to delay reflective cracking by two to three years. Overall, pavement performance against reflective cracking was improved by the use of ISAC compared to the untreated pavements. However, the present cost of ISAC strips of $10 to $14 per foot limits its cost effectiveness especially that it only delayed reflective cracking by two to three years.

Al-eis (2004) reported on the construction of an experimental section incorporating the ISAC system *[107]*. The experimental plan was to mill 2 in from the existing pavement and replace it with a 2 in HMA Overlay. The transverse joints were cleaned and sealed after milling. The ISAC system was placed in strip application over the joints before applying the HMA Overlay. After compacting the overlay, bumps were observed along the transverse edge of the ISAC fabric. Due to the occurrence of these bumps, the overlay along with the ISAC system was removed and then a new overlay was reapplied without the ISAC membrane. According to the manufacturer, the appearance of the bumps was the result of the old age (almost three years) of the ISAC material, which caused it to wrinkle. The in-situ evaluation was not possible due to the removal of ISAC system.

SPECIAL PURPOSE ASPHALT MIXTURES

While special purposes asphalt mixtures such as Stone Matrix Asphalt (SMA), HMA with crumb rubber, and Open-Graded Friction Course (OGFC) have not been developed to resist reflective cracking, their use may be beneficial in HMA overlay. A study by the National Center of Asphalt Technology (NCAT) has evaluated the use of this mixture on overlays on top of distressed rigid pavements *[108]*. The use of SMA appeared to reduce reflection cracking, and even when reflective cracks appeared, these few cracks remained tight and were not raveling. This was attributed to the high asphalt content and to the use of polymers, which allow SMA to remain intact adjacent to the cracks.

Brown et al. (1991) evaluated use of crumb rubber HMA to reduce rutting and reflective cracking in Georgia *[109]*. The crumb rubber mix was produced by mixing ground tire rubber and asphalt binder using the wet process. A test section was established containing 6% of crumb rubber by weight of binder. The section was evaluated for a service period of 4 years. It was observed from the field results that the addition of crumb rubber caused the mix to become very brittle over time as revealed from the increase in viscosity and the large frequency of reflective cracking. Due to the increased viscosity and decreased penetration, the test section was more susceptible to reflective cracking compared to other sections with conventional mixes. Overall, results showed that crumb rubber did not reduce reflective cracking and was also expensive to produce and install.

Serfass and Mahe (2000) presented the state of practice in using fiber-modified asphalt in order to reduce reflective cracking *[110]*. Fibers considered in this application include mineral fibers such as glass, artificial rock, and chrysotile, and organic fibers such as cellulose. According to the authors, fibers can be used to reduce reflective cracking based on two approaches. In the first approach, the use of fibers increases the shear resistance of the overlay and results in higher binder content due to the absorption of asphalt by the fibers. In the second approach, fiberized sand asphalt is used as a stress relieving interlayer at the bottom of the overlay. The monitoring of pavement sections built with the second approach has shown that reflective cracking is controlled and remained tight with no spalling. The use of high asphalt cement also allowed the mix to heal when cracked. Laboratory tests (crack opening and cyclic bending) were performed on two-course overlays with sand-asphalt interlayer and thick asphalt concrete. The fiber-reinforced mixes were observed to provide better resistance against reflective cracking compared to the reference specimens. Laboratory testing also showed that a fiber-modified asphalt specimen of thickness 1.2 in is more effective than a conventional 2.4 in thick asphalt cement layer.

Harvey et al. (2001) evaluated the two approaches used by Caltrans to rehabilitate existing flexible pavements: overlay with dense-graded asphalt concrete and overlay with asphalt rubber gap-graded mix *[111]*. Accelerated-pavement testing (APT) experiments were conducted using a heavy-vehicle simulator in order to induce rutting and cracking damage in the overlays. From the rutting study, it was determined that dense-graded and asphalt-rubber mix performed similarly. From the cracking study, all four test sections failed by reflective cracking. However, both overlay strategies exceeded the expected performance of 1.0 million ESALs. Results presented in Figure 37 show that the half thickness overlays (ARHM) performed similarly to the full thickness dense-grade overlay (DGAC). However, the authors cautioned that this performance many not entirely represent field conditions due to the minimal construction variability in the APT experiment.

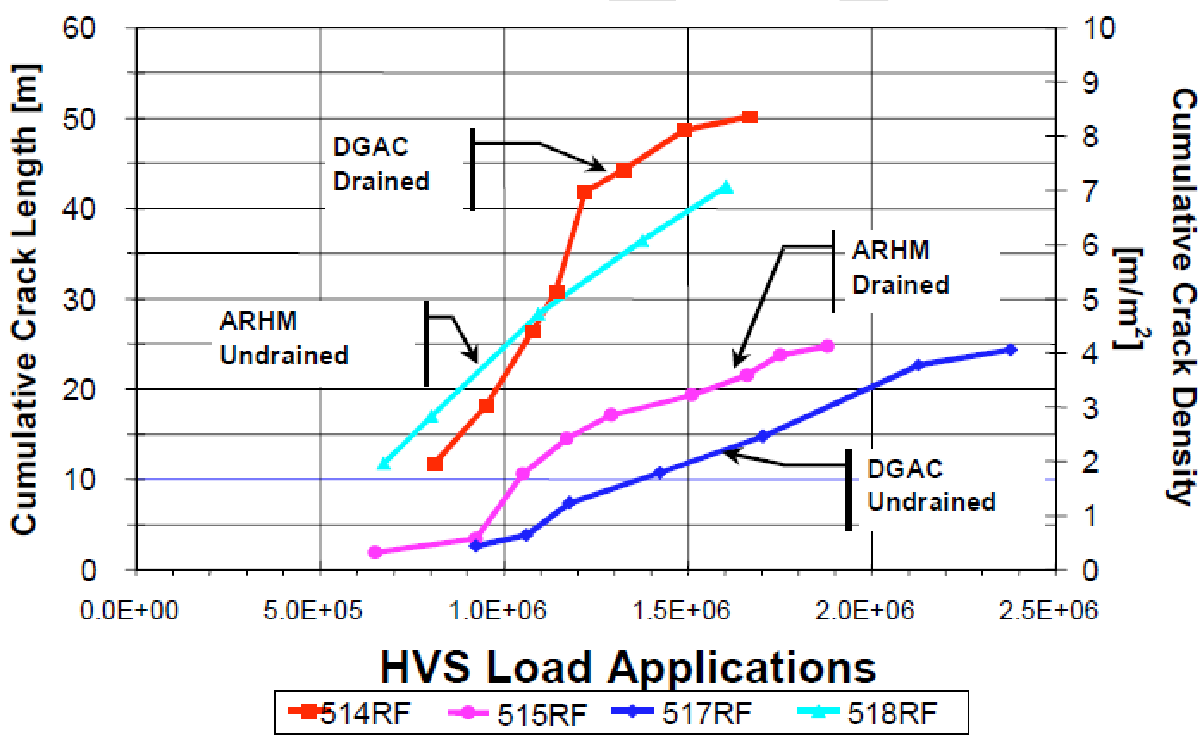


Figure 37
Crack Length Accumulation *[111]*

Jung et al. (2002) conducted a life-cycle cost analysis of conventional and asphalt rubber pavements using the Highway Design and Maintenance Standard Model (HDM-4) and the MicroBENCOST computer programs *[112]*. In the analysis, 11 years of field performance data, including IRI and PCR, were available from ADOT. Further, a 25-year analysis period was selected to reflect long-term cost effects including multiple rehabilitation stages. The conventional pavement consisted of 11 in asphalt concrete, 6 in of bituminous treated base, and 4 in of aggregate base. The asphalt rubber modified pavement consisted of 0.5in asphalt rubber open graded friction course, 2 in of asphalt-rubber gap graded mix, 3 in of conventional asphalt concrete, and 8 in of aggregate base. A 4-mile long pavement section was selected and the comparison was performed under similar conditions. The ADT noted on the pavement was approximately 20,000 with 4% annual growth rate and 20% trucks. Agency costs (cost of initial construction, rehabilitation, and maintenance) and user costs (travel time delay cost, vehicle operating cost, and accident costs) were taken into account in the analysis. The pavements with modified asphalt rubber were found to be cost effective for the two projects analyzed in the study with respect to both agency and user costs. Further, the use of asphalt rubber mix would increase the service life of pavement, which will reduce the life cycle cost. The initial and maintenance cost comparisons for the conventional and modified pavements are presented in Figure 38.

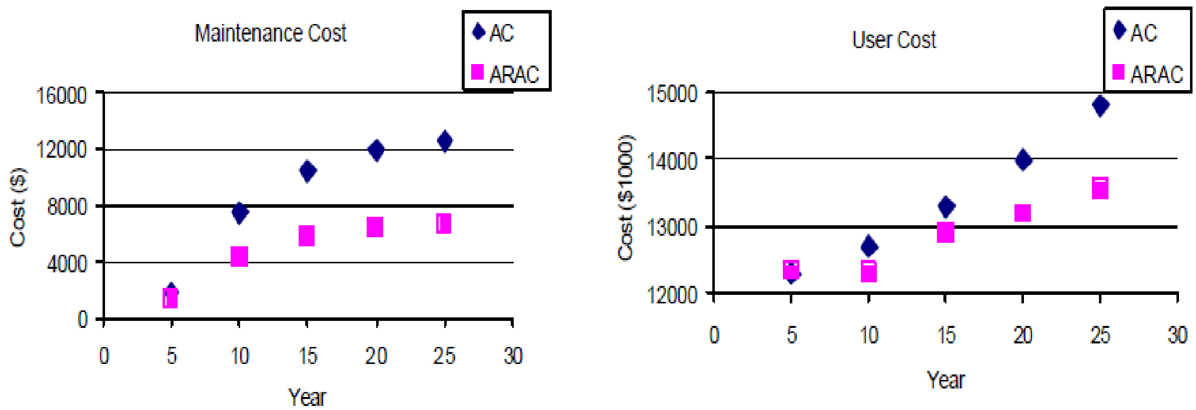


Figure 38
Maintenance and User Cost Comparison *[112]*

CHIP SEAL

A study was conducted to evaluate the use of nonwoven paving fabrics under chip seal in 33 field projects located in seven temperature zones in the US *[113]*. The crack control treatment strategy consists of placing a paving fabric on an existing pavement, which should be structurally sound, followed by a single or double chip seal application, Figure 39. Based on past experiences, the proposed treatment method shall not be used on vertical grades greater than 10%, the last 100 feet approaching intersections, roads with ADT greater than 10,000, roads with severe freeze-thaw cycles, and roads with poor drainage conditions. A life-cycle cost analysis conducted by the county of San Diego found that chip seal over paving fabric eliminated reflective cracks and crack sealing and had an annual cost of one half that of chip seal with crack sealing. In warm climate areas like Texas and California, incorporation of fabric improved the life of chip seal by 50 to 75%. In Michigan, the test section with paving fabric and chip seal performed well compared to the control section. The authors recommended the fabric binder application rate to vary depending on the climatic conditions. For cold and hot climates, binder application rates should range between 0.30 and 0.35 gal/yd^2 and between 0.25 and 0.30 gal/yd^2, respectively.

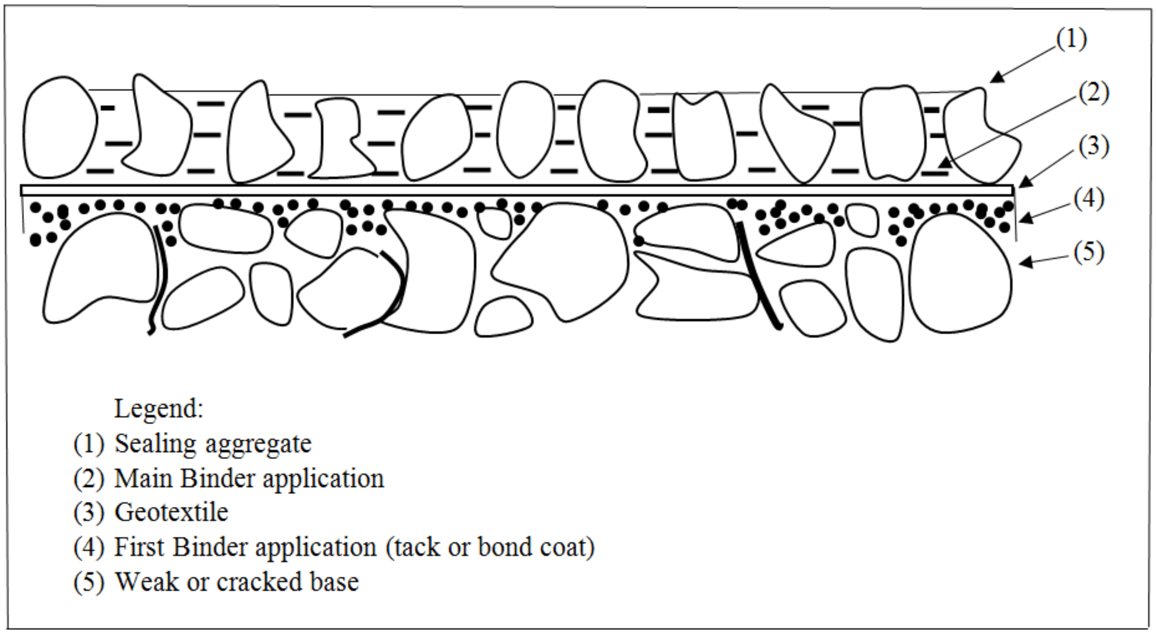


Figure 39
Paving Fabric Placed under Single Chip Seal *[113]*

STRATA® REFLECTIVE CRACKING RELIEF SYSTEM

The Strata® Reflective Crack Relief System consists of a polymer-rich dense fine aggregate mixture layer that is placed on top of the deteriorated pavement and is then overlaid with HMA *[114]*. As indicated by the manufacturer and owner of this technology (SemMaterials), the use of the Strata® system delays the appearance of reflective cracking for two years and extends the overlay service life against reflective cracking by five years. The manufacturer recommends using this system on structurally-sound concrete pavement in which any severe distresses should be repaired prior to application. Since its first application in 2001, at least 28 states have tested the Strata® system with mixed performance. The mechanism of delaying reflective crack by using Strata® is illustrated in Figure 40.

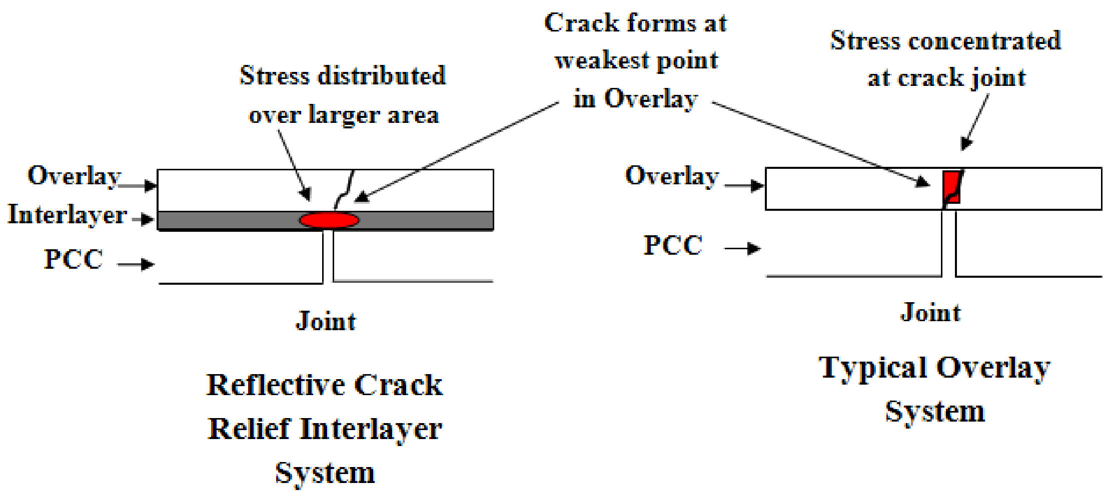


Figure 40
Mechanism of Strata® in mitigating reflective cracking 115*]*

Bischoff described the evaluation of the Strata® system in Wisconsin *[114]*. Two separate concrete pavement rehabilitation projects on I-94 were selected. In the first project, a 10-in. jointed reinforced concrete pavement (JRCP) subjected to an average daily traffic (ADT) of 128,000 was overlaid with a 1-in. Strata® interlayer followed by two 2-in HMA layers. A control section built without the Strata® interlayer was constructed with a 1-in. Superpave layer followed by two 2-in. HMA layers. In the second project, a 9-in. JRCP subjected to an ADT of 39,300 was overlaid with a 1-in Strata® interlayer followed by a 2.0-in. SMA overlay. The control section as well as the rest of the project consisted of a 2.5-in. Superpave layer followed by a 2-in. SMA overlay. The Strata® mixture was produced and installed using standard paving equipment. Performance evaluation included annual measurement of reflective cracking for four years and ride measurements using the International Roughness Index (IRI).

Results of this study showed that the construction of the Strata® system was effective with no problems encountered during installation. In the first project, the Strata® system was able to delay reflective cracking for two years, see Table 13. After the first two years, one Strata® test section performed similarly to the control section while another Strata® section performed the best with only 6% reflective cracking after four years, see Table 13. Most of the reflective cracks were found on top of the joints. In the second project, one of the control sections performed the best overall. Extracted cores did not validate that the Strata® system protected underlying materials from moisture infiltration. Based on these findings, this study recommended not using the Strata® system in Wisconsin.

Table 13
Percentage of Reflective Cracking in Driving Lane, Racine Country Project *[114]*

Sections	2002 (1-year)	2003 (2-Year)	2004 (3-Year)	2005 (4-Year)
Test Section 1	0 %	5 %	16 %	21 %
Control 1	0 %	11 %	15 %	19 %
Test Section 2	0 %	1 %	6 %	6 %
Control 2	0 %	13 %	19 %	20 %

COLLECTIVE EVALUATION OF TREATMENT METHODS

Elseifi and Bandaru (2011) investigated the performance and cost-effectiveness of crack control treatment methods used in Louisiana to delay reflective cracking *[5]*. In this study, pavement sections built with crack control treatment methods in Louisiana were identified. Projects with sufficient years in service and with available untreated segments were selected for detailed performance and economic evaluation. In total, the performance of 50 different sites that were constructed with various treatments was evaluated for a period ranging from 4 to 18 years. Results of this analysis assessed the benefits of crack control techniques in terms of performance, economic worthiness, constructability, and long-term benefits. Among various treatments that were analyzed, saw and seal and chip seal as a crack relief interlayer showed the most promising results in terms of performance and economic worthiness. The cost effectiveness of fiber-glass grid was not validated as compared to regular overlays. Stress absorbing membrane interlayers and high strain asphalt crack relief interlayers (Strata®) showed mixed results in terms of performance. In addition, there were an insufficient number of projects for paving fabrics to allow for drawing conclusions on the cost-effectiveness of this treatment method.

Chen et al. (2006) studied the performance of different rehabilitation techniques to mitigate reflective cracking in JPCP *[116]*. The treatments that were analyzed include crack retarding grid, Strata, Petromat fabric, crumb rubber asphalt mix, flexible base, and Arkansas mix (open graded AC interlayer). In the first field project, Petromat and Strata were evaluated. In this project, the Strata and Petromat were placed in two sections followed by a 2.0 in overlay with a PG 76-22 binder. The cost of Strata was about 10 to 20 times higher than the cost of the Petromat fabric. After two years in service, about 10% reflective cracks were observed in the section with Petromat while only about 3% of the cracks were observed in the Strata section. However, the authors expressed concerns about its skid resistance in wet conditions. In the second field project, a crack retarding grid was placed in strip application over the transverse joints followed by a 2-in overlay. The section with the crack retarding grid did not perform well and was removed after one year while the control section is performing well. The failure of the grid was attributed to debonding during construction. In the third field project, seven different treatment methods were evaluated: (1) full-depth repair, (2) break and seat, (3) crushed stone base interlayer, (4) open-graded AC interlayer (Arkansas mix), (5) SBS modified interlayer, (6) dense-graded overlay, and (7) thin dense graded overlay. Results showed that full-depth repair was the most expensive method and was not successful in controlling reflective cracking with 100% of the joints reflecting. The break and seat was also not successful and the section with the SBS modified interlayer failed and was replaced possibly due to problems with the surface layer. On the other hand, the dense-graded overlay performed relatively well with 35% of the joints reflecting. Overall, the authors concluded that the best performing section was the section with the crushed stone base interlayer and the section with the Arkansas mix. In the fourth project, a crack retarding grid was compared to crumb rubber asphalt mix. In this project, both sections with the crack retarding grid and control were overlaid after nine years while the crumb rubber section was not overlaid as it only showed minimal reflective cracking. In summary, the authors recommended to use a crushed stone interlayer for sections with poor slab support.

Ellis and Langdale (2002) evaluated the performance of various anti-reflective treatment techniques in military airfields in the UK *[116]*. Evaluated treatment methods included reinforcing fiber-glass grid and steel grid, SAMIs, overlays with polymer-modified binder, multiple lifts overlay with a flexible mix, crack and seat, and asphalt inlay over concrete joints. Field evaluation showed that crack and seat performed well with no reflective cracking after six years. Further, the steel grid failed after six months and is no longer used as an anti-reflection cracking treatment. Results also showed that a SAMI reduced reflective cracking by about 80% after nine years in service. The use of polyester grid and fiberglass grid installed on an asphalt leveling layer and not directly on a milled surface reduced the reflective cracking for a service period of 7 years.

Loria et al. (2008) conducted a study to determine the long-term performance of reflection cracking mitigating techniques for existing asphalt pavements in Nevada *[118]*. Distress data analysis and Principal Component Analysis (PCA) was performed to analyze the performance of 33 field projects. The evaluated treatment methods included cold-in-place recycling (CIR), reinforced fabrics, stress relief courses, and mill and overlay. CIR projects with low traffic did not experience any distresses; further, the CIR project with high traffic performed well after six years in service. For the projects with fabrics, three of the six projects performed well; however, two projects with high traffic performed poorly. The projects with stress relief asphalt layer showed excellent performance for a period of three years for different traffic volumes; however, reflective cracking was observed to appear considerably after a period of five years. Mill and overlay treatment was effective in preventing the reflective cracking for a period of three years for the pavements with less distresses and traffic volume. However, the performance was poor on the project with the highest traffic volume. Overall, the study showed that CIR and mill and overlay were the most effective except when severe alligator cracking is present.

Von Quintus et al. (2010) evaluated the field performance of various reflective crack control techniques in airport pavements *[119]*. The techniques were rated on the basis of information and data from previous studies, field evaluation of airport pavements, and frequent site surveys. Probability of success and risk values were multiplied to rate the performance of different crack control treatment techniques. Data collected in the literature and frequent site visits were used to determine the success rate or the probability of success for a treatment method. The risk factors indicate the uncertainty of the techniques resulting from the limited use in the field and the limited availability of performance results in the database. Based on the findings from literature review site visits on various airports and highway projects, the authors concluded that no pavement rehabilitation method has been effective in preventing reflective cracking with the exception of rubblization. Specifically, the following findings were presented:

- Rubblization of PCC pavements and full depth reclamation of flexible pavements are comparatively effective techniques in mitigating reflective cracking.

- Fabrics perform better when placed over an old HMA pavement with closely spaced (width less than 1/8 inch) random or alligator cracking and are less effective when placed over existing PCC pavements or HMA pavements with wider thermal cracks.

- SAMI is effective in reducing the reflective cracking when used over old pavements with smaller crack spacing and widths. Steel reinforcement and geogrids also perform well when placed over old HMA pavements but are less effective for jointed concrete pavements.

- Saw and seal method is an effective treatment technique to arrest reflective cracking in HMA overlay placed over concrete pavements and several highway agencies has preferred it over other rehabilitation techniques. However, the agencies should be cautious for applying saw and seal on high speed facilities as problems may arise due to ‘tenting’ of the sealant.

Al-Qadi et al. (2009) evaluated the cost-effectiveness of five types of interlayer systems (area and strip type non-woven fabric, self-adhesive membrane interlayer system, conventional stress absorbing membrane interlayer (SAMI), ISAC strip treatment, and a sand-sized aggregate gradation with high polymer modified binder) *[120]*. The Performance Benefit Ratio (PBR) parameter was introduced to assess the performance of treated pavements in comparison to untreated pavements. Based on the PBR analysis, the SAMI outperformed other treatment methods followed by ISAC. Life Cycle Cost analysis (LCCA) was performed to assess the engineering value of the interlayer systems. Benefit Cost (B/C) ratio was calculated through LCCA, which was used to evaluate the cost effectiveness of the treatments. The B/C ratio model was found to be effective for estimating the B/C of interlayer systems over a 30-year analysis period using just three variables: performance-benefit ratio (PBR), material cost ratio (MCR), and construction time ratio (CTR). Of the five treatment techniques, three with the positive PBR were evaluated: area-wide non-woven fabric, SAMI, and ISAC. Results showed that the B/C of area-type non-woven fabric ranged from -29.4% to 16.0%; while SAMI and ISAC had B/C ratios of -9.7% to 28.5% and 4.0% to 59.8%, respectively. Strip type non-woven fabric were found to have negative B/C, due to their poor performance against reflective cracking. Among the three interlayer systems, SAMI had the widest application range in terms of ESALs, average temperature, and joint spacing, especially in colder regions in Illinois with lower traffic volume. ISAC was found to be cost effective in warmer regions with higher traffic volume. As joint spacing increased, the application range of SAMI diminished. Area-type non-woven fabric showed a marginal performance benefit, Figure 41.

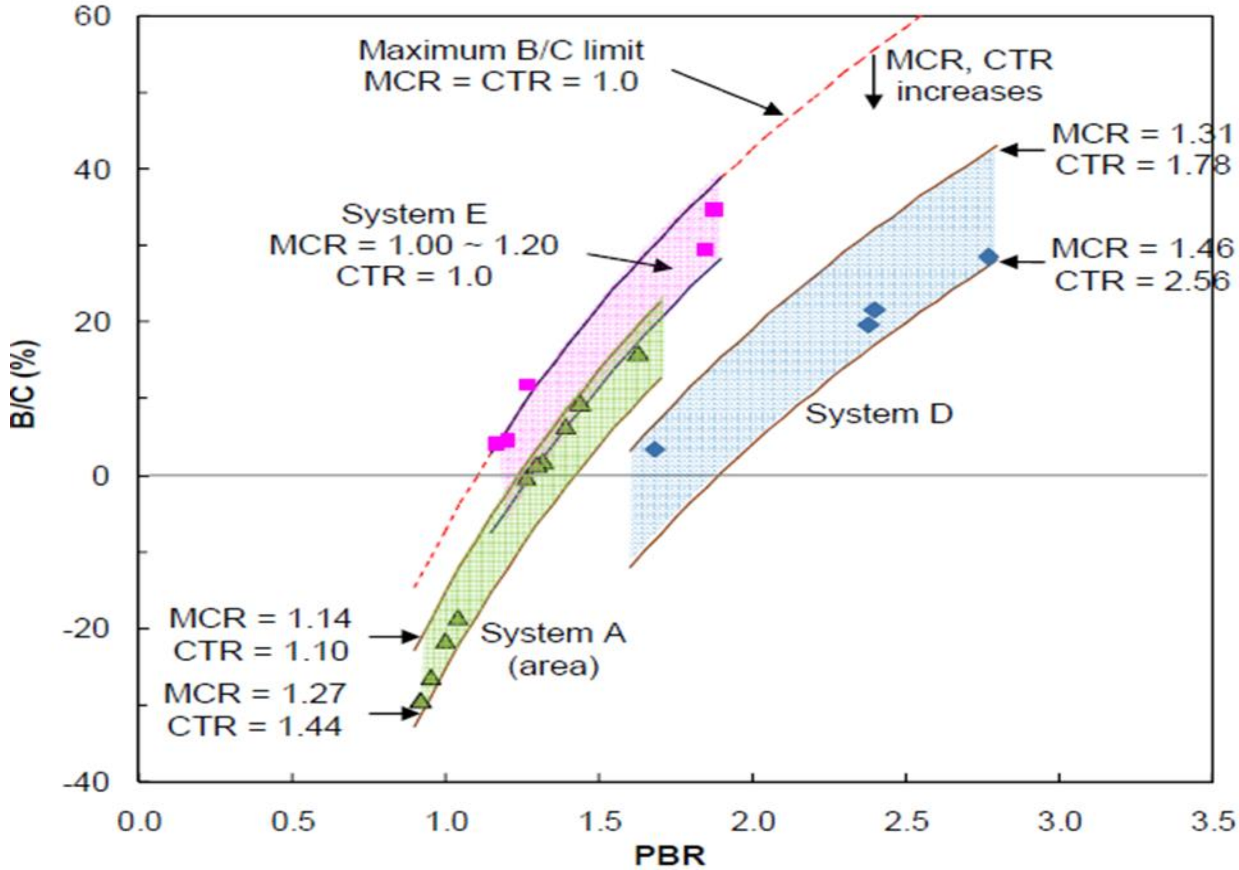


Figure 41
Upper and lower B/C limits for Area-Type Non-Woven Fabric System A, System D (SAMI), and System E (ISAC) at AADT of 5000 *[120]*

The National Center for Asphalt Technology (NCAT) has initiated in 2012 a study to evaluate the performance of pavement preservation treatments on a local asphalt road (Lee Road 159) with a high percentage of trucks *121]*. Evaluated treatments were placed in 100-ft test sections and included fog seals, crack seals, chip seals, cape seals, plant mix overlays, ultra-thin bonded wearing course, and lightweight aggregates. Field performance showed that crack sealing stopped the development of interconnected cracks observed in the control section. Further, the moisture content in the sealed section had been consistently lower than in the control section.

CHAPTER VI

DISCUSSION OF RESULTS

Starting from the early 1960s, different crack control treatment methods have been evaluated to control reflective cracking including metallic grids, different types of geosynthetics, asphalt-based interlayers, and fractured-slab approaches. Fractured slab approaches include crack and seat, break and seat, and rubblization. While the performance of a number of treatment methods has been mixed, others have predominantly shown benefits. Based on the results of the comprehensive literature review as well of the survey questionnaire, the research team has identified a number of treatment methods that should be considered by the Southeastern Transportation Consortium for further evaluation. To assess the performance and cost-effectiveness of these methods, a number of field projects shall be selected to construct and compare these approaches prior to full implementation as part of a systematic crack control policy. The recommended treatment methods are as follows:

- **For existing HMA pavements, one of the following treatment methods may be selected:**
    - Crack sealing and overlay (pros: low cost and suitable for cracked asphalt pavements; cons: reflective cracking may still appear)
    - Chip seal and open-graded interlayers (pros: low cost and adequate control of reflective cracking)
    - Full-depth reclamation (pros: prevent reflective cracking, suitable for heavily cracked pavements, environmentally-friendly; cons: cost)
    - Cold-in place Recycling (pros: prevent reflective cracking; cons: not suitable for heavily cracked pavements with fatigue cracking)
- **For existing PCC pavements, one of the following treatment methods may be selected:**
    - Saw and seal (pros: low cost and well-proven performance)
    - Chip seal and open-graded interlayer system (pros: low cost and adequate control of reflective cracking, can be used with weak subgrade)

- Rubblization (pros: eliminates slab action, high probability of success; cons: only suitable in projects with suitable subgrade/base support, cost, thick overlay, may require shoulder work and/or guardrail adjustment)

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The objective of this study was to evaluate and compare different reflective cracking control treatments by evaluating the performance, constructability, and cost-effectiveness of pavements built with these treatments across the state. Results of this analysis assessed the benefits of crack control techniques in terms of performance, economic worthiness, constructability, and long-term benefits. Based on the results of the literature review and the survey questionnaire, a summarized assessment is presented for each of the treatment method:

- Paving fabric: results have been mixed; reported beneficial for cracked asphalt pavements in combination with a single or a double application of chip seal.

- Fiber-Glass grid: results have been mixed. Further, the cost-effectiveness is uncertain as compared to other treatment methods.

- Rubblization: the majority of the studies reported acceptable performance. However, rubblization was not recommended in pavements with poor subgrade and base support. Further, the performance of rubblization with CRCP is debatable. It is also important to note that rubblization requires a thick overlay, which would also require guardrail adjustments and/or shoulder work.

- Crack and seat: results have been mixed and its use with JRCP is not recommended.

- NovaChip: results have been mostly positive for rehabilitation of existing asphalt pavements. While the literature available for this treatment method is limited, a number of states have reported positive experience.

- Saw and seal: the most favored method for rehabilitation of PCC pavements; however, its use for rehabilitation of existing asphalt pavements is not recommended.

- Steel mesh: results have been limited in the US and construction issues have been reported.

- SAMI: results have been mostly positive; however, recent studies raise concerns on rutting acceleration due to the interlayer.
- Composite System (ISAC): results have been mixed and cost effectiveness is questionable.
- Chip Seal Interlayer: the majority of the studies reported acceptable performance. Its use with paving fabric was positive in the majority of the studies but it appears to be suited for low to medium traffic roads.
- Rubberized asphalt mixes: results have been overwhelmingly positive in Arizona; however, other states did not report similar success against reflective cracking. It is possible that the hot dry climate in Arizona may explain this inconsistency.
- Cold-in-place recycling: results have been overwhelmingly positive in numerous states for the rehabilitation of asphalt pavements.
- Strata: results have been mixed and cost effectiveness is uncertain.

RECOMMENDATIONS

Based on the results of this study, the research team recommends that a follow-up study be conducted in order to evaluate the cost-effectiveness of the most promising treatment methods and to develop guidelines for the control of reflective cracking. It is envisioned that an easy to use computer program would be developed to allow the designer to enter information for a given project and with the output providing the recommended crack control treatment method along with cost saving estimates based on project conditions. To this end, the following four research tasks are recommended.

Task 1: Identify Field Sections

The objective of this task is to identify field projects in the states that are part of the STC and in which crack control treatment methods have been installed. It is recommended that identified sections include existing PCC and asphalt pavements; further, JPCP, JRCP, and CRCP should be included if possible. Test sections shall have been in service for at least five years and should include control sections in each field project. If not control section is available, a nearby section will be considered as the control section in the analysis. The research team recommends considering the following treatment strategies: crack sealing and overlay, chip seal interlayer, NovaChip, open-graded interlayer, full-depth reclamation, cold-in place recycling, saw and seal, chip seal and open-graded interlayer system, and rubblization.

Task 2: Document Construction and Cost

The objective of this task is to search state databases and construction documents in order to estimate the costs of each crack control treatment method; this data will be used in the benefit/cost analysis and to assess the cost effectiveness of each treatment method. Data will be categorized based on local conditions for each state in the consortium.

Task 3: Predict Long-Term Performance of Field Projects

The objective of this task is to collect performance data from state databases in order to predict the long-term field performance of the evaluated sections against reflective cracking as well as against other failure mechanisms (i.e., rutting, fatigue cracking, etc.). To assist in the evaluation, IRI, cracking, and rutting data will be collected from state databases. The research team will then use the collected performance data to predict the service life of each treatment method. Maintenance and repair activities shall also be documented to assist in the evaluation.

Task 4: Cost-Effectiveness of Treatment Methods and Development of Crack Control Guidelines

The objective of this task is to assess the performance and cost-effectiveness of crack control treatment methods used to delay/prevent reflective cracking. Based on these results, recommended guidelines will be developed for adoption in the STC states. The developed crack control guidelines will present recommended treatment methods for different classes of rehabilitated pavements in order to achieve adequate control of reflective cracking in a cost effective manner. Results will be incorporated in a simple prediction computer tool that can be used by the designer to determine the recommended treatment method for a given project and to estimate cost savings if the recommended treatment method is used.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ARAN	Automatic Road Analyzer
AST	Asphaltic Surface Treatment
cm	centimeter(s)
CRCP	Continuously Reinforced Concrete Pavement
CRM	Crumb-rubber modified
ESAL	Equivalent Single Axle Load
FE	Finite Element
FHWA	Federal Highway Administration
ft.	foot (feet)
FWD	Falling Weight Deflectometer
GPR	Ground Penetrating Radar
HMA	Hot Mix Asphalt
HPMS	Highway Performance Monitoring System
IRF	International Road Federation
IRI	International Roughness Index
in.	inch(es)
ISAC	Interlayer Stress Absorbing Composite
JRCP	Joint Reinforced Concrete Pavement
ksi	Kilo pounds per square inch
LADOTD	Louisiana Department of Transportation and Development
lb.	pound(s)
LTPP	Long Term Pavement Performance
LTRC	Louisiana Transportation Research Center
m	meter(s)
NCAT	National Center for Asphalt Technology
NHS	National Highway of Significance
NMAS	Nominal Maximum Aggregate Size
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PMS	Pavement Management System
psi	Pounds per square inch

PVC	Poly Vinyl Chloride
RC	Number of Cracks Reflected
RCI	Reflective Cracking Index
RDD	Rolling Dynamic Deflectometer
RHS	Rural Highway of Significance
SAMI	Stress Absorbing Membrane Interlayer
SBS	Styrene Butadiene Styrene
SHS	State Highway of Significance
SMA	Stone Matrix Asphalt
STC	Southern Transportation Consortium
TAC	Total Annual Cost
TOPS	Tracking of Projects System
USDOT	United States Department of Transportation

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APPENDIX A

List of respondents to the survey questionnaire

Arkansas
Colorado
District of Columbia
Florida
Georgia
Illinois
Iowa
Kansas
Kentucky
Louisiana
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri
Montana
Nevada
New Mexico
North Carolina
Ohio
Oregon
QUBEC DOT
Saskatchewan Ministry of Highway and Transportation
South Carolina
South Dakota
Texas
Washington

	Regular Actions against Reflective Cracking	
	Yes	No
Arkansas	X	
Colorado	X	
D.C.	X	
Florida	X	
Georgia	X	
Illinois	X	
Iowa		X
Kansas	X	
Kentucky		X
Louisiana	X	
Maryland	X	
Massachusetts	X	
Michigan	X	
Minnesota		X
Mississippi		X
Missouri		X
Montana		X
Nevada	X	
New Mexico		X
North Carolina	X	
Ohio	X	
Oregon	X	
QUBEC DOT	X	
Saskatchewan Ministry of Highway and Transportation	X	
South Carolina		X
South Dakota	X	
Texas	X	
Washington	X	

	Regularly Used Reflection Cracking Treatments											
	Paving Fabric (Strip)	Paving Fabric (Area)	Geogrid	Glassgrid	Chip Seal	Saw and Seal	SAMI	Strata	Novachip	Crack Sealing	Rubbilization	Others
Arkansas										X	X	
Colorado	X			X	X			X			X	X
D.C.						X						X$^{\$}$
Florida												X$^{\alpha}$
Georgia	X				X	X				X		X$^{\infty}$
Illinois	X	X					X		X		X	
Iowa												X$^{@}$
Kansas						X		X		X		
Kentucky						X		X			X	
Louisiana			X	X	X	X	X	X	X	X	X	
Maryland												X
Massachusetts	X			X	X	X	X	X	X	X	X	
Michigan										X	X	X$^{\delta}$
Minnesota												
Mississippi						X				X		
Missouri									X			X
Montana										X		X$^{\#}$
Nevada				X	X		X			X		X$^{\#}$
New Mexico										X		
North Carolina					X				X			
Ohio	X			X							X	X
Oregon										X		X$^{\beta}$
QUBEC DOT										X		X$^{\#}$
Saskatchewan Ministry of Highway and										X		

Transportation													
South Carolina													
South Dakota													X[^]
Texas			X	X	X			X	X				X[&]
Washington										X			X[%]

@ 1-inch layer similar to strata
\# Cold in place recycling
$ Clean and fill joints with sealant
% Cracking, Seating and Overlaying
^ Quantity of fine mix to tight blade into the surface prior to overlay
& Rubber seals
δ Crack relief layer with multiple course overlay
∞ Open graded interlayer and fiber reinforced HMA
β Mill 2 inches off surface, place 6” of HMAC and use thin layer of rich binder polymer mix approximately 5in. deep.
α ARMI or open graded crack relief layer.

	Regular Evaluation of Reflection Cracking Treatments												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Arkansas	X	X	X	X	X					X	X		X
Colorado		X		X						X			X
D.C.								X					
Florida	X	X	X	X								X	X
Georgia		X					X	X			X	X	
Illinois	X	X			X				X	X	X		X
Iowa		X							X	X		X	X
Kansas								X		X	X		
Kentucky	X		X	X		X		X	X	X			X
Louisiana			X	X			X	X		X	X	X	X

Maryland	X	X	X	X		X			X				
Massachusetts	X			X			X	X	X	X	X	X	X
Michigan	X	X								X	X	X	X
Minnesota							X	X			X	X	
Mississippi		X						X				X	
Missouri	X	X		X				X		X			X
Montana												X	
Nevada	X	X						X	X				
New Mexico							X					X	
North Carolina	X	X		X			X			X			
Ohio	X			X			X	X	X		X		X
Oregon	X			X								X	
QUBEC DOT					X				X			X	X
Saskatchewan Ministry of Highway and Transportation				X				X				X	
South Carolina													
South Dakota													
Texas				X									
Washington	X											X	

1 Paving Fabrics (Strip)
2 Paving Fabrics (Strip Area)
3 Geogrid
4 Glass-Grid
5 Geocomposite
6 Steel Mesh
7 Chip Seal Interlayer
8 Saw and Seal
9 SAMI
10 Strata
11 Novachip
12 Crack Sealing and Overlay
13 Rubbilization

	Overlay Performance against Reflective Cracking			
	Improved	Worsen	Same	Unsure
Arkansas	9,10,13	3	1,2,4,8	
Colorado	13		2	4,10
D.C.	8			
Florida	12,13			1,2,3,4
Georgia	1,7,8,11,12			2
Illinois		2	1,9,10,11,13	5
Iowa	13		10,11	
Kansas	8,10,12		9,10	1
Kentucky	3,4,6,8,13			9
Louisiana	4,7,8,10			
Maryland			2,3,4,6,9	1
Massachusetts	7,8,9,10,11,12,13		1,4	
Michigan				1,2,9,10,11,12,13
Minnesota	7,10,11		2	
Mississippi				1,8,12
Missouri	1,2,4,10,13		9	4
Montana	12,13			
Nevada	4,9		7,8	1,2
New Mexico	7,12			
North Carolina	7,11	2	1	3,4
Ohio	8,13			1,4,7,9
Oregon	1,4,12			
QUBEC DOT	13		5,12	
Saskatchewan Ministry of Highway and Transportation	8		4,12	
South Carolina				

South Dakota				
Texas	4			
Washington			12	1

1	Paving Fabrics (Strip)	8	Saw and Seal
2	Paving Fabrics (Strip Area)	9	SAMI
3	Geogrid	10	Strata
4	Glass-Grid	11	Novachip
5	Geocomposite	12	Crack Sealing and Overlay
6	Steel Mesh	13	Rubbilization
7	Chip Seal Interlayer		

	Overlay Performance against Reflective Cracking			
	Improved	Worsen	Same	Unsure
Arkansas			1,2	
Colorado	1,4,5			
D.C.				5,6
Florida				
Georgia	1,3	6	2,5	
Illinois				1,2,3,4,5,6
Iowa	4		5,6	
Kansas	4		5,6	1,2,3
Kentucky	1		2,3,5	
Louisiana	1,3			2,4,5,6
Maryland	1			
Massachusetts	2,4	6	3,5	1
Michigan				1,2,3,4,5,6
Minnesota	1,4	6		
Mississippi				
Missouri				
Montana	1	4,6	5	

Nevada	4		2,3	1,5,6
New Mexico			1,3,6	5
North Carolina	3			5,6
Ohio			1,5	4,6
Oregon				1,2,3,4,5,6
QUBEC DOT	6		1,2,3,4,5	
Saskatchewan Ministry of Highway and Transportation	2		6	1,3,4,5
South Carolina		3	5	
South Dakota	1,2,4			5,6
Texas	1,2,5	4,6		
Washington	1,4		5	2,6

1 Stone Mastic Asphalt (SMA)
2 Rubberized HMA
3 OGFC
4 Cold in place recycling
5 Warm-mix asphalt
6 High RAP/RAS asphalt mixtures

	Systematic Crack Control Policy against Reflective Cracking		
	Yes	No	Unsure
Arkansas		X	
Colorado		X	
D.C.			X
Florida		X	
Georgia			X
Illinois		X	
Iowa		X	
Kansas		X	
Kentucky		X	

Louisiana		X	X
Maryland	X		
Massachusetts		X	
Michigan		X	
Minnesota		X	
Mississippi		X	
Missouri		X	
Montana	X		
Nevada		X	
New Mexico		X	
North Carolina		X	
Ohio		X	
Oregon		X	
QUBEC DOT		X	
Saskatchewan Ministry of Highway and Transportation		X	
South Carolina		X	
South Dakota		X	
Texas		X	
Washington		X	