Evaluating Alternative Solutions to Reflective Cracking Through Asphalt Overlays

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The problem of reflection cracking through asphalt overlays can be approached from the design perspective of the factors or mechanisms involved, the alternative treatments available, and the analyses and testing required to evaluate the treatments. Then, a selection of the best alternative, provided it satisfies economic criteria, can be made and implemented. This paper concentrates on evaluation and first illustrates how an analytical method, based on a wide-crack band theory in finite element formulation, can effectively be used for the first step of the process. Then, it illustrates how the most promising alternative treatments can be experimentally evaluated. Test procedures and example results are used for this purpose, and relationships between induced stress, or strain energy, and cycles to failure are presented. Selection, installation, and follow-up considerations are briefly discussed. It is pointed out that even with the most technically and economically feasible alternative, proper laydown and construction are important to realizing success. Follow-up monitoring would primarily involve periodic crack surveys. The major conclusions of the paper are that both analytical and experimental evaluations should be performed to screen potential crack reflection treatments, and that proper construction is essential after the best treatment has been selected.

Asphalt concrete overlays are the most commonly used method for rehabilitating deteriorated pavements. However, they often do not perform as satisfactorily as is desirable because of existing cracks that propagate through the newly constructed overlay within a short period of time. This problem of "reflection cracking" is widespread and was in fact considered the most dominant existing pavement problem in a recent Canadian study (*1*).

Reflection cracking is caused by one or more cycles of thermal contraction, by repeated traffic loads, or by a combination of these two mechanisms. Existing methods of design do not generally provide crack reflection criteria. In efforts to minimize or delay occurrence of the problem, however, alternatives such as increase of the thickness of overlay, modification of asphalt properties, and placement of stress-relieving interlayers have been attempted. The degree of success has usually been limited.

There is a need to approach the reflection cracking problem from a perspective that includes a consideration of both of the following questions: (1) If the problem exists, what are the factors or mechanisms and what are the alternatives available? (2) How can the alternatives be screened or evaluated to find the best solution, and how should it be implemented? Figure 1 provides a schematic of the key elements involved in this total perspective or process.

This paper concentrates on the second aspect, evaluation and implementation, after briefly considering the first aspect. More specifically, it has the following objectives:

1. To provide a summary of the factors and mechanisms involved in reflection cracking and the basic alternative treatments available;
2. To present a review of the available analytical evaluation methods, with an example to illustrate how the alternative treatments may be screened;
3. To discuss experimental evaluation methods, as a necessary complement to analytical evaluation, and to provide examples; and
4. To consider some of the key aspects of laydown, construction, and monitoring follow-up.

FACTORS AND MECHANISMS

The basic factors that lead to reflection cracking are (1) repeated traffic loading, (2) thermally induced stresses or strains, and (3) a combination of both. In addition, the temperature-dependent stiffness of the materials and flaws in the overlay (i.e., built-in cracks during construction) can have a major effect.

Thermally induced stresses or strains, with low cyclic frequency, are thought to be the major factor in most cases. Two basic mechanisms can exist for this situation: (1) cracking initiates at both the top and bottom of the overlay, and propagates toward the middle, under very cold conditions; and (2) cracking initiates at the bottom of the overlay, owing to stress concentration around the old crack in the existing pavement, and propagates up under thermal cycling.

A possible third mechanism has been postulated by Abdelhalim et al. (*2*), whereby cracks built in during construction may subsequently propagate through the depth of the overlay with thermal cycling.

The mechanisms of cracking are directly related to the type of displacement induced. Figure 2 shows that this consists of three distinct modes: (1) normal tension, in the case of ther-

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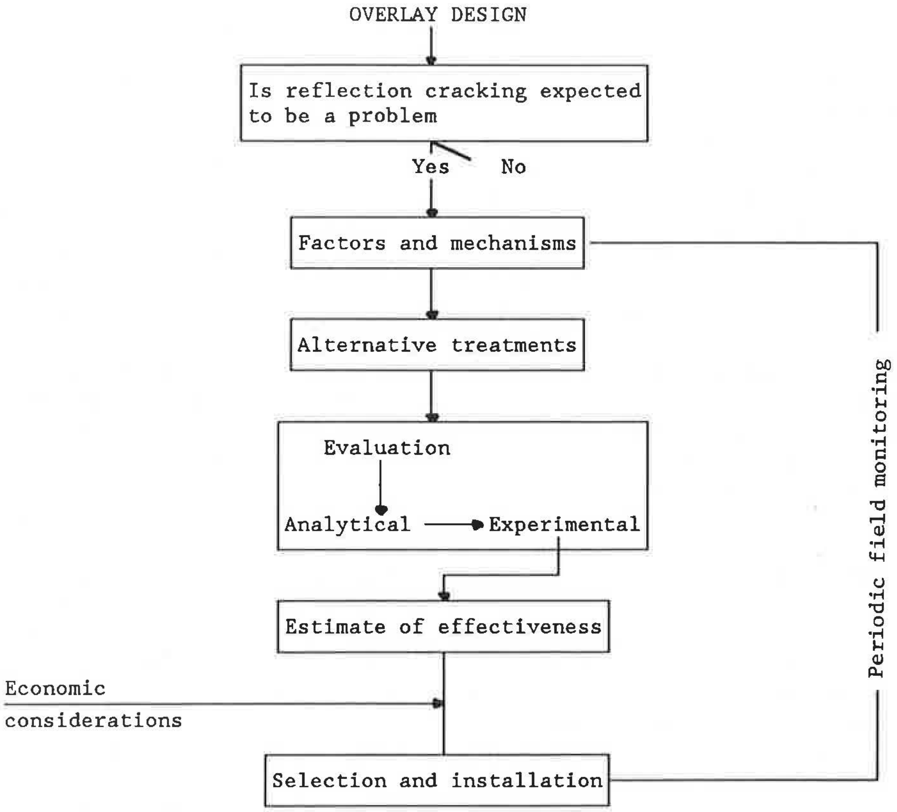

FIGURE 1 Key elements in the total process of handling the reflection cracking problem.

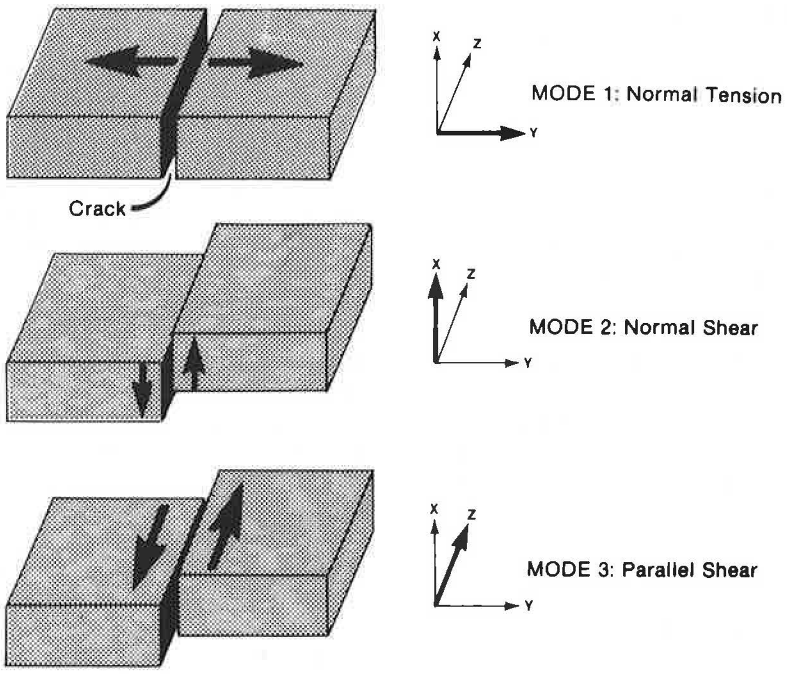

FIGURE 2 Modes of crack displacement.

mally induced displacements; (2) normal shear, usually associated with traffic or differential volume changes; and (3) parallel shear, which may occur only infrequently, for example, under lateral displacement due to instability.

A number of studies have been conducted to calculate the stress distribution in the overlay for Modes 1 and 2. For example, Cheetham and Haas (*3*) have shown how thermal stresses vary through the depth of the overlay for Mode 1, while Luther et al. (*4*) developed a finite element-based method for calculating stress distribution for Mode 2. Joseph (*5*) has shown how tensile and compressive stresses vary through the depth of the overlay under a combination of Modes 1 and 2.

The actual mechanism of crack initiation and propagation involves fracture of the overlay when the tensile stresses exceed tensile strength, under the particular conditions. A considerable amount of attention has been directed to the analysis of these mechanisms, as subsequently discussed.

ALTERNATIVE TREATMENTS

Various treatments have been tried in the past to control reflective cracking through asphaltic concrete overlays. These include the use of low-modulus, stress-relieving interlayers, geogrids, and fabrics. Other alternatives would include modifying the asphalt concrete overlay properties and pulverizing the existing pavement. While the latter can be successful, it is actually a form of reconstruction. Consequently, the following discussion focuses on the first three types of treatment.

Low-Modulus Interlayer

Fracture mechanics suggests that any attempt to reduce reflection cracking must be centered on reducing the stress concentration at the crack front. It has theoretically been established that provision of a lower-modulus, stress-relieving medium above the existing crack can reduce the rate of crack growth (*6*).

Geogrid or Fabric Reinforcement

The use of fabric or geogrid reinforcement has the potential to control crack propagation. The major types of geogrids used for this purpose are polymer-based, or glass grids. Wire meshes have been attempted in the past but are prone to corrosion. A large variety of fabrics is marketed for overlay application.

It is difficult to quantify adequately on an analytical basis the ability of grid or fabric reinforcement to control crack growth after initiation of the crack. Thus, it is important to supplement such analytical evaluation with experimental studies.

A Composite Stress-Relieving Interlayer

As a potential solution to the reflection-cracking problem, the use of a composite interlayer has been suggested (*3*). It involves a combination of low-modulus material with geogrid reinforcement placed on the existing cracked pavement. The expectation is that the low-modulus layer will act as a stress attenuator between the existing pavement and the overlay and that the reinforcement will carry any remaining stress.

ANALYTICAL EVALUATION METHODS

It is logical first to evaluate or screen any potential reflection cracking treatments on an analytical basis so that the experimental evaluation can be made more efficient.

Reflection cracking treatments can be evaluated analytically using a finite element technique. For example, Coetzee (*7*) carried out a limited finite element analysis to evaluate the effect of soft interlayers on asphalt overlay cracking due to low temperature. Also, attempts have been made (*4*) to model the effect of traffic load on reflection cracking using the finite element method.

The principal intent of this section is fourfold: (1) to present very briefly some of the existing analytical methodologies; (2) to provide the basis for selecting a suitable criterion for the analysis of reflection cracking; (3) to present a new approach using a blunt or smeared-crack band concept; and (4) to present some examples of analytical results.

Available Analytical Methodologies

Some of the methodologies that have been used for analyses of the reflection cracking problem include those developed by Majidzadeh and Sucharieh (*8*), Hung-Sun et al. (*9*), and Monismith and Coetzee (*10*).

A design methodology for the opening mode, low-temperature reflection cracking of an asphalt overlay on concrete pavement was developed by Majidzadeh and Sucharieh (*8*). They assumed that cracking initiates at the surface of an overlay because of contraction and curling of the underlying old pavement surface. Stresses due to horizontal joint movements were estimated using a finite element analysis. Subsequently, they established nomographs to estimate the tensile stress in the overlays.

A design process to arrive at an overlay resistant to environmental reflection cracking has been developed using linear elastic and viscoelastic stress analysis and fracture mechanics at Texas A & M University (*9*). Initially, thermal stresses in the overlay and old asphalt surface were calculated using viscoelastic theory. A crack propagation model was then proposed for the pavement material subjected to these thermal stresses using an empirical relationship developed by Paris and Erdogan (*11*). The stress-intensity factors necessary for this analysis are calculated using a finite element technique with special crack tip elements. Because of the anisotropic and heterogeneous nature of the overlaid pavement, however, the question exists as to whether stress-intensity factor is the best characterization to use.

Monismith and Coetzee (*10*) used finite element analyses, with effective stress as the criterion, to study the stress distribution around the crack (with and without a rubber asphalt membrane interlayer) due to traffic load and thermally induced stresses. They concluded that a softer interlayer has the potential to attenuate the stress concentration around the crack front. They also found that variables such as thickness and stiffness of both the rubber asphalt layers and the asphalt concrete overlay, and stiffness of the existing cracked layer, have some influence on the stress distribution for any load application.

Monismith and Coetzee suggested that design charts should be developed where stresses or strains could be utilized with an appropriate fatigue relationship to define cumulative damage. They also suggested that future experiments should consider the use of a relatively large slab to which a horizontal displacement can be applied to simulate cracking behavior.

Fracture Criteria

Fracture mechanics provide the following criteria for modeling of fracture: (1) stress-intensity factor, (2) critical strain energy, and (3) maximum stress.

The stress-intensity factor is very difficult to estimate for pavement overlays with underlying cracks because the material is anisotropic and nonhomogeneous. Also, the existing crack is not well represented by the typical mathematical formulations used in the application of fracture mechanics.

An energy criterion is very useful for modeling of fracture, particularly for the study of crack propagation. It represents the global characteristics of the system and does not depend on the detailed distribution of stress and strain near the fracture front. Therefore, it follows that the choice of element size around the crack tip in a finite element analysis will not have any significant effect on the results. Hence, a predictive model relating the energy criterion to the number of cycles required for complete fracture should be useful.

The strength criterion represents the local characteristics of the system and can be used to identify the critical section that is likely to initiate cracking. It could indicate whether or not a crack is likely to initiate at the top or bottom of the overlay, so that any potential treatment can be effectively evaluated. The main disadvantage is that it depends on the chosen mesh size in the elastic finite element analysis of cracking. This problem, however, can be circumvented by maintaining the same type and size of elements for evaluation of all potential treatments.

Joseph (*5*) has concluded that both the strength and energy criteria should be used—that is, the strength criterion for an initial analytical screening and determination of effective potential treatments, and the energy criterion to develop design charts on the basis of experimental results.

Blunt-Crack Band Theory

Fracture of a heterogeneous aggregate material such as concrete has been modeled in large finite element programs as systems of parallel cracks that are densely distributed (smeared) over the finite element. This was originally proposed by Rashid (*12*) and is known as the "blunt-crack band theory."

A detailed account of the analytical development and subsequent implementation of this theory in finite element analyses can be found in Bazant and Oh (*13*) and Joseph (*5*). Only some typical results and the relevant assumptions made in the analyses are presented in the following discussion.

Finite Element Modeling Using Crack Band Theory

A sample application involves the use of (1) low-modulus interlayer, (2) geogrid reinforcement, and (3) composite interlayer. The three-dimensional pavement structure has been simplified into a two-dimensional plane strain problem. The reason for considering plane strain is that the Poisson contraction in the z-direction can be neglected in view of sufficiently large pavement dimensions. More specifically, the following assumptions are made in the finite element analysis.

1. The average spacing of transverse cracks in the old pavement is assumed to be 12 m, based on field observations;
2. Perfect, uniform bonding is assumed between the overlay and the old pavement;
3. Adhesive strength between the overlay and the old pavement is greater than the "strength" of the overlay;
4. Coefficient of thermal shrinkage is the same for all layers and is equal to 27×10^{-6}°C (*3*);
5. Crack band width of 30 mm is assumed (Figure 3) based on the energy criterion (*5*, *13*); and
6. The linear thermoelastic stress-strain relationship is represented by the following equation:

$$\varepsilon_{ij} = \frac{(1 + \nu)\sigma_{ij}}{E} - \frac{\nu}{E}\delta_{ij}\sigma_{kk} + \alpha\Delta T\delta_{ij}$$

where

ε = strain in the element,
σ = induced stress,
E = elastic modulus of the layer,
ν = Poisson's ratio,
α = coefficient of thermal contraction,
ΔT = change in temperature, and
δ_{ij} = 1 for $i = j$, and = 0 for $i \neq j$.

Induced thermal stresses are estimated initially for two different boundary conditions: first, free horizontal movement between the existing, old pavement and the base course material; and second, the horizontal movement is completely restrained. The actual field situation would lie somewhere between these extremes. For evaluation of potential treatments only, the upper-bound situation is considered, that is, free movement between old pavement and the base course.

A typical finite element representation is shown in Figure 4. Temperature drop in each element corresponds to observed field data from the Ste. Anne Road Test (*14*). These input data are required for the finite element program SP23B (*15*).

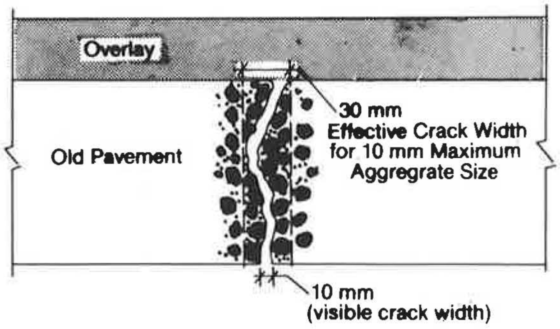

FIGURE 3 Effective width of existing crack.

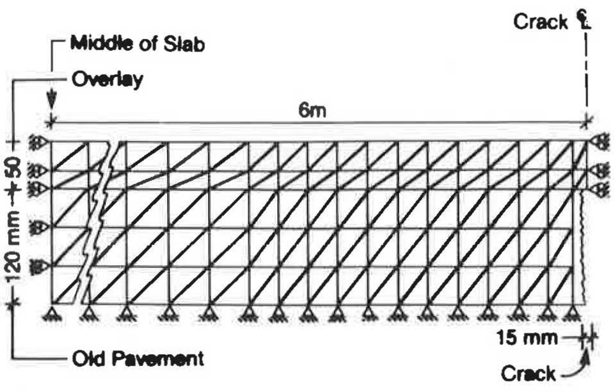

FIGURE 4 Finite element representation.

The material properties and temperature gradient used in the analysis are given in Tables 1 and 2 (compiled from Ste. Anne Road Test temperature measurements for low-temperature cycle, December 17, 1967 to January 11, 1968).

For the analysis of reinforced pavement overlays, additional discrete bar elements are used to represent reinforcement in the pavement section (Figure 5). Bar-element data include the cross-sectional area and the elastic modulus. It is assumed that bars are attached to the asphaltic concrete in nodes of the mesh.

Results of the analysis are given in Figure 6 through 10. In summary, they indicate the following:

1. A stress concentration exists around the crack front, because of the existing crack in the underlying pavement (Figures 6 and 7). The noticeable difference of stress values between two extreme boundary conditions indicates that the stress concentration can be reduced significantly by preventing movement of the underlying pavement. The only method available at the present time, however, is breaking up or pulverizing existing pavements. Figures 6 and 7 further indicate that the vertical section above the crack front is rather critical. This suggests that potential treatments for reflection cracking can be evaluated on the basis of the induced thermal stress distribution across the pavement overlay above the crack front. Figures 8 and 9 give the vertical stress distribution for treated and untreated pavement overlays.
2. The best location for the reinforcement is at the interface (Figure 8). Even though this reduces the induced stress by only approximately 15 to 20 percent, it has been observed that a 2 percent reduction in stress can lead to a 30 percent increase in life, illustrating the importance of stress amplitude in fatigue (*16*).
3. In a comparison of various treatments Figure 9 indicates that the composite interlayer (stress-absorbing membrane interlayer, "SAMI" reinforced with tensar geogrid) with 30-mm overlay thickness produces the same result as that of the SAMI alone with a 50-mm overlay thickness.
4. Figure 10 considers the gradual formation of microcracks leading to a macrocrack ahead of the existing flaw in the old pavement. During this process it is assumed that the stiffness modulus of the material represented by the crack band will gradually decrease to zero. The stress ahead of the crack band (point A) with and without the reinforcement is computed for three different stages of crack formation, with the stiffness modulus of the material changing from 100 percent (no crack) to 50 percent (microcracks), and finally to 0 percent (macrocracks) of the original value. It can be seen from Figure 10 that the reinforcement becomes increasingly effective as the crack propagates. This suggests that reinforcement can have a good potential to retard subsequent crack propagation after initial crack formation.

Analytical evaluation such as the foregoing is valuable in screening alternative treatments. In this example, for the conditions analyzed, all three treatments appear to have a potential for retarding reflection cracking. However, experimental

TABLE 1 MATERIAL PROPERTIES

Material	Elastic Modulus (MPa)	Poisson's Ratio	Thermal Coefficient (°C)
Old Pavement	6,894	0.4	27×10^{-6}
Overlay	2,069	0.4	27×10^{-6}
Softlayer	138	0.4	27×10^{-6}
Geogrid (Tensar)	15,000	0.4	27×10^{-6}
Fibreglass (Glass Grid)	76,000	0.4	27×10^{-6}

TABLE 2 TEMPERATURE GRADIENT FOR AN AMBIENT TEMPERATURE OF −32°C

Depth (mm)	Pavement Temperature (°C)	Depth (mm)	Pavement Temperature (°C)
0	-28.5	77	-21.6
10	-27.8	103	-18.0
20	-27.0	117	-16.2
37	-26.0	143	-12.6
43	-25.6	157	-10.8
63	-23.4		

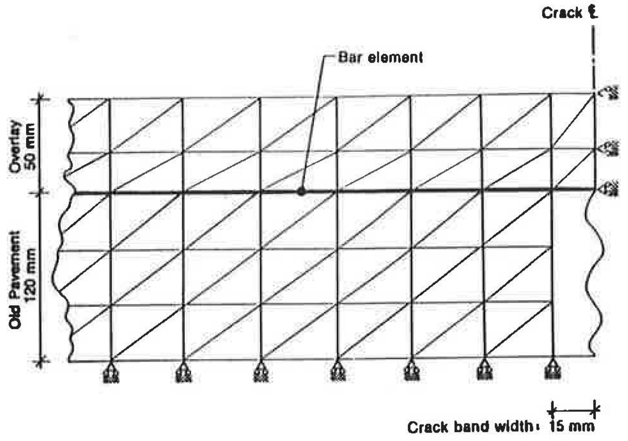

FIGURE 5 Finite element model representation using bar elements.

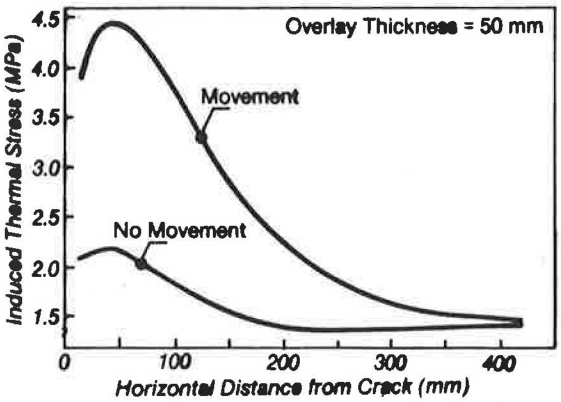

FIGURE 6 Stress distribution in the top of the asphalt overlay for different conditions.

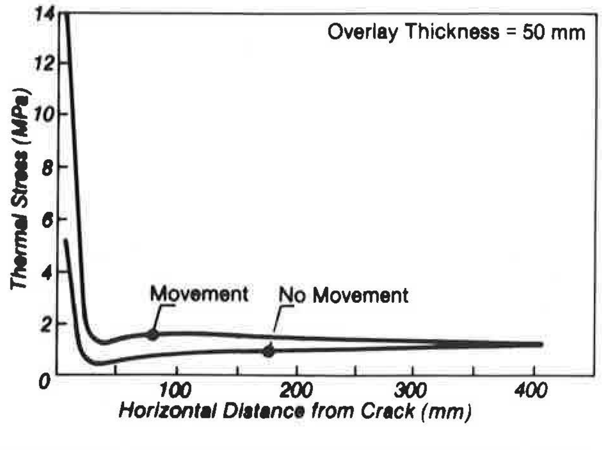

FIGURE 7 Stress distribution in the bottom of the asphalt overlay for different boundary conditions.

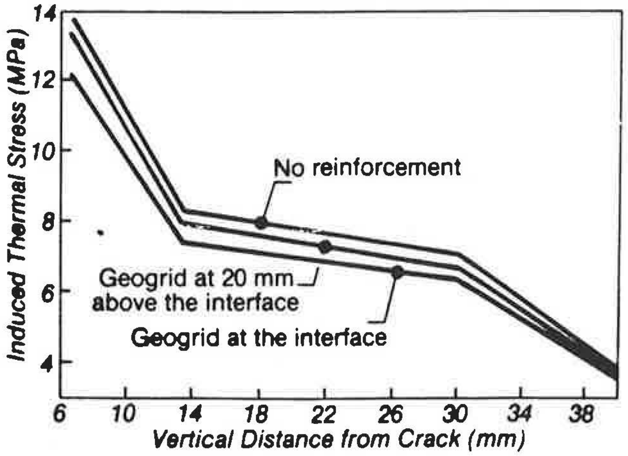

FIGURE 8 Effect of geogrid reinforcement on induced thermal stress.

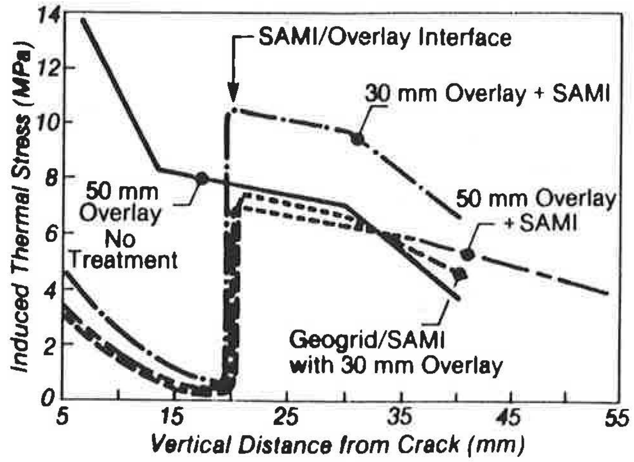

FIGURE 9 Comparative effect of various treatments.

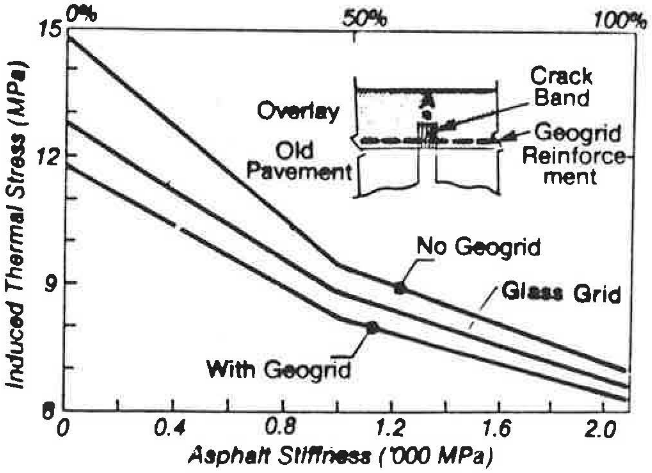

FIGURE 10 Comparative effects of glass-grid and geogrid reinforcements on crack growth for stiffness in the crack band 100 percent, 50 percent, and 0 percent.

evaluation should be used to provide confirmation and to give a better basis for final selection and actual field implementation. An example is given in the next section.

EXPERIMENTAL EVALUATION METHODS

The main objective of an experimental evaluation should be to evaluate potential treatments screened by analytical study and to develop a suitable design methodology. This would ideally involve laboratory tests that completely simulate field conditions. However, it is difficult to reproduce all field conditions, such as temperature gradients, interface conditions, and so forth.

An example experimental program involving two of the treatments (geogrid and glass grid) to follow the analytical evaluation previously described is summarized in the following discussion.

Major Variables

The variables that might be considered include initial crack-width opening, rate of movement of the underlying pavement or rate of drop in temperature, temperature gradient, overlay thickness, temperature and number of cycles, traffic loads and number of cycles, combination of thermal stress and wheel loading, type and location of treatment, and overlay mix type or design.

The most important variable is temperature. When the surrounding temperature drops significantly, thermal stresses are induced in the overlay, and movement of the underlying pavement occurs because of thermal shrinkage. This effect can be simulated mechanically, as illustrated by Joseph et al. (*17*). They developed a large-scale piece of equipment designed for both thermal and traffic load simulation. Their initial investigation, however, considered only thermally associated loads, and the example in this section is based on that work.

Experimental Equipment and Tests

A key part of Joseph et al.'s equipment consists of two steel plates, one fixed and the other horizontally movable on rollers with the aid of ball end bearings. The movable plate is linked to a mechanism designed to move the plate back and forth at variable, very slow rates equivalent to the crack opening or closing in an underlying old pavement. A cooling chamber is built into the system and is capable of maintaining a temperature as low as −40°C.

The equipment was used to test overlay slabs (approximately 450 mm long by 225 mm wide) sawed from constructed field pavements involving control plus reinforced sections, as described in detail by Joseph (*5*). It was felt that building such field sections to provide samples for testing, using standard construction techniques and equipment, would be more desirable than laboratory fabrication, particularly for the reinforcement treatments.

Figure 11 shows the factorial arrangement used for the testing program. Actual testing of each specimen included the following major steps:

Treatment Type	Control			Geogrid Reinforcement			Glass-grid Reinforcement		
Induced Displacement / Number of Replicates	Low	Med.	High	Low	Med.	High	Low	Med.	High
1	•	•	•	•	•	•	•	•	•
2	•	•	•	•	•	•	•	•	•
Average	•	•	•	•	•	•	•	•	•

NOTE: • = number of cycles to complete fracture

FIGURE 11 Factorial arrangement for the reinforced overlay test program (test temperature −30°C).

1. Cooling the specimen to −30° ± 2°C, until the temperature gradient reached a steady state; and
2. Subjecting the specimen to a uniform cyclic load at a predetermined displacement level, under controlled strain, until fracture propagates through the full depth. Three displacement levels (Figure 11) were chosen to cover the anticipated range of movements of old pavements in the field. A single displacement rate (.0399 mm/min) was used.

Example Results

Crack growth rates for the control and reinforced overlay samples are given in Figure 12. The effectiveness of both types of reinforcement in retarding crack growth at the low level of displacement (0.21 mm) is obvious. Even though a crack up to about 30 percent of the thickness developed after only 3 cycles, subsequent propagation was very slow and did not reach the full depth until after 200 cycles. Only 5 cycles at this displacement level were required to propagate a full-depth crack in the control sample.

At a higher level of induced displacement (0.26 mm) the glass grid reinforced section cracked to full depth in less than 10 cycles, while the geogrid reinforced sample took 25 cycles. Moreover, the glass grid reinforced samples showed some separation of matrix from the reinforcement.

The foregoing results suggest that glass grid and geogrid have potential in retarding crack growth rate. What remains to be seen in the field is whether they would provide effective "crack control" (i.e., keep the crack closed) after full-depth propagation.

The test results can also be presented in the form shown in Figures 13 and 14. These effectively become design charts corresponding to cyclic temperature variation between 0°C and −30°C.

To develop comprehensive thermal fatigue curves for asphalt overlays, it would be necessary to have a larger number of observations, including high cycle fatigue tests under different cyclic temperature variations. However, Figures 13 and 14 demonstrate that the experimental technique used can provide good relationships between stress or strain energy and fracture lives even with a limited number of observations.

In reality, of course, pavement structures are subjected to complex, fluctuating-temperature environments. The development of accurate fatigue-life prediction procedures for overlays requires characterization of the variable-amplitude, cycle-temperature fluctuations. This may best be done through

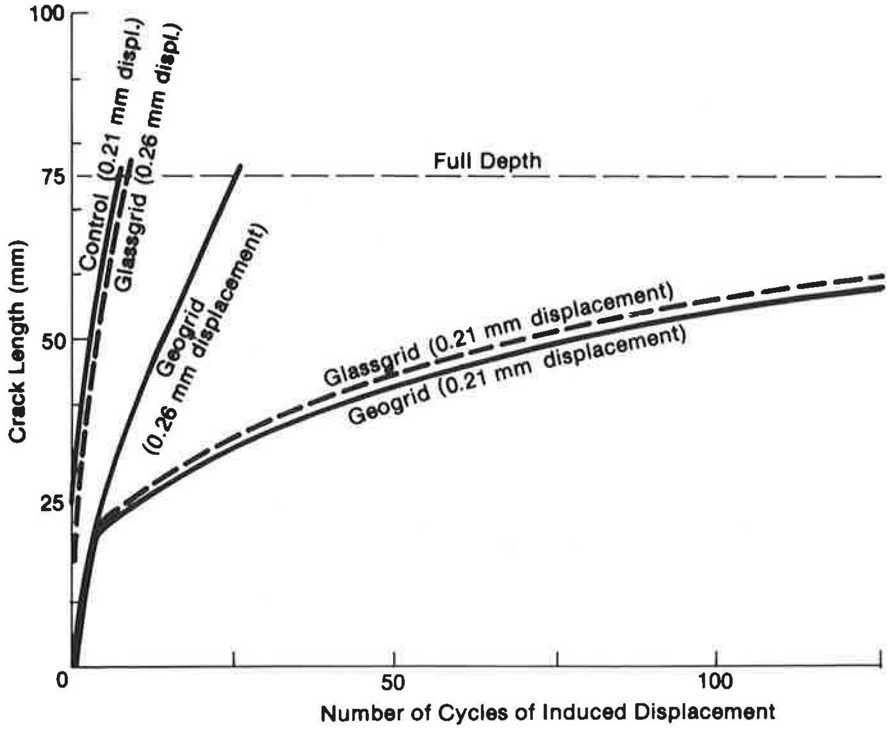

FIGURE 12 Crack growth curves for various overlay treatments.

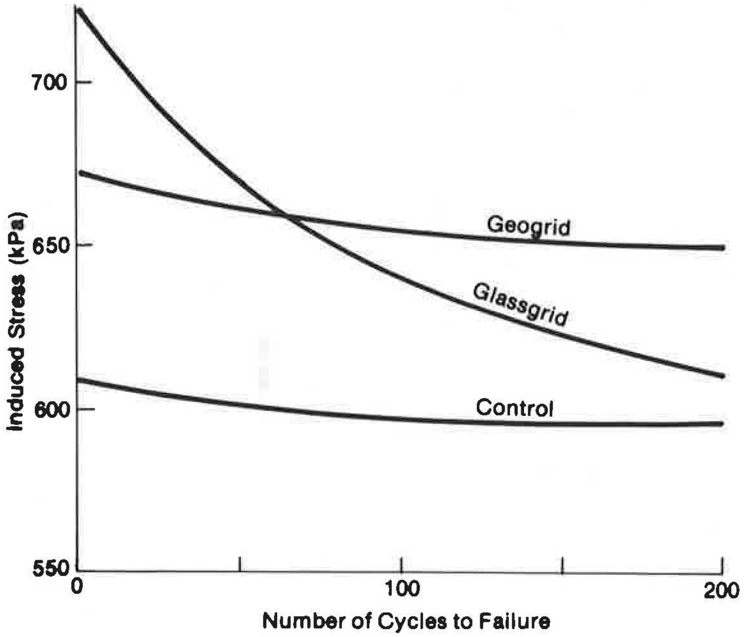

FIGURE 13 S-N curves for various overlay treatments.

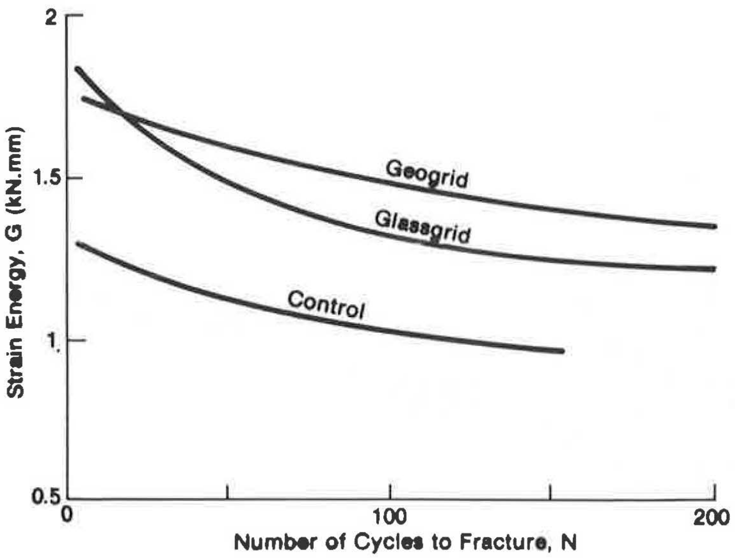

FIGURE 14 G-N curves for various overlay treatments.

the use of probability-density curves applied to the temperature history for a particular region. Then a cumulative damage approach, such as Miner's rule (*18*), could be used to represent the range of conditions.

SELECTION, INSTALLATION, AND FOLLOW-UP

The foregoing analytical and experimental screening or evaluation suggests that both the geogrid and the glass grid showed good potential for retarding reflection cracking in the conditions considered. If the displacement level of 0.21 mm is one of the applicable conditions, then both types of reinforced overlay should be able to withstand 200 very cold (−30°C) temperature cycles. This could cover several winters, depending on the variations at the particular location.

Economic considerations (Figure 1) are also important with regard to selection. The extra costs of geogrid or glass grid purchase and installation would have to be offset by longer service life of the reinforced overlay. Unfortunately, the technology of reflection cracking, including feedback from field observations of behavior and performance, is not yet sufficiently developed to allow for proper life-cycle economic evaluations to be performed.

Assuming that such an economic evaluation were favorable, certain construction or laydown considerations also apply to crack reflection treatments. These include the following:

1. Placement around sharp curves (except for SAMI treatments). Proper tensioning, particularly of geogrids, can also be difficult.
2. Proper bonding between the treatment and the old pavement. If this is insufficient, high traction forces from the paver can dislodge the material, and/or delamination can subsequently occur in service.
3. Roughness or undulations in the old pavement. If this is severe enough, a leveling course may have to be placed first before a treatment can be effectively applied (particularly fabrics, geogrid, or glass grid).
4. Proper bonding or interlocking between the overlay material and the treatment. This is important for fabrics and grids.
5. Temperature of the overlay mix during construction. In the case of polymer geogrids, this can, if too high, cause severe distortion.

Behavior and performance of the installed treatment can be evaluated in several ways. Perhaps the most important is simply to perform periodic crack surveys to determine what percentage of cracks has reflected through the overlay compared with the control or nontreated section. Also, condition or severity of the cracks can be assessed, which is important where a treatment has not prevented cracking but is effective in keeping the cracks closed. In this case the treatment would have more strain capability than the overlay material; that is, it would not have ruptured.

CONCLUSIONS

The problem of reflection cracking through overlays is widespread. It can be approached from the perspective of the factors or mechanisms involved and the alternatives available, combined with an analytical plus experimental evaluation to determine the best alternative for implementation.

This paper has concentrated on the latter aspect, evaluation, and one of the major conclusions is that a crack band theory in the finite element analysis can effectively be used to analyze treatment alternatives for minimizing or controlling reflection cracking. Also, the method allows for the analysis of alternative treatments at various stages of crack propagation without changing the mesh configuration and nodal points.

A further conclusion is that such analytical screening is valuable but not sufficient. Experimental evaluation should also be carried out. Testing procedures and sample results in the paper indicate how the potential success of the most promising treatments can be estimated. Relationships between induced stress and cycles to failure, and strain energy and cycles to failure, are used for this purpose. Such relationships can also be used to develop suitable design criteria so that reflection cracking can be minimized and/or effectiveness can be estimated in terms of life expectancy.

Finally, it is concluded that economic viability is important and, if this exists for the best alternative, then certain laydown and construction considerations are also important to realizing success.

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