A Four-Year Performance Review of North American and International Fibre-Reinforced Membrane Systems

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ABSTRACT

Fibre-reinforced membrane systems used as a thin surfacing system or in combination with other traditional thin surfacing systems address reflective cracking specifically and quantitatively. These systems were developed in the United Kingdom in the late 1980’s and they are now used in many countries worldwide as “Stress Absorbing Membrane” (SAM) or as “Stress Absorbing Membrane Interlayer” (SAMI) to inhibit pavement cracking and/or to mitigate reflective cracking. The first road trials in the United States were placed in the fall of 2003 near Niagara Falls in New York State while the first Canadian road trials were placed in York Region north of Toronto, Ontario in the summer of 2005.

This paper presents an overview of fibre-reinforced membrane technology including a discussion on the current state of practice in North America with respect to design, equipment and construction procedures. The performance and the effectiveness of this type of treatment have been researched in several countries including the University of Nottingham in the UK, the “Laboratoire régional des ponts et chaussées d’Autun in France and more recently the Penn State University in the USA. The findings of the European studies, as well as the current North American research, are detailed in the paper.

RÉSUMÉ

Les systèmes de membranes renforcées aux fibres utilisés comme système de surfaçage mince ou en combinaison avec d’autre système de surfaçage mince traite spécifiquement et quantitativement la fissuration de réflexion. Ces systèmes ont été développés au Royaume Uni dans les dernières années 1980 et sont maintenant utilisés dans plusieurs pays à travers le monde comme membrane absorbant les contraintes SAM ou comme inter couche de membrane absorbant les contraintes SAMI pour freiner la fissuration ou pour diminuer la fissuration de réflexion. Les premiers essais routiers des USA ont été placés à l’automne 2003 près des Chutes Niagara dans l’état de Newyork alors que les premiers essais routiers canadiens ont été placés à l’été 2005 dans la région de York au nord de Toronto en Ontario.

Cet exposé présente une vue générale de la technologie des membranes renforcées aux fibres incluant une discussion sur l’état courant de la pratique en Amérique du Nord en ce qui concerne le design, l’équipement et les procédures de construction. La performance et l’efficacité de ce type de traitement ont été étudiées dans plusieurs pays dont l’université de Nottingham au RU, le laboratoire central des Ponts et Chaussées d’Autun en France et plus récemment l’Université Penn State aux USA. Les résultats des études européennes aussi bien que les recherches courantes en Amérique du Nord sont présentés en détail dans cet exposé.
1.0 INTRODUCTION

The most common pavement structure found in North America consists of unbound granular base layers overlaid with a bituminous surfacing system, which may be made of one or more layers of Hot Mix Asphalt (HMA), or a bituminous seal coating system such as chip seal or graded-aggregate seal. A large number of concrete pavements also exist, especially on high-traffic volume roadways. In the latter periods of their service life, both types of pavements exhibit crack distresses; fatigue, thermal and aged cracking in bituminous pavements, faulting and mid-slab cracking in concrete pavements. These cracking mechanisms are attributed to traffic loading, temperature and oxidation of the binder in the case of bituminous pavements.

Following the application of an overlay to an existing pavement (flexible or rigid), physical deterioration of the overlay takes place as a result of movement at the joints and re-propagation of cracks in the underlying pavement layers. This is known as reflective cracking and it occurs in nearly all types of overlays. To ensure the proper lamination of the HMA overlay over an existing pavement surface, it is current practice to place a tack/bond coat at the interface. While lamination of the layers is necessary for pavement structural strength, bonding of the overlay with the underlying cracked substrate pavement induces strain in the overlay joint/crack, which eventually will exceed the strain tolerance of the overlay material. Temperature induced horizontal movements concentrated at the underlying joints/cracks in the existing pavement lead to tensile stresses, which are an important contributor to reflective cracking. Furthermore, vertical movements induced by traffic loading lead to shear stresses in the overlay, which also contribute to the upward propagation of the crack.

This paper presents an overview of fibre-reinforced membrane technology including a discussion of the current state of practice and performance in North America. This paper also presents the performance of fibre-reinforced systems when used as an interlayer to extend the life of the overlay compared with no treatment. Finally, results of technical studies and field performance reviews undertaken on fibre-reinforce membrane systems in North America, as well as elsewhere around the world are discussed.

2.0 REFLECTIVE CRACKING

Effective pavement preventive maintenance programs encompass a full range of techniques with the goal of enhancing pavement performance in a cost-effective and proven manner. Unfortunately, reflective cracking above all other form of pavement deterioration remains one of the most difficult pavement defects to correct. Traditional preventive maintenance treatments such as conventional chip seals, microsurfacing and thin hot mix asphalt are sufficient to correct surface defects such a ravelling, surface oxidation, minor rutting and pavement friction deficiency, but are inadequate for mitigating reflective cracking. Moreover, traditional maintenance techniques are often only considered as a “quick fix,” since their service life is strongly influenced by the cracking conditions of the underlying pavement.

Fibre-reinforced membranes, either as a bituminous surfacing course or as an interlayer, have high shear and tensile strength in addition to high ductility and can act as crack relieving layers when placed on or between the old and new surface. Crack propagation through fibre-reinforced membrane systems requires more energy and stress concentrations, which ultimately leads to a delay in the formation of the reflective cracks. The ductility of a membrane used as an interlayer allows it to absorb some of the strain energy developed at the bottom of the new overlay as the wheel loads are applied cyclically on the top of the pavement as shown in Figure 1.
Cracking also occurs through asphalt concrete pavements due to cold temperatures and/or temperature cycling, especially in the more northern states and provinces of North America. Cracking that occurs from cold temperatures is referred to as low temperature cracking, whereas cracking due to thermal cyclic changes is referred to as thermal fatigue cracking. Both forms can propagate through new asphalt overlays or bituminous surface treatments as reflective cracks. These thermal-induced cracks allow the ingress of water into the layers below, deteriorating these layers through freeze-thaw cycles and/or by freezing and expansion of ice focal points that may produce an upward force on the pavement overlay. The result from both traffic and thermal-induced fatigue is a deterioration of pavement life and a reduction in ride quality for the end-user.

3.0 FIBRE-REINFORCED MEMBRANE PROCESS

3.1 Overview

The fibre-reinforced membrane process produces a fibre-impregnated reinforcing layer that waterproofs the pavement and allows dissipation of some of the stresses generated in the pavement. The membranes are installed in a manner nearly identical to a conventional chip seal. The membranes may be used as a fibre-reinforced chip sealing surfacing system, or as fibre-reinforced interlayer system in combination with another thin surfacing system. These systems were developed in the United Kingdom in the late 1980’s and they are now used in many countries worldwide as Stress Absorbing Membrane (SAM) or as Stress Absorbing Membrane Interlayer (SAMI). The first highway pavement trials in the United States were placed in the fall of 2003 near Niagara Falls in New York State, while the first Canadian trials were placed in York Region north of Toronto, Ontario in the summer of 2005.

3.2 Equipment and Placement

The installation of a fibre-reinforced membrane is carried out using a specific binder/fibre placement applicator along with conventional chip sealing equipment. The binder/fibre placement applicator is mounted on a trailer unit (Figure 2), which also includes storage for the columns of fibre spools. In advance of the fibre distribution, a layer of binder is applied through a traditional slotted jet distributor.
spray bar arrangement. Strands of fibreglass are then taken and fed pneumatically through lines to the fibre distribution system. The fibre distribution system includes a fibre-chopping unit and a chamber that allows random distribution of the fibres using an air blowing system. A second slotted jet distributor spray bar follows the fibre distribution system to apply a second layer of binder to encapsulate the fibres and complete the membrane component. Chippings are then applied on top of the fibre-reinforced membrane and embedded into the binder to form a fibre-reinforced surfacing or interlayer system.

The trailer unit previously described contains sufficient fibre in storage for the placement of 38,000 to 64,000 m² of fibre-reinforced membrane before re-loading. The daily production rate could reach up to 85,000 m². The width of placement can vary from 0.3 to 4.0 m, which ensures, in the majority of instances, a full lane pass for any typical North American roadway. The spray bars and fibre distribution system fold vertically in the middle for easier access and transportation (Photo 1).

As previously noted, the placement process of the fibre-reinforced membrane is nearly identical to chip sealing (Photo 2). As a result, the cost surcharge for the fibre encapsulation remains low. The total cost of the fibre-reinforcement system is extremely competitive compared to other types of reflective cracking mitigation treatments. Finally, following an application of chippings over the membrane, the surface may be open to traffic before the placement of the overlay, making the process practical and convenient to use.

3.3 Fibre-Reinforced Membrane Systems

Fibre-reinforced membrane systems may be used as thin bituminous surfacing treatment akin to chip seal (SAM) or as interlayer systems (SAMI). The membrane systems consist of polymer-modified asphalt emulsions applied at total rates of 1.4 l/m² to 2.4 l/m² and chopped glass fibres of nominally 60 mm length applied at rates from 30 to 120 g/m², but typically 60 g/m². This fibre-emulsion mixture surface seals the pavement, as shown in Photo 3, in a manner that cracks are effectively bridged, filled with fibres and residual polymer-modified bituminous binder.
Photo 1. Folding Spray Bar/Fibre Placement Unit

Photo 2. Fibre-Reinforced Membrane Placement including Chippings Application
Photo 3. Emulsion/Fibre Mixture

Fibre-reinforced membrane systems provide pavements with a waterproofing layer to protect the pavement structure and give enhanced tensile properties to dissipate stresses. The installation of a fibre-reinforced membrane is quick and the systems are cost effective compared to other type of SAM or SAMI. Furthermore, the existence of such a layer within the pavement structure does not impede pavement recycling in future years.

The effectiveness any type of system, SAM or SAMI, is made certain if the membrane system bonds to the existing substrate and provides an anchor of adhesion for the subsequent layer(s) in the case of SAMIs. The binder applied to the existing substrate through the first spray bar of the double spray bar system ensures adhesion of the fibre-reinforced membrane to the substrate, while the binder applied through the second spray provides the anchor of adhesion for the overlaying surfacing material. Both layers of binder fuse with one another encapsulating the fibres and consequently avoiding a possible delaminating plane within the fibre layer. A supplemental light tack coat may be applied on the membrane protective chippings when the chipping coverage exceeds 90 percent and an overlay is to be subsequently applied. The binder is applied as an emulsion through a spray bar system design to provide full and uniform coverage of the substrate surface. The membrane residual binder rate exceeds 1.0 kg/m², which is in most circumstances sufficient to ensure pavement waterproofing.

Membrane systems utilized as SAM or SAMI are specifically designed to absorb some of tensile stresses generated in the pavement. There are no systems on the market that absorb all pavement tensile stresses. The SAM and SAMI systems dissipate tensile stress concentrations, which would ultimately lead to pavement cracking. By virtue of the glass fibres introduced between the two binder spray bars, enhanced tensile strength and ability for the pavement to withstand some of these tensile stresses are gained.
The application of fibre-reinforced membrane system is very simple. Fibre-reinforced systems are fabricated in-place and applied as a uniform membrane totally adopting the underlying shape and form of the substrate without any kinks or torn & ripped areas. Surface preparation is minimal and daily applied surface areas may be well in excess of 50,000 m², which is extremely rapid compared to other SAM or SAMI systems.

Pavement recycling is an important engineering factor to consider in the evaluation of any pavement technology. Experience has shown that the chopped fibreglass strands within fibre-reinforced membranes systems do not behave as a continuous textile-like fabric, which significantly hampers milling operations. Consequently, pavement and HMA materials containing fibres may be reprocessed and reutilized easily in any form of pavement recycling process, therefore not reducing pavement material residual value and possibly enhancing it by the its contribution within the recycled layer.

4.0 PERFORMANCE REVIEW

The benefit of using the fibre-reinforced membrane as a surfacing system or as the interlayer system has not only been proven in the field, but also through several international and North American technical studies. A brief summary of the findings of each study is provided in this section.

4.1 Recent North American Studies and Field Performance Review

The introduction of the fibre-reinforced membrane process in North America quickly generated (and continues to generate) interest among road engineers. The need to quantify the benefits and the performance became important. A comparative field review of the performance of a fibre-reinforce chip seal system versus a conventional chip seal system was undertaken in 2003. In addition, two important North American studies were initiated in 2005; one by the Texas Transportation Institute and a second study by the Pennsylvania Transportation Institute. Results are available for both studies and are summarized henceforth.

4.1.1 Groad Road, Town of Murray, Orleans County, New York State

Groad Road was one of the first North American fibre-reinforced surfacing system projects. The project was completed in the fall of 2003 and it consisted of the installation of a conventional emulsion-based chip sealing system on one lane and the installation of a fibre-reinforced chip sealing surfacing system on the other lane. Photos 4, 5 and 6 provide a side-by-side outlook of the performance of both treatments over a three-year period. The roadway was subjected to extensive and aggressive snowplough operations.

After the first six months (March 2004), longitudinal reflective cracks had started to reappear on the regular chip seal side while no cracks had appeared on the fibre-reinforced membrane side of the roadway (Photo 4) and yet cracking had initially been present on both sides. In January 2005 (Photo 5) longitudinal reflective cracking and snowplough damage were evident on the chip seal side, while the fibre-reinforced side was still in very good condition.

In January 2006 (Photo 6), further evidence of snowplough damage was noted along with water pumping from the lower layers on the chip seal side while only nominal slight damages started to occur on the fibre-reinforced membrane side; all the while the membrane itself was still intact.
Photo 3. Groad Road, Town of Murray, Orleans County, New York State, March 2004

Photo 4. Groad Road, Town of Murray, Orleans County, New York State, January 2005
4.1.2 The Texas Transportation Institute Study

The purpose of the Texas Transportation Institute (TTI) study was to evaluate the reflective cracking and fracture mechanics of a pavement structure that incorporates a fibre-reinforced membrane interlayer system. The study work began with laboratory testing to create a cracking life model to be followed by a possible field study to verify the laboratory findings.

The laboratory testing was performed using a device that replicates, in a control setting, the field thermal cracking mechanism. The device generates a “cracking number”, which can be compared against other interlayer systems. The testing was performed using a device developed in the early 1980’s called the “Overlay Tester”. The device induces a cyclic and controlled displacement at the bottom of a typical overlay as shown in Figure 3 to initially produce a crack at the base of the test specimen and then continues to induce repetitive horizontal displacements, which cause the crack to propagate upward through the specimen. This process is intended to simulate the cyclic tensile stresses/strains of pavements due to cyclic thermal variations.

Initially, the TTI cracking finite element model assumed that reflective cracking propagates vertically directly above the crack below. However, this is not to date what has been observed and there is more work ongoing. The results obtained to date suggest that the delay of crack propagation is increased; i.e., cycles to failure, by at least 3 fold where the fibre-reinforced membrane interlayer system is used. The method also suggested horizontal crack migration through the plane of the membrane that eventually migrated vertically.

Photo 5. Groad Road, Town of Murray, Orleans County, New York State, January 2006
4.1.3 The Pennsylvania Transportation Institute Study

The Pennsylvania Transportation Institute has also undertaken an evaluation study of the fibre-reinforced membranes interlayer and surfacing systems for the Pennsylvania Department of Transportation, Bureau of Municipal Services.

The study involves the comparison of systems with and without fibres on test sections of Pennsylvania Transportation Institute’s Test Track, in addition to laboratory testing of the constituent materials of the interlayer. The evaluation process included the following tasks:

- Bending Beam Rheometer (BBR) tests on the residual binder with and without fibres.
- Continuous performance monitoring of the test sections on the test track.
- Accelerated pavement testing on the test sections using a Mobile Model Load Simulator Scale 3.
- Analysis of surface moduli using a Portable Seismic Property Analyzer.

The stiffness and the strength of the binder/fibres system at low temperature are indicative of the effectiveness of the membrane in reducing reflective cracking. The BBR test was selected as it allows characterizing residual binder with fibres and without fibres at low temperature. The BBR test provided a comparative assessment of the effectiveness of the membrane to reduce reflective cracking with and without fibres. The deflection of the specimen with fibres was reduced and the stiffness of the binder/fibres system was increased compared to the binder without fibres. Yet, the BBR test results suggest that the binder with fibres has an increased elastic behaviour compared to the binder without fibres.

Resurfacing test sections with and without the fibre-reinforced interlayer system are being evaluated on the Pennsylvania Transportation Institute Test Track. An extensive distress survey of the existing substrate was carried prior to the placement of the overlay. Both the fibre-reinforced interlayer system section and the control section were monitored from June 2005 to December 2006. As of the end of 2006 there was no reflective cracking visible at the surface of both sections. However, coring performed in November 2006 on top of pre-existing cracks clearly showed upward crack propagation in the overlay of the control section (Photo 7) while no crack propagation was visible in the core extracted from the fibre-reinforced interlayer system section (Photo 8).
Photo 7. Upward Crack Propagation in Control Section

Photo 8. Crack Mitigation in Fibre-Reinforced Interlayer System Section
One million cycles were applied on two areas of the fibre-reinforced interlayer system section where a wide crack was known to be present in the underlying substrate. The accelerated pavement testing was performed using the Mobile Model Load Simulator Scale 3 (MMLS3). No visible cracks were observed under the MMLS3 wheel path for both tested area (Photo 9a and 9b).

![Photo 9. Accelerated Testing using the Mobile Model Load Simulator Scale 3 (MMLS3) Device](image)

The surface moduli of the overlay were also evaluated using Portable Seismic Property Analyzer (PSPA) in the fibre-reinforced and the control sections where pre-existing substrate cracks were present. Moduli were measured at –7 and at 7°C. The results at -7°C suggest that for locations with pre-existing cracks, the modulus of the control section is higher than that of fibre-reinforced interlayer system. The higher modulus of the control section stems from the high modulus of ice entrapped in the reflected crack in the top 50 mm (2”) of the control section, which implies more voids or that the reflective crack is more prominent. Comparing cracked and non-cracked sections, both cracked sections were higher than those without cracks, because of the high modulus of ice.

For the higher temperatures (+7°C on top of the pre-existing crack), the fibre-reinforced interlayer system section has a higher modulus than the control due to absence of the reflective crack. For the section on top of no pre-existing cracks, the fibre-reinforced interlayer system section has a lower modulus due to the inclusion of the chip seal interlayer, which has a lower modulus than a regular HMA overlay. This fact makes the treated section less stiff and more ductile. Comparing sections with cracks and no cracks, the same observations as in the lower temperatures were observed.

4.2 International Studies

The fibre-reinforced membrane process was also evaluated in other countries, including the United Kingdom with the first study in 1987, France in 1991, Ireland in 1993 and Australia in the mid-1990s. Results are summarized hereafter.

4.2.1 The University of Nottingham Study (United Kingdom, 1987)

In 1987, Nottingham University in the UK, conducted a study looking at several fibre-reinforced interlayer systems. The test method used was designed to be a simulation of the actual situation occurring in practice when a cracked substrate is resurfaced. The study revealed that any of the fibre-reinforced...
interlayers act as a strain attenuating membrane between the cracked substrate and the resurfacing HMA. The study also revealed that stress concentration in the overlay is not located directly above the substrate crack (Figure 4a), as in the case of an overlay without a fibre-reinforced interlayer system (Figure 4b). In the region of the gap in the substrate, the interlayer spreads the transient movements over a larger area of the underside of the resurfacing HMA reducing the magnitude of the strain. This generally results in a series of unconnected micro-cracks that are less damaging than a few wide cracks and could be treated more readily with cost-effective treatments such as a fog & sand seal.

Figure 4. Cracking Mechanism of Overlay with and without Fibre-Reinforcement

4.2.2 The “Laboratoire Régional des Ponts et Chaussées d’Autun” Study (France, 1991)

In 1991, the “Laboratoire Régional des Ponts et Chaussées” in Autun, France conducted a study to compare various interlayer systems; fibre-reinforced and geogrid-reinforced. Testing was also carried out with non-reinforced control specimens utilizing a binder rich sand mixture/HMA system and conventional HMA to evaluate the effectiveness of the reinforcement. Each specimen was subjected to two types of stress under constant temperature conditions: traction, to simulate thermal contraction and cyclic vertical flexure, to simulate the traffic.

The study demonstrated that either fibre or geogrid reinforcement is highly effective in inhibiting reflective cracking compared to the control specimen and even compared to a binder rich sand mixture/HMA system. The fibre-reinforced specimen took approximately 50 percent longer to crack than the sand mixture/HMA system and 150 percent longer compared to the conventional HMA without any crack inhibiting system. Among all the systems studied it was noted that the fibre-reinforced interlayer system was the only specimen not to crack completely at the end of the test.

4.2.3 The University of Ulster Study (Ireland, 1993)

In 1993, Ulster University in Ireland studied the system in more detail. Three main test methods were chosen to examine the performance of a fibre-reinforced interlayer system in delaying reflective cracking:
tensile strength, fatigue and wheel tracking. The study looked at the effect of the emulsion and the coverage, the length of the fibreglass, and the rate of spread of the fibreglass.

The tensile strength was tested using an Instron test rig. At the time, the combination of K1-70 emulsion (CRS-2 equivalent) with 60 g/m² of a 60 mm length of fibre proved to be most effective, with a tensile strength of 0.77 N/mm² compared with 0.57 N/mm² for the control specimen (HMA with no fibre-reinforced interlayer).

The fatigue test was conducted using a Dartec testing device incorporating a three-point loading system. Again, the combination of K1-70 emulsion (CRS-2 equivalent) with 60 g/m² of a 60 mm length of fibre afforded the membrane the longest time to failure. The number of cycles to crack was 3,300 and 6,300 for complete failure, as compared to 2,500 to crack and 4,700 for complete failure for the control specimen.

The wheel-tracking test indicated that the combination K1-70 emulsion and 30 g/m² of 60 mm glass fibres provided the greatest delay to failure and it was closely followed by the K1-70 and 60 g/m² of 60 mm length fibre system. The fibre-reinforced systems cracked after an average of 15,000 cycles compared to 2,500 cycles for the control.

4.2.4 The Road Transportation Authority of South Wales Study (Australia, mid-1990s)

Through the mid-1990’s, field and laboratory evaluations were undertaken in New South Wales in Australia. The laboratory study replicated the earlier study at Nottingham University whereby the control sample produced larger cracks and eventually the fibre-reinforced specimen showed the presence of finer cracks due to the strain being distributed and delayed through the horizontal plane of the reinforced interlayer.

Australia conducted extensive field trials to evaluate and document the field performance of fibre-reinforced interlayer and surfacing systems. Information related to 17 different sites was obtained over several years. The Australian field assessment study clearly indicated that fibre-reinforcement provided effective control of reflective cracking over a wide range of pavement conditions. The assessment also indicated that the effectiveness of crack retardation is a function of the initial condition of the substrate and the loading regime to which the pavement is subjected.

5.0 CONCLUSIONS

Effective pavement preventive maintenance programs encompass a full range of techniques with the goal of enhancing pavement performance in a cost-effective and proven manner. Reflective cracking above all other forms of pavement deterioration remains one of the most difficult pavement defects to correct. The value-added benefits and the service life of traditional preventive maintenance treatments can be strongly hampered by the cracking conditions of the underlying pavement.

Fibre-reinforcement is versatile, as it addresses reflective cracking specifically and it can be used as a surfacing system or as an interlayer system. Furthermore, as demonstrated through laboratory testing and site monitoring over an extended period of time, fibre-reinforced systems are sufficient to inhibit reflective cracking. Even though the North American experience with fibre-reinforcement is recent, the results of the North American laboratory work and field reviews are similar to the findings of international studies carried out to quantify and qualify the performance of fibre-reinforced systems.
Fibre-reinforced interlayer and surfacing systems are installed in a manner nearly identical to chip sealing. Consequently, the surcharge for the cost of installation compared to no crack mitigation treatment is low and the fibre-reinforcement is extremely competitive compared to other types of reflective crack mitigation treatments. Furthermore, following an application of chippings over the membrane, the surface may be opened to traffic before the placement of the overlay, making the process practical and convenient to use.

Versatility of use, mitigation of reflective cracking, ease of placement and cost effectiveness are positive attributes of fibre-reinforcement. Fibre-reinforcement offers road engineers a means of controlling reflective cracking in pavement preventive maintenance.

REFERENCES


