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Mitigation strategies for reflection cracking in rehabilitated pavements – A synthesis

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Abstract

The placement of an asphalt overlay on top of an existing pavement is rarely a lasting solution. Due to continuous movement of the existing pavement, existing discontinuities such as cracks and joints propagate through the overlay causing reflection cracking. Reflection cracking is a serious challenge associated with pavement rehabilitation. Practical experience shows that reflection cracking propagates at a rate of 1 in. per year. As the need grows for new rehabilitation methodologies to improve the performance of overlays against reflection cracking, a number of state transportation agencies tasked the authors of this paper to conduct a comprehensive review of treatment methods available to delay or to prevent reflection cracking in rehabilitated pavements and to survey current state of practice in addressing this distress. Based on the results of the literature review and the survey questionnaire, a summarized assessment is presented for each treatment method. Further, a number of treatment methods were identified for further evaluation by the state transportation agencies. For existing HMA pavements, crack sealing and overlay, chip.

Keywords: Reflection cracking; Mitigation strategies; Fractured slab approaches; Saw and seal; SAMI; Chip seal

1. 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; however, overlays may still show cracking patterns similar to the ones, which existed in the old pavement after a short period of time [1–3]. This distress is known as 'reflection cracking.' The discontinuities (cracks or joints) in underlying layers cause reflection cracking, 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 often propagate to the surface within one to five years; as early as few months have 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 on finding new and relatively inexpensive techniques to delay reflection cracking [6]. Different methods, including the use of interlayer systems, have been suggested for enhancing pavement resistance to reflection

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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 reflection cracking can be achieved through two different mechanisms: (1) reinforcing the overlay 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; (2) and dissipating strain energy in the vicinity of cracks through the use of a soft layer [8].

Although it is generally recognized that each 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 treatment methods. Further, an opinion exists among practitioners that even when a technique is successful in delaying reflection cracking, the cost is equivalent to the cost of repairing the cracks [9]. This opinion appears inaccurate when considering the appearance of the reflection cracking a few months after application of the overlay [10]. Contradictory opinions and experiences are also a major problem 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 [11,12].

2. Background

2.1. Mechanism of reflection cracking

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 as shown in Fig. 1 [14]. Thermal movements also contribute to reflection cracking. 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 [15]:

- 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.

It is generally recognized that the reflection of cracks in rehabilitated pavements is a complex process involving a mixed mode of loading identified in the literature as a combination of Mode I and Mode II loading [16]. The overlay life against reflective cracking can be described by the process of crack intrusion in the overlay (crack initiation) and

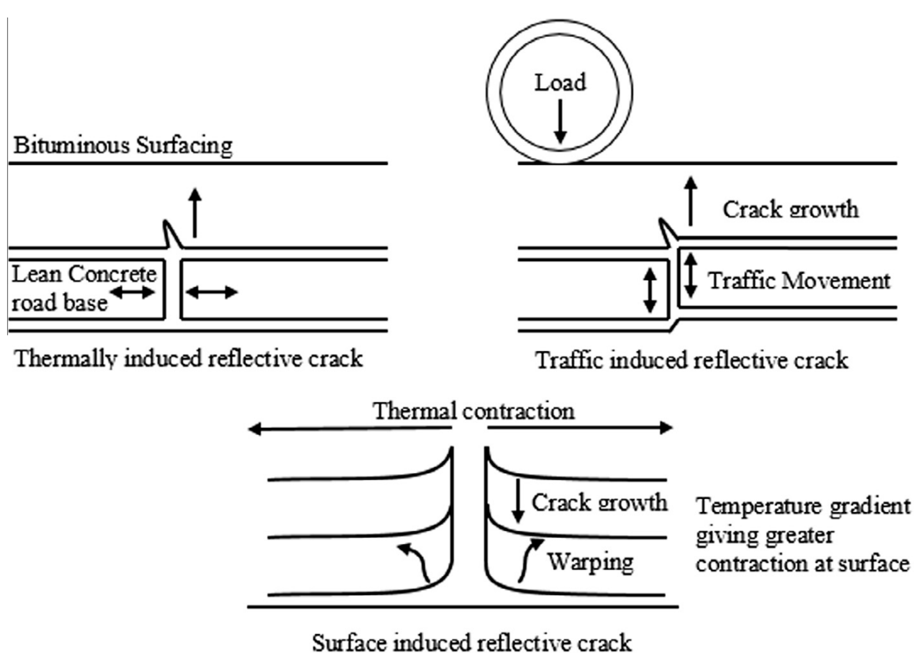
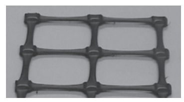
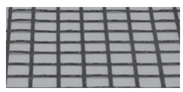
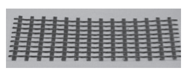
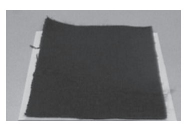
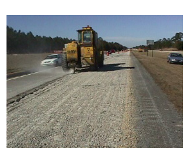
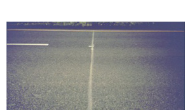


Fig. 1. Mechanisms of reflection cracking. Adapted from Sheng et al. [14].

Table 1
Major types of crack control treatment methods.

Treatment	Picture	Functions	Estimated cost
Galvanized steel netting		Reinforcement	$3.00\text{–}5.00\ \$/\text{yd}^2$
Geogrid		Reinforcement	$1.80\text{–}4.00\ \$/\text{yd}^2$
Geonet		Reinforcement	$3.00\text{–}4.00\ \$/\text{yd}^2$
Glass-grid		Reinforcement	$4.00\text{–}7.00\ \$/\text{yd}^2$
Paving fabric		Stress relief	$0.60\text{–}1.05\ \$/\text{yd}^2$
Geocomposite		Stress relief	$8.00\text{–}9.20\ \$/\text{yd}^2$
SAMI		Stress relief	$3.50\text{–}6.50\ \$/\text{yd}^2$
Fractured slab methods		Eliminates movement in concrete layer	$6.00\text{–}8.50\ \$/\text{yd}^2$
NovaChip		Stress relief	$3.00\text{–}4.00\ \$/\text{yd}^2$
Strata		Stress relief	N/A
Saw and seal		Control reflection cracking by sawing overlay	1.00–2.00 $/ft.

crack propagation (neglecting the ultimate failure stage). For the original position of the crack (crack initiation in the overlay), both the opening and shearing mode control the propagation of the crack in the overlay. However, at about one-third of the overlay depth, Mode I loading becomes less significant and only Mode II loading will propagate the crack to the surface [16].

2.2. Review of treatment methods

Starting from the early 1960s, different treatment methods have been suggested for controlling reflection cracking including metallic grids, different types of geosynthetics, asphalt-based interlayers, and fractured-slab approaches. Table 1 illustrates the major types of treatment methods that have been evaluated to control reflection cracking. The price ranges presented in Table 1 are based on review of bid items and would naturally vary with locations and time. The following sections present an overview of each class of treatment methods. Additional details are available elsewhere [17].

2.2.1. Geosynthetics

"Geosynthetics" consist of synthetic polymeric materials incorporated in soils, pavements, and bridge decks [18]. Geosynthetics are divided into seven major categories: geotextile, also known as paving fabric; geogrid; fiberglass; geocell; geomembrane; geonet; and geocomposite. Geotextile, geogrid, fiberglass, and geocomposite have been tested as reflection cracking control treatments by acting as reinforcement or as a strain energy absorber, also known as stress relieving layer. The effectiveness of these products as crack control treatments has been mixed and was reported to depend on many factors including the installation procedure and conditions of the existing pavement. 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% or greater [19]. Product manufacturers recommend that a minimum overlay thickness of 1.5 in. (38.1 mm) should be used and that if the surface has been milled, a leveling course should be applied prior to installing the interlayer system [20]. Additional details on the use of geosynthetics against reflection cracking have been presented elsewhere [17].

2.2.2. 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 reflection cracking [21]. 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 2–3 passes of 35–50 ton rubber tire roller. In this case, the concrete is broken down into pieces, approximately 18–24 in. (457.2–609.6 mm) in size, 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 [22]. 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 reflection cracking does not occur after construction. While reducing slab size reduces movement and the potential for reflection cracking, it decreases the slab stiffness and its ability to carry heavy loads. California usually recommends a transverse strike every 4– ft. (1.2–1.8 m); however, other states such as North Dakota and Minnesota specify a transverse strike every 3 ft. (0.9 m). A suitable overly thickness ranging from 4 to 6 in. (101.6–152.4 mm) is also needed to prevent reflection cracking. Choubane et al. (2001) recommended the use of an asphalt–rubber membrane interlayer prior to the overlay to reduce reflection cracking [23]. 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 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 reflection cracking and may only delay it for a period from three to 5 years [24].

Rubblization, which is the most promising fracturing slab technique, has been used with all types of concrete pavements. It consists of destroying slab action by transforming the concrete layer into an aggregate base [21]. The size of the broken concrete pieces usually ranges from 2.0 to 6.0 in. (50.8–152.4 mm) and therefore, this process results in a significant loss of concrete strength. A study reported that the resulting rubblized layer has a strength that is 1.5–3 times greater than high quality dense-graded crushed stone base [25]. 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 head breaker. The resonant pavement breaker (RPB) utilizes 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 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 consists of a series of 12–16 and 102–123 lbs. hammers to crush a concrete width ranging from 2.0 to 12.5 ft. (0.6–3.8 m) with a production rate of 0.75–1.0 lane-mile/day.

2.2.3. 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 DOT has significant experience with the use of NovaChip on high traffic Interstates. Through communication with North Carolina DOT, the authors learned that NovaChip® 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.

2.2.4. 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 overlay to create transverse and longitudinal joints at the exact locations of the PCC joints followed by sealing of the constructed joints. Success of the saw and seal method depends on applying the treatment at the exact locations of the joints [26]. 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 using 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. The final step is to seal the joints with a low-modulus rubberized sealant [27]. Most of the grooves are overfilled from bottom up and then followed by squeegeeing to flush the applied sealant with the pavement surface. Sealing the created joints prevents the infiltration of water and incompressible materials from getting into the underlying layers. Sealing the overlay joints properly plays an instrumental role in extending pavement service life as water infiltration and the possible stripping of HMA are the major causes of pavement deterioration [28].

Elseifi et al. (2011) evaluated the performance of saw and seal in the pavements with HMA overlaid on existing Portland cement concrete pavement (PCCP) [29]. 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 1–12 years while 13% showed negative results. 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%. Theoretical investigation conducted using 2-dimensional finite element (FE) analysis indicated that the use of saw and seal method significantly reduced the strains levels at the joints in rigid pavement. This will result in the control of crack initiation at bottom of overlay and propagation with repetition of loads. Saw and seal dissipates the energy due to wheel loading and expansion and contraction of the concrete and allows the movement of the slabs underlying the overlay without formation of the cracks.

Fig. 2. Steel reinforcing mesh.

2.2.5. Steel reinforcing mesh

One of the oldest interlayer systems used in flexible pavement to delay reflection cracking 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 [30]. 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 in Europe. 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

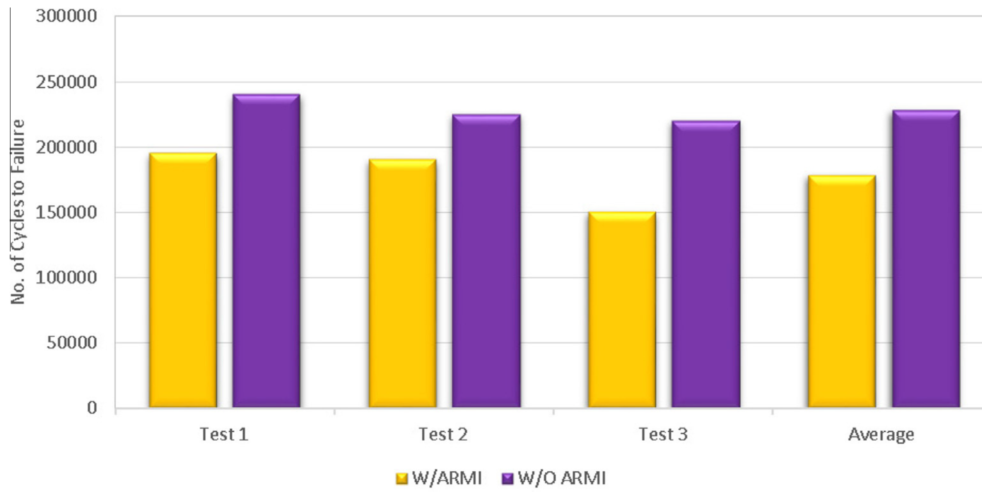


Fig. 3. Number of cycles to failure for pavement sections with and without ARMI. Adapted from Greene et al. [33].

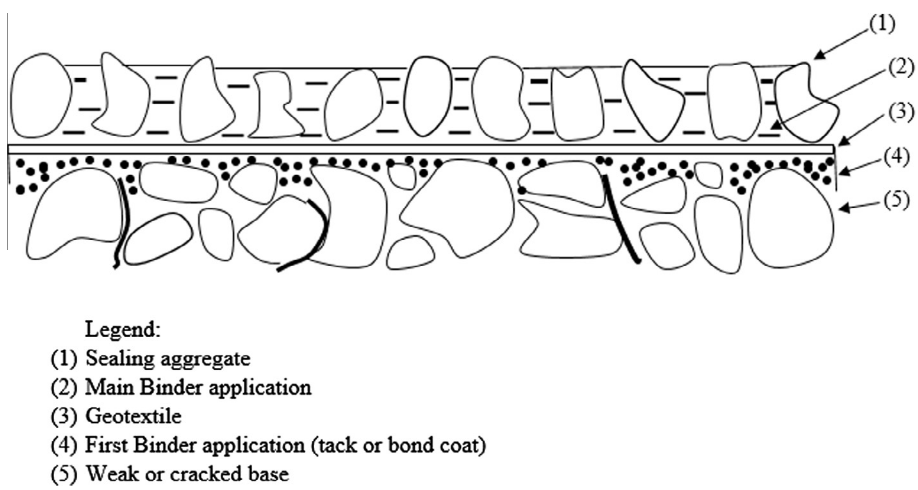


Fig. 4. Paving fabric placed under single chip seal. Adapted from Davis and Miner [34].

or torsioned flat-shaped) inserted in the double twist, as shown in Fig. 2. 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. Hughes and Al-Qadi (2001) reported on the installation of the new generation of steel nettings in Pennsylvania. The authors recommended that a standard methodology 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 [31].

2.2.6. 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 reflection cracking will take place. 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 [32]. 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. Further, the application of the overlay when the pavement is in fair condition proved more cost-effective as compared to its application when the pavement reaches a poor condition.

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 [33]. 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 reflection 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 better performance than the section with ARMI, see Fig. 3. This study provided the basis for Florida Department of Transportation to not to consider ARMI as a primary treatment method for mitigating reflection cracking and attempt to identify a more effective treatment method.

2.2.7. 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 [34]. The 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, Fig. 4. Based on experiences, the proposed treatment method shall not be used on vertical grades greater than 10%, the last 100 ft. (30.5 m) 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 reflection 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 50–75%. 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/yd2 and between 0.25 and 0.30 gal/yd2, respectively.

2.2.8. Strata® reflection cracking relief system

Strata® 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 [35]. As indicated by the manufacturer and owner of this technology (SemMaterials), the use of the Strata® system delays the appearance of reflection cracking for two years and extends the overlay service life against reflection 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.

Bischoff described the evaluation of the Strata® system in Wisconsin [35]. Two separate concrete pavement rehabilitation projects on I-94 were selected. In the first project, a 10-in. (254.0-mm) jointed reinforced concrete pavement (JRCP) with a joint spacing of 40 ft. subjected to an average daily traffic (ADT) of 128,000 was overlaid with a 1-in. (25.4-mm) Strata® interlayer followed by two 2-in. (50.8-mm) HMA layers. A control section built without the Strata® interlayer was constructed with a 3-in. (76.2-mm) HMA layers. In the second project, a 9-in. (228.6-mm) JRCP with a joint spacing of 80 ft. subjected to an ADT of 39,300 was overlaid with a 1-in (25.4-mm) Strata® interlayer followed by a 2.0-in. (50.8-mm) SMA overlay. The control section as well as the rest of the project consisted of a 2.5-in. (63.5-mm) HMA layer followed by a 2-in. (50.8-mm) SMA overlay. The Strata® mixture was pro-

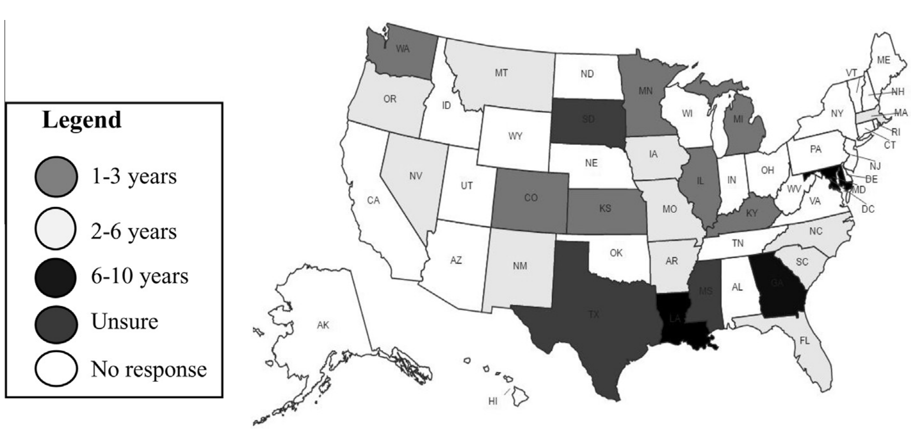


Fig. 5. Average service life of a 1.5–2.0 in. (38.1–50.8 mm) HMA overlay against reflection cracking.

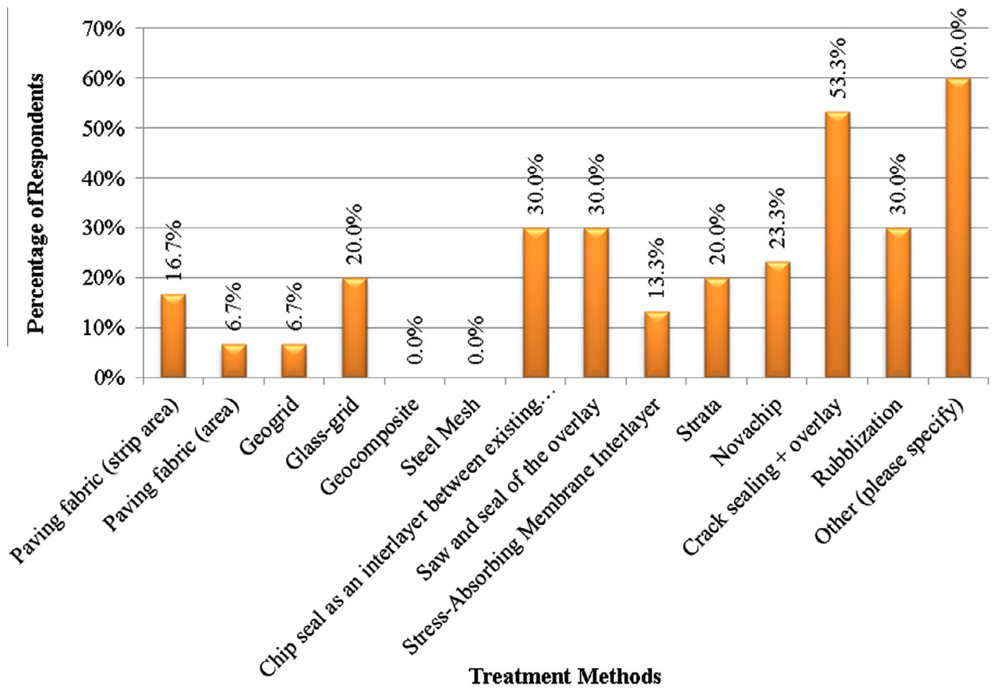


Fig. 6. Treatment methods regularly used to delay reflection cracking.

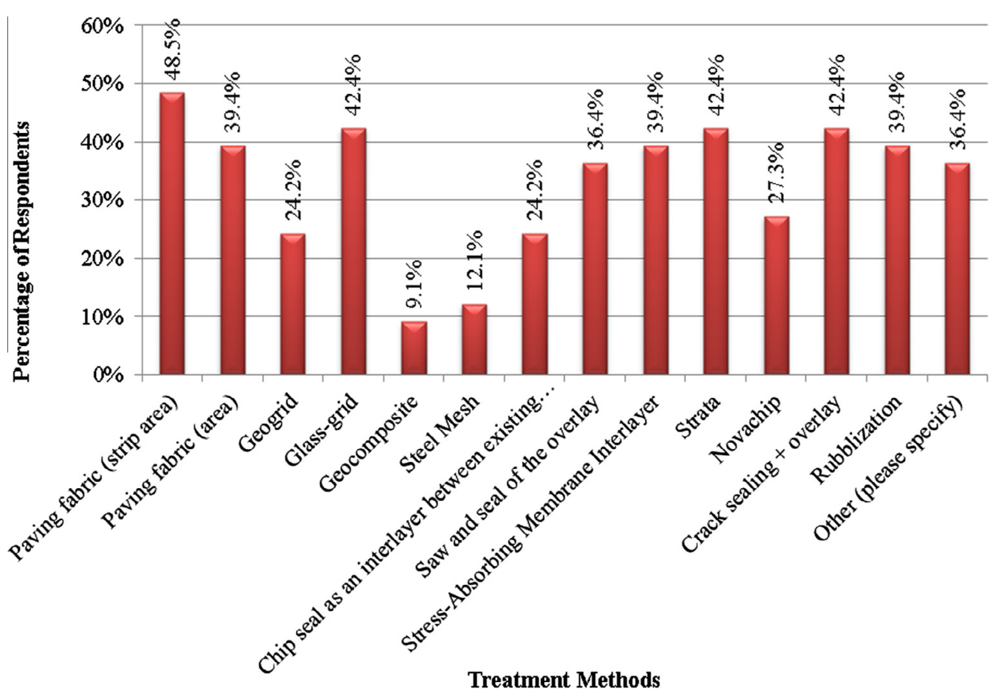


Fig. 7. Evaluation of treatment methods.

duced and installed using standard paving equipment. Performance evaluation included annual measurement of reflection 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. However, 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% reflection cracking after four years. Most of the reflection 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.

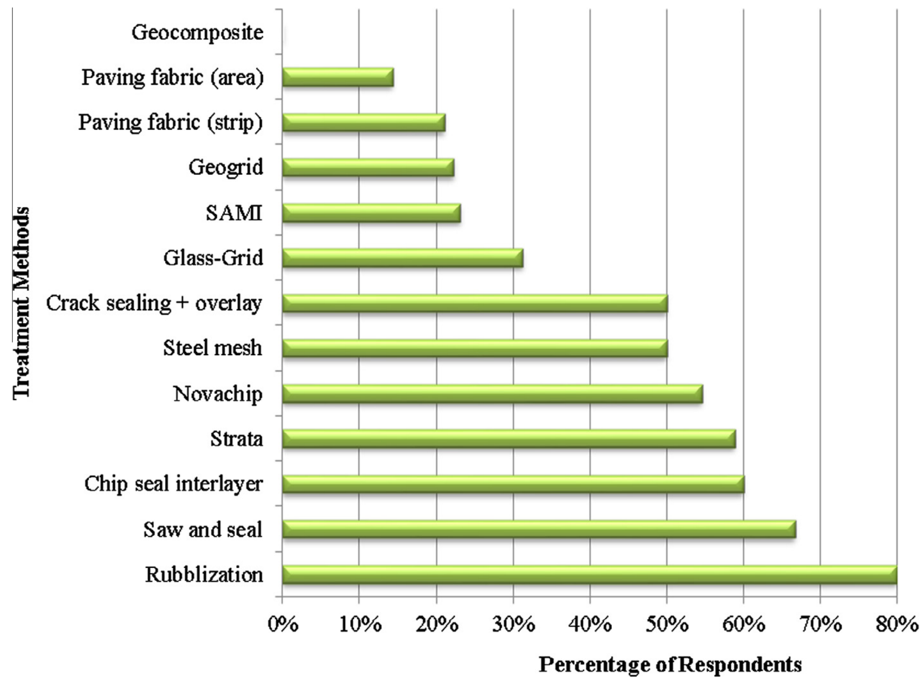


Fig. 8. Treatment methods that positively contribute to delay reflection cracking.

3. Survey of state of practices

A survey was conducted to collect information from highway agencies in the US and Canada on the current state of practices to address reflection cracking. In total, 35 responses were received from 25 states, the Quebec Department of Transportation, and the Saskatchewan Ministry of Highway and Infrastructure (Canada). To expedite the response to the survey, the survey questionnaire was limited to nine main questions, see Appendix A. The following sections present the main findings from the survey.

3.1. Average service life of HMA overlay against reflection cracking

Fig. 5 presents the average service life of a 1.5–2.0 in. (38.1–50.8 mm) HMA overlay against reflection cracking. The majority of the respondents (73%) indicated that average service life of a 1.5–2.0 in. (38.1–50.8 mm) HMA overlay against reflection cracking is between 1 and 6 years, which is a very short service life. Only 12% reported that the average service life of the overlay against reflection cracking is between 6 and 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., Georgia, Maryland, Florida, and Massachusetts) that take regular actions to address reflection cracking. These responses clearly indicate that in spite of the numerous studies conducted in the past 40 years on 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), they 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 reflection cracking.

3.2. Treatment methods regularly used to delay reflection cracking

Among the various treatment methods available to delay reflection cracking, the most commonly used method is crack sealing and overlay while there is no or minimal use of geocomposite material and steel mesh. Fig. 6 presents a summary of the treatment methods that are regularly used to address reflection 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 reflection cracking. A respondent indicated that with crack sealing, at least a year passes before overlaying to avoid rubber sealant expansion.

3.3. 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 Fig. 7. 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 interlayer stress absorbing composite (ISAC). Georgia mentioned that the state is currently evaluating open-graded interlayer in a section at the National Center for Asphalt Technology (NCAT) test track.

3.4. Performance of the overlay for the evaluated treatment methods

Fig. 8 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 treatment to address reflection 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. Georgia indicated that open-graded interlayer appears promising in delaying reflection cracking. Two other agencies (Iowa and Quebec) indicated that cold-in place recycling was the most effective in their states.

4. Recommended treatment methods

Based on the results of the literature review and the survey questionnaire, the following treatment methods are recommended for further evaluation:

- 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: reflection cracking may still appear).
  - Chip seal interlayer (pros: low cost and adequate control of reflection cracking).
  - Full-depth reclamation (pros: prevent reflection cracking, suitable for heavily cracked pavements, environmentally-friendly; cons: cost).
  - Cold-in place recycling (pros: prevent reflection 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 or open-graded interlayer system (pros: low cost and adequate control of reflection 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).

5. Summary and conclusions

The objective of this study was to evaluate and compare different reflection cracking control treatments by evaluating the performance, constructability, and cost-effectiveness of pavements built with these treatments. 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 for continuously reinforced concrete pavement (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 reflection cracking. 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.

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Appendix A

Survey questionnaire

- What is the average service life in years of a regular 1.5–2 in. (38.1–50.8 mm) HMA overlay in your state against reflection cracking (i.e., time for the reflection of 50% of joints or cracks)?
- How severe do you consider the problem of reflection cracking in your state when applying an HMA overlay?
- Does your state take regular actions to address reflection cracking in HMA overlay?
- Which of the treatment methods are regularly used in your state to delay reflection cracking?
- Of the treatment methods, which have been evaluated on a trial basis in your state in the past ten years to delay reflection cracking?
- For the methods that you evaluated, was the overlay performance against reflection cracking improved, worsened, or was about the same?
- For the following asphalt mixtures, was the overlay performance against reflection 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?

References

[1] L.M. Pierce, N.C. Jackson, J.P. Mahoney, Development and implementation of a mechanistic, empirically-based overlay design procedure for flexible pavements, Transportation Research Record 1388, National Research Council, Washington, DC, 1993, pp. 120–129.
[2] F.M. Bayomy, F.A. Al-Kandari, R. Smith, Mechanically based flexible overlay design system for Idaho, in: Transportation Research Record 1543, National Research Council, Washington, DC, 1996, pp. 10–19.
[3] M.M.J. Jacobs, A.H. De Bondt, A.A.A. Molenaar, P.C. Hopman, Cracking in asphalt concrete pavements, Proc., 7th International Conference on Asphalt Pavements, International Society for Asphalt Pavements, Nottingham University, UK, 1992, pp. 89–105.
[4] H.J. Chen, D.A. Frederick, Interlayers on flexible pavements, in: Transportation Research Record 1374, National Research Council, Washington, DC, 1992, pp. 90–94.
[5] M.A. Elseifi, R. Bandaru, Cost effective prevention of reflection cracking of composite pavement, Research Report FHWA/LA.10/478, Louisiana Transportation Research Center, 2011.
[6] R.D. Barksdale, S.F. Brown, F. Chan, Potential benefits of geosynthetics in flexible pavements, Transportation Research Record 315, National Research Council, Washington, DC, 1989.
[7] A.O. Abd El Halim, R. Haas, W.A. Phang, Geogrid reinforcement of asphalt pavements and verification of elastic theory, in: Transportation Research Record 949, National Research Council, Washington, DC, 1983, pp. 55–65.
[8] J.W. Button, R.L. Lytton, Evaluation of fabrics, fibers and grids in overlays, Proceedings of the 6th International Conference on Structural Design of Asphalt Pavements, Ann Arbor, MI, 1, 1987, pp. 925–934.
[9] C.S. Huges, K.H. McGhee, Results of reflection crack questionnaire survey, Report No. VHRC 72-R25, Virginia Highway Research Council, 1973.
[10] E.R. Steen, Road maintenance: technical aspects regarding the choice of geosynthetics, Proc., 4th International RILEM Conference – Reflection Cracking in Pavements, E & FN Spon, Ontario, Canada, 2000, pp. 507–516.
[11] G. Kennepohl, N. Kamel, J. Walls, R.C. Hass, Geogrid reinforcement of flexible pavements design basis and field trials, Proc., Annual Meeting of the Association of Asphalt Paving Technologists, San Antonio, TX, 54, 1985, pp. 45–75.
[12] H.S. Donna, Crack-reduction pavement-reinforcement glassgrid. Colorado Department of Transportation, Cooperation with the US Department of Transportation, Federal Highway Administration, 1993.
[13] R.L. Lytton, Use of geotextiles for reinforcement and strain relief in asphalt concrete, Geotext. Geomembr. 8 (1989) 217–237.
[14] H. Sheng, F. Zhou, T. Scullion, Reflection cracking-based asphalt overlay thickness design and analysis tool, in: Transportation Research Record 2155, National Research Council, Washington, DC, 2010, pp. 12–23.
[15] M.A. Elseifi, I.L. Al-Qadi, A simplified overlay design model against reflection cracking utilizing service life prediction, Paper No. 03-3285, Transportation Research Board, National Research Council, Washington, DC, 2003, pp. 169–191.
[16] M.A. Elseifi, I.L. Al-Qadi, Modeling and validation of strain energy absorbers for rehabilitated cracked flexible pavements, J. Transp. Eng. ASCE 131 (9) (2005) 653–661.
[17] M.A. Elseifi, N. Dhakal, Mitigation strategies of reflection cracking in pavements, Research Report No. FWHA/LA. 14/541, Louisiana Transportation Research Center, Baton Rouge, LA, 2015.
[18] R.M. Koerner, Designing with Geosynthetics, third ed., Prentice Hall, NJ, 1994.
[19] J.W. Button, R.L. Lytton, Guidelines for using geosynthetics with hot-mix asphalt overlays to reduce reflection cracking, in: Transportation Research Record 2004, National Research Council, Washington, DC, 2007, pp. 111–119.
[20] Saint Gobain (Technical Fabrics), GlasGrid Pavement Reinforcement Grid, 2005, Grand Island, NY.
[21] D.H. Timm, A.M. Warren, Performance of rubblized pavement sections in Alabama, Final Report. No. IR, 402, Highway Research Center, Auburn University, 2004.
[22] R. Calkins, Performance of the Crack, Seat, and Overlay Rehabilitation Technique for Concrete Pavements in California (MS thesis), California Polytechnic State University, San Luis Obispo, 2011.
[23] B. Choubane, H. Godwin, B. Birgisson, A. Nazef, J.A. Musselman, Long-term field performance of crack-and-seat rehabilitation strategy, Paper No. 01-2271 Presented at the 2001 TRB Annual Meeting, Washington, DC, 2001.
[24] M.R. Thompson, Hot-mix asphalt overlay design concepts for rubblized PCC pavements, Transportation Research Record 1684, 1999.
[25] H. Ceylan, R. Mathews, T. Kota, K. Gopalakrishnan, B.J. Coree, Rehabilitation of concrete pavements utilizing rubblization and crack and seat methods, Report No. IHRB Project TR-473, Ames, IA, 2005.
[26] M. Marquart, Evaluation of saw and seal over the overlaid existing concrete joints, Final Report, Project NH-3-002(040)212, Department of Transportation, North Dakota, 2001.

[27] A.C. Deborah, R. Cheng, R.J. Eger, L. Grusczynski, J. Marlowe, A. Roohanirad, H. Titi, Highway preventive maintenance implementation: comparing challenges, processes and solutions in three states, Paper presented at the 83rd Transportation Research Board Annual Meeting, Washington, DC, 2004.

[28] I.L. Al-Qadi, E.H. Fini, M.A. Elseifi, J.F. Masson, K.M. McGhee, Viscosity determination of hot-poured bituminous sealants, Journal of the Transportation Research Board 1958, National Research Council, Washington, DC, 2006, pp. 74–81.

[29] M.A. Elseifi, R. Bandaru, Z. Zhang, S. Ismail, Field evaluation and cost effectiveness of the saw and seal method to control reflection cracking in composite pavements, Transportation Research Record: Journal of the Transportation Research Board, 2227, Washington, DC, 2011, pp. 33–42.

[30] I.L. Al-Qadi, M.A. Elseifi, D. Leonard, Development of an overlay design model for reflection cracking with and without steel reinforcement, J. Assoc. Asphalt Pave. Technol. 72 (2003) 388–423.

[31] J.J. Hughes, I.L. Al-Qadi, Evaluation of Steel Paving Mesh. RP-2000-058, Construction Report, 2001.

[32] A.D. Morian, Y. Zhao, J. Arrelano, E.D. Hall, Analysis of asphalt pavement rehabilitation treatment performance over twenty years, in: Transportation Research Record 1905, National Research Council, Washington, DC, 2005, pp. 36–43.

[33] J. Greene, B. Choubane, S. Chun, S. Kim, Effect of asphalt rubber membrane interlayer (ARMI) on instability rutting and reflection cracking of asphalt mixture, Report No. FL/DOT/SMO/12-552, Florida Department of Transportation, 2012.

[34] L. Davis, J. Miner, Assessment of surface treatment with textiles for pavement rehabilitation and maintenance, TRB Paper No. 10-2739, Transportation Research Board, Washington, DC, 2010.

[35] D. Bischoff, Evaluation of Strata® reflection crack relief system, Report No. FEP-01-07, Wisconsin Department of Transportation, Madison, 2007.