FINITE ELEMENT ANALYSIS OF ARIZONA'S THREE-LAYER OVERLAY SYSTEM OF RIGID PAVEMENTS TO PREVENT REFLECTIVE CRACKING

BY

NAN JIM CHEN, P.E., Ph.D.
JOSEPH A. DI VITO, P.E.
GENE R. MORRIS, P.E.

OF

ARIZONA TRANSPORTATION RESEARCH CENTER
ARIZONA DEPARTMENT OF TRANSPORTATION

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ABSTRACT

Asphalt-rubber has been used as a Stress Absorbing Membrane Interlayer (SAMI) for overlay of flexible and rigid pavement for more than ten years in Arizona to retard reflective cracking with satisfactory performance.

This paper discusses several field experiments of asphalt-rubber overlays on rigid pavement with a three-layer system which consists of an asphalt concrete leveling course, a SAMI and a wearing course. This three-layer overlay system has provided a very smooth ride on an interstate highway for two years without a single visible reflective crack. The Average Daily Traffic (ADT) is approximately 100,000 with nine percent commercial vehicles.

Analytical studies utilizing the Finite Element Method (FEM) indicate this 3 layer system is far superior to simple overlays without interlayers. Stresses in an overlay above an existing joint are reduced significantly (up to 95% or more) due to the presence of a SAMI, and overlay life is extended.

As a result of the analysis, the three-layer system is recommended for overlay of a rigid pavement, especially when the rideability of the existing pavement needs to be improved. The leveling course not only improves rideability of the final overlay, but also the performance of SAMI.
INTRODUCTION

Reflection cracking has been defined as the cracking of a resurface or overlay pavement above underlying cracks or joints. Reflection cracks may be induced by environmental conditions or traffic loads or a combination of the two. It is a worldwide problem occurring in virtually all types of pavements unless steps are taken to prevent it. The problem is especially critical in overlays of rigid pavements and this paper is directed towards that problem.

Several treatments have been used to reduce reflective cracking in asphalt concrete overlays with varying degrees of success. Generally they fall into one of the following categories:

1. Treatments to existing concrete pavements (such as breaking into small sections) prior to any rehabilitative work,
2. Stress or strain relieving interlayers,
3. Cushion courses or special overlay treatments,
4. Increased overlay thickness.

Arizona's three-layer asphalt-rubber overlay system has been used on several experimental projects where Portland Cement Concrete Pavements (PCCP) were overlaid. The asphalt-rubber materials have been discussed thoroughly in other reports (1 through 9) and will not be discussed in this paper. The 3-layer system incorporates a thin flexible overlay placed in two layers with a low modulus asphalt-rubber interlayer between. It consists of an open-graded mix 1/2" to 3/4" thick placed as a leveling course directly on the cracked, rigid pavement followed by an asphalt-rubber flush-in with cover material. The final course is another open-graded mix 1/2" to 3/4" thick. The result is a thin, flexible overlay that resists reflective cracking for a much longer time than conventional overlays. Figure 1 is a simplified cross-section of this system.
ASPHALT-RUBBER FLUSH-IN
BLOTTED WITH COVER MATERIAL

ACFC OR LEVELING COURSE
OPEN GRADED PRE-MIX

PORTLAND CEMENT
CONCRETE PAVEMENT

22.9 CM

BASE MATERIAL

FIGURE 1. TYPICAL CROSS SECTION OF ARIZONA'S THREE-LAYER ASPHALT-RUBBER OVERLAY SYSTEM
As with most of the previously mentioned treatments, trial and error applications preceded mathematical modeling. The same is true for asphalt-rubber and the need currently exists to prepare analytical studies to verify field performance. The intent of this research was to establish an appropriate mathematical model to verify empirical observations. The analytical study consisted of a finite element analysis of stresses and strains with different layer configurations and is explained in detail in Part II. Part I will address the design and performance of the various experimental projects that received this specialized overlay treatment.

PART I - PROJECT PERFORMANCE

All pavements overlaid with the three-layer system were plain, undoweled pavements exhibiting varying degrees of structural cracking and load failure. Three of the projects are in the Flagstaff area at an approximate elevation of 7000 feet, while the three other projects are in the Phoenix valley area. Comparison of the two climate extremes has been informative. Flagstaff winter temperatures have been as low as -30°F while Phoenix summer temperatures can be as high as +115°F.

Table 1 provides a description of each of the projects and the dates overlaid with the three-layer system. A detailed description of each project follows.

1. 1-17 at Bell Road - This section of Interstate 17 in north Phoenix was not originally scheduled to receive the three-layer overlay system. In June, 1974, an open-graded Asphalt Concrete Friction Course (ACFC) was placed and asphalt-rubber was flushed into the mat with cover material applied. The treatment served very well until another adjacent resurfacing project in 1980 called for an ACFC to be placed over this experimental section,
### TABLE 1. SUMMARY OF FIELD PROJECTS WITH THE THREE-LAYER ASPHALT-RUBBER OVERLAY SYSTEM

<table>
<thead>
<tr>
<th>Project</th>
<th>Three-Layer System Placement Date</th>
<th>Length and Width</th>
<th>Traffic ADT and Commercial Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Southbound I-17 at Bell Road (Phoenix area)</td>
<td>Summer, 1974</td>
<td>1500 feet 38' wide</td>
<td>50,000+, 9%</td>
</tr>
<tr>
<td>2. Eastbound and Westbound I-40 Riordan to I-17 (Flagstaff area)</td>
<td>Summer, 1974</td>
<td>4 miles 38' wide</td>
<td>6,000, 20%</td>
</tr>
<tr>
<td>3. Westbound I-40 at Butler T.I. (Flagstaff area)</td>
<td>Summer, 1974</td>
<td>3000 feet 38' wide</td>
<td>7,500, 28%</td>
</tr>
<tr>
<td>4. Mesa Country Club Drive S.R. 87 (Phoenix area)</td>
<td>Fall, 1976</td>
<td>4000 feet 68' wide</td>
<td>25,000, 5%</td>
</tr>
<tr>
<td>5. Westbound I-40 at East Flagstaff T.I. (Flagstaff area)</td>
<td>Fall, 1977</td>
<td>1000 feet 38' wide</td>
<td>7,500, 28%</td>
</tr>
<tr>
<td>6. Southbound I-17 at Durango Curve (Phoenix area)</td>
<td>Fall, 1979</td>
<td>1500 feet 48' wide</td>
<td>95,000+, 9%</td>
</tr>
</tbody>
</table>
making it a three-layer overlay. So far, it has not exhibited any reflective cracks. Before 1980, the original treatment controlled 90% of the reflection of all joints and cracks.

2. I-40, Riordan to I-17 - A three-layer system was placed on this four-mile divided interstate highway project in 1974 in an attempt to control severe structural failure related to frost heave and thaw weakening. Cracking and joint faulting had progressed to the point where the highway had to be inspected daily for broken chunks of concrete. Structural failure (cracking) had occurred in a very large percentage of the travel lane. A typical view of cracking and skewed joints prior to overlay is shown in Figure 2. In addition, severe faulting was evident throughout the section. Prior to overlay, the integrity of the structural section was restored with sub-slab grouting. Structural cracks were grouted and sealed with asphalt-rubber as was the longitudinal edge joint. The PCCP was originally built 9" thick, unreinforced, with centerline tie bars. Shoulders were constructed of asphalt concrete. Since the three-layer layer has been in place, approximately 25% of the travel lane transverse joints in the PCCP have reflected through as cracks in the overlay. The cracks that have reflected are narrow, have not spalled and have not required any major maintenance. There is little reflective cracking in the passing lane. Approximately 10% of the longitudinal edge joint has cracked through the overlay. However, neither the tied centerline joint nor the structural cracks have appeared on the surface. All surface cracks have remained narrow and have not spalled, very likely due to the
TYPICAL VIEW OF CRACKING AND SKEWED JOINTS PRIOR TO OVERLAY

FIGURE 2. TYPICAL VIEW OF CRACKING AND SKEWED JOINTS PRIOR TO OVERLAY
extended flexibility of the asphalt-rubber at cold temperatures. While not completely controlling joints and cracks, the three-layer system has performed well in rehabilitating this section of highway that really should have been reconstructed.

3. **Butler Traffic Interchange, I-40** - Except for sub-slab grouting, this section was exactly like the Riordan experiment and was placed at the same time, summer 1974. Performance has also been similar to the Riordan project indicating that magnitude of vertical deflection may not be critical.

4. **Mesa Underpass on S.R. 87** - This experiment was originally established to test different application rates of the asphalt-rubber flush-in on the three-layer overlay system. It was constructed in the fall 1976. The lower ACFC layer was placed using two different gradations to test the effect of voids in the mat versus reflective crack prevention. After close observation for four years, the entire project had no reflective cracks. Since no changes were apparent in traffic patterns or loading, or any other factor, it is believed that asphalt-rubber stiffness properties may have changed or the life of fatigue crack propagation has been reached. Some surface instability was observed in the areas where 0.8 to 1.2 gallons per-square-yard (gpsyd) of asphalt-rubber was placed. Application rate was originally specified as 0.4, 0.6 and 0.8 but some areas received as much as 1.2 gallons per-square-yard. At date of this report, the surface has approximately 10% reflective cracking. Again, these cracks are hairline and have required no maintenance. Application rate (in the range of 0.4 to 0.8 gpsyd)
seems to have no effect on reflective cracking prevention nor did the variable gradation of the first-layer. Figures 3 and 4 were typical pavement conditions before overlay and five years after overlay.

5. **East Flagstaff, I-40** - The three-layer overlay system was placed as one of six different overlay test sections and is the only one of the six to perform well. All others have already been dismissed as unacceptable. The three-layer system has prevented 90% of all cracks and joints from reflecting through to the surface. It was placed in late summer, 1977 and to date, has shown very good results.

6. **Durango Curve on I-17** - The overlay of this urban Phoenix freeway section of rigid pavement took place in November, 1979. The three-layer system was to be compared with the very expensive alternative of grinding and grooving to restore ride and skid number. At the time of design, it was estimated to be 1/3 the cost of grinding. In addition, it could be constructed in a much shorter time period. After two years of service there are no reflective cracks of joints whatsoever. (An 18" transverse hairline crack was observed during January, 1982 inspection.) The only surface defects noticeable are two small areas (less than three square yards each) exhibiting rutting and shoving. They are the result of inadvertent excessive applications of asphalt-rubber during construction, a problem not attributed to design nor one that should occur during normal project construction. Figures 5 and 6 were pavement conditions before overlay and two years after overlay.
FIGURE 3. MESA UNDERPASS ON S.R. 87 BEFORE OVERLAY IN 1976

FIGURE 4. MESA UNDERPASS ON S.R. 87 FIVE YEARS AFTER OVERLAY (JANUARY, 1982)
FIGURE 5. DURANGO CURVE ON I-17 BEFORE OVERLAY IN 1979

FIGURE 6. DURANGO CURVE ON I-17 TWO YEARS AFTER OVERLAY (JANUARY, 1982)
The three projects in the Flagstaff vicinity have all demonstrated similar performance. Some reflective cracking is evident but it is essentially confined to the transverse joints in the travel lane. This indicates reflective cracking is related to the combination of thermal and load associated stresses. The fact that structural cracks did not reflect through demonstrates loading alone is insufficient to cause reflective cracking of the three-layer overlay system.

Also, the passing lane of the three projects is virtually crack-free which indicates thermal stresses alone are insufficient to cause cracking. The tied centerline joint has not cracked through, further supporting these conclusions.

The Phoenix area experiments demonstrate the three-layer overlay system will prevent reflective cracking of joints and cracks for up to four years in mild climatic environments. After this length of service, approximately 10% cracking is apparent. The Durango curve project has proven the system is very stable under the extreme conditions of high traffic volume with heavy loadings combined with extreme high summer temperatures.

In all cases, the system has maintained good surface friction qualities (high skid numbers) and good ride quality. The system is far less expensive than grinding to smooth PCCP and much less disruptive to traffic during construction.
PART II - ANALYTICAL STUDIES

To explore the basic reason why asphalt-rubber prevents reflective cracking of rigid pavement and to determine the structural adequacy of the system, an analysis was conducted of the theoretical behavior of the overlay structure. Several Finite Element Method (FEM) computer programs were utilized for the analysis of stresses and strains with different layer configurations. The primary computer program used for this study was a slightly modified static analysis program for solid structures - SOLID SAP by Wilson (10). The slight modification of this program was in the calculation of the effective stresses (11), which is essentially the "root mean square" shear stresses, and defined by using the normal and shear stresses in an orthogonal Cartesian coordinate system as

\[
S_{\text{eff}} = \frac{1}{N^2} \left[ (S_{11} - S_{22})^2 + (S_{22} - S_{33})^2 + (S_{33} - S_{11})^2 + 6(S_{12}^2 + S_{23}^2 + S_{31}^2) \right]^{1/2} \quad \ldots \ldots (1)
\]

They were considered to be a realistic determinant for fracture (cracking) under the triaxial stress state existing in the overlay pavement. In order to reduce the cost of computer time, a linear elastic plane strain analysis was assumed with 685 nodes and 620 elements. Among the field experiments, there are several overlay configurations with different existing conditions. The finite element analysis was simplified by studying a nine-inch concrete pavement (PCCP) with a 0.3-inch joint overlayed by different thicknesses of asphalt concrete and a SAMI. The general configuration of the pavement overlay system is shown in Figure 7. Seven different overlay designs were analyzed ranging from a very thin (1 5/8") three-layer design to a seven-inch overlay. Information on input thickness and layer arrangement is given in Table 2. Mechanical properties
FIGURE 7. GENERAL CONFIGURATION OF THE OVERLAY SYSTEM ON RIGID PAVEMENT
<table>
<thead>
<tr>
<th>OVERLAY DESIGN THICKNESS</th>
<th>SURFACE COURSE CM (IN.)</th>
<th>SAMI Course CM (IN.)</th>
<th>LEVELING COURSE CM (IN.)</th>
<th>TOTAL CM (IN.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 1</td>
<td>1.59 0.625</td>
<td>0.95 0.375</td>
<td>1.59 0.625</td>
<td>4.13 1.625</td>
</tr>
<tr>
<td>CASE 2</td>
<td>3.18 1.25</td>
<td>0.95 0.375</td>
<td>0.0 0.0</td>
<td>4.13 1.625</td>
</tr>
<tr>
<td>CASE 3</td>
<td>4.13 1.625</td>
<td>0.0 0.0</td>
<td>0.0 0.0</td>
<td>4.13 1.625</td>
</tr>
<tr>
<td>CASE 4</td>
<td>9.21 3.625</td>
<td>0.95 0.375</td>
<td>0.0 0.0</td>
<td>10.16 4.0</td>
</tr>
<tr>
<td>CASE 5</td>
<td>10.16 4.0</td>
<td>0.0 0.0</td>
<td>0.0 0.0</td>
<td>10.16 4.0</td>
</tr>
<tr>
<td>CASE 6</td>
<td>16.83 6.625</td>
<td>0.95 0.375</td>
<td>0.0 0.0</td>
<td>17.78 7.0</td>
</tr>
<tr>
<td>CASE 7</td>
<td>17.78 7.0</td>
<td>0.0 0.0</td>
<td>0.0 0.0</td>
<td>17.78 7.0</td>
</tr>
</tbody>
</table>

TABLE 2. ARRANGEMENT OF OVERLAY THICKNESS
of different pavement layers used for analysis are listed in Table 3. From the results of very limited tensile and shear tests on viscoelastic properties of asphalt-rubber, the ranges of creep compliance values can be roughly determined as shown in Figure 8. The elastic moduli of SAMI were selected accordingly for finite element analysis. For the study of moving traffic, 2000 psi was selected and 10 psi chosen for the thermal study.

The thermal effect on an overlay was studied by using two different temperature profiles from the surface of the overlay down to the subgrade, with the higher one used as a stress free temperature. A profile of temperature differences is given in Figure 9. A 50-degree (°F) temperature change on the surface of the overlay was used for analysis.

Moving traffic on the overlay was represented by a 12" long, 100 psi load for the FEM computer analysis. The location of this loading was moved every two inches from one side of the joint to the other (see Figure 7) and influence lines of stresses above the existing joint were plotted and evaluated.

The stresses which were investigated in this study are located approximately 0.09" right above the existing joint (center of the lowest layer of mesh within overlay used for finite element analysis) and those stresses are not the average stresses in different layers. A higher stress indicates that reflective cracking may start to propagate sooner than that with a lower stress.

The major findings of this study are as follows:

(a) **Three-layer overlay system** - The three-layer overlay analyzed, consisted of a thin (5/8") asphalt concrete leveling course, a 3/8" SAMI and a thin (5/8") asphalt concrete surface wearing
<table>
<thead>
<tr>
<th></th>
<th>ELASTIC MODULUS (E)</th>
<th>SHEAR MODULUS (G)</th>
<th>POISSON RATIO (μ)</th>
<th>THERMAL COEF. (α)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURFACE AND LEVELING COURSE</td>
<td>2070 300 MPa KSI</td>
<td>828 120 MPa KSI</td>
<td>0.3</td>
<td>0.0000125 °F</td>
</tr>
<tr>
<td>SAMI (TRAFFIC)</td>
<td>13.8 2 MPa KSI</td>
<td>5.52 0.8 MPa KSI</td>
<td>0.35</td>
<td>0.0000150 °F</td>
</tr>
<tr>
<td>SAMI (THERMAL)</td>
<td>0.069 0.01 MPa KSI</td>
<td>0.0276 0.004 MPa KSI</td>
<td>0.35</td>
<td>0.0000150 °F</td>
</tr>
<tr>
<td>PCCP</td>
<td>27600 4000 MPa KSI</td>
<td>11040 1600 MPa KSI</td>
<td>0.2</td>
<td>0.0000039 °F</td>
</tr>
<tr>
<td>SUBGRADE</td>
<td>69 10 MPa KSI</td>
<td>27.6 4 MPa KSI</td>
<td>0.48</td>
<td>0.0000100 °F</td>
</tr>
</tbody>
</table>

TABLE 3. ELASTIC PROPERTIES OF OVERLAY COMPONENTS FOR ANALYSIS
FIGURE 9. TEMPERATURE PROFILE USED FOR THERMAL ANALYSIS
course. The major advantage of this system over a 2-layer (SAMI and AC) system is that the leveling course will provide a very smooth surface for the SAMI to behave as a stress absorbing layer. Without this leveling course, very often, the asphalt-rubber will flow into joints or large cracks and a continuous stress absorbing layer can not be achieved. Results of the analytical study indicate stresses in the leveling course above the joint are very high but due to the existence of the SAMI, stresses in the surface course are very low. See Figures 10 and 11. Both shear stress ($S_{12}$) and effective stress ($S_{eff}$) are at a maximum when the simulated traffic loading is completely on one side of the concrete slab. The very low stress level in the surface course indicates a very low stress intensity factor which in turn will provide a longer service life for the overlay versus reflective cracking.

(b) Overlay Thickness - Overlay thickness from 1 5/8" to 7" were studied, with and without a SAMI. The typical influence lines of shear and effective stresses within the overlay are indicated in Figures 12 and 13. The stresses in the overlay reduced significantly because of the existence of the SAMI. For an overlay without a SAMI, stresses reduce significantly due to increasing thickness (refer to Figures 14 and 15). However, for an overlay with a SAMI, stresses were only slightly reduced due to the increasing overlay thickness (Figure 16). This indicates, from an economical point of view, a thick overlay may not be justified for a reflective overlay design when a SAMI is utilized.
Figure 10. Influence lines of shear stress above the crack tip due to moving load (three-layer system)
FIGURE 11. INFLUENCE LINES OF EFFECTIVE STRESS ABOVE THE CRACK TIP DUE TO MOVING LOAD (THREE-LAYER SYSTEM)
FIGURE 12. TYPICAL INFLUENCE LINES OF SHEAR STRESS ABOVE THE CRACK TIP DUE TO MOVING LOAD
FIGURE 13. TYPICAL INFLUENCE LINES OF EFFECTIVE STRESS ABOVE THE CRACK TIP DUE TO MOVING LOAD
FIGURE 14. INFLUENCE LINES OF SHEAR STRESS ABOVE THE CRACK TIP DUE TO MOVING LOAD (WITHOUT SAMI)
FIGURE 15. INFLUENCE LINES OF EFFECTIVE STRESS ABOVE THE CRACK TIP DUE TO MOVING LOAD (WITHOUT SAWI)
FIGURE 16. EFFECTS OF SAMI ON SHEAR AND EFFECTIVE STRESSES
(c) **Thermal Effects** - The elastic moduli of asphalt concrete (AC) and asphalt concrete friction course (ACFC) for thermal study were assumed to be the same as that for traffic study, i.e., 300 ksi, this value may be too high for slow loading such as thermal changes. Unfortunately, no effect was being made to study the visco-elastic behavior of AC and ACFC. Results of this study indicate the horizontal tensile stress near an existing joint is reduced significantly with the low modulus interlayer, especially for thin overlays. The SAMI does not reduce the overall horizontal stress in an asphalt concrete (AC) or asphalt concrete friction course (ACFC) due to thermal expansion or contraction. However, it will significantly reduce stress concentration above the existing joint, minimizing reflection cracking. For an overlay without a SAMI, horizontal tensile stress reduces significantly due to increasing thickness as shown in Figure 17. For an overlay with a SAMI, horizontal tensile stress is only slightly reduced due to the increasing overlay thickness. In a three-layer overlay system, horizontal tensile stresses are very high in the leveling course and may cause cracks. Stresses in the surface course are very uniform and the influence of existing cracks can hardly be detected. This indicates a SAMI can effectively retard or eliminate reflection cracking due to thermal expansion or contraction of a jointed rigid pavement.

(d) **Effects of Moving Traffic** - Throughout the analytical study, it was assumed there was no load transfer capability across the joint. This condition would exist when vertical differential
FIGURE 17. EFFECTS OF SAMI ON THERMAL HORIZONTAL TENSILE STRESS
movement of a joint is relatively small under loading. Sufficient vertical movement can occur that aggregate interlock and dowels may not have an effect in reduction of shear stress. This study has revealed that both shear and effective stresses are at a maximum when traffic loading is completely on one side of the concrete slab. Results also indicate that a SAMI can reduce horizontal thermal stress, effective stress and shear stress in the overlay which many researchers believe to be the major factors causing reflective cracking.

SUMMARY AND CONCLUSIONS

Based on the field performance of several projects and analytical studies, the following conclusions can be made:

1. The three-layer system can be used for reducing reflective cracking when placed over a rigid pavement. The leveling course provides a smooth surface for a SAMI to behave as a continuous stress absorbing layer. The stresses in the surface course are extremely low and insure a much longer service life.

2. When a SAMI is used in the three-layer overlay system, asphalt-rubber application rate is important because excessive rates promote instability of the system. A specified rate of approximately 0.60 gallon-per-square-yard yields good results.

3. Field performance indicates that load stress alone or thermal stress alone are insufficient to cause major reflective cracking. The combination of these stresses in cold climatic regions may be sufficient to cause reflective cracks.

4. Field performance indicates that those cracks that do reflect through are narrow, do not spall and require little if any maintenance.
5. A three-dimensional finite element analysis with improved time and temperature dependent material properties will provide better results. However, computer time required may increase 10 to 20 times. The primary purpose of this study is to report a successful application of asphalt rubber as a SAMI in rigid pavement overlay and attempt to provide analytical explanations for the apparent success of this new approach in pavement rehabilitation.

6. "Shearing" action is more inducive to reflective cracking of overlays than "Bending" action when a traffic loading is moving from one side of a joint to the other.

7. SAMIs can not only reduce stresses caused by thermal changes but also vertical shear stresses due to moving traffic loading.

8. It is intuitively obvious that reduced stress level will result in increased service life of overlay. The prediction of service life with or without SAMI could be accomplished by analyzing the fatigue behavior of the systems.

9. When a SAMI is utilized, the thickness of overlay becomes less critical. This may result in very economical approaches to overlay design.

10. A better understanding of SAMI properties is needed through continued laboratory testing.
REFERENCES


