Asphalt Rubber Interlayer Benefits in Minimizing Reflective Cracking of Overlays over Rigid Pavements

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Abstract. This paper provides an overview of the asphalt rubber interlayer benefits on reflective crack retardation in overlays over rigid pavements. These interlayers are known in California as asphalt rubber absorbing membrane interlayers (SAMI-R) or as asphalt rubber aggregate membrane interlayers (ARAM-I) chip seals. The paper focuses on the performance in terms of field project reviews, laboratory performance tests and finite element analysis. SAMI-R has been given a reflective cracking equivalent thickness of 15 mm of asphalt rubber hot mix overlays or 30 mm of dense graded hot mix overlays. The finite element analysis confirms the quantified reflective cracking benefits of SAMI-R and provides optimum design alternatives to conventional dense grades asphalt concrete overlays. The paper concludes that SAMI-R is effective in minimizing reflective cracking distress and in extending pavement life.

Introduction

In the rehabilitation of rigid pavement structures using asphalt concrete overlays, interlayers are often used to minimize reflective cracking. One of these types of interlayers are asphalt rubber chip seals which possess low stiffness and high deformability. These interlayers dissipate the stress and strain energies that accumulate at the crack and joint tips of an rigid pavement which would otherwise get transferred to the underside of the HMA overlay. The dissipation of these high level stresses and strains minimizes the potential of reflective cracking in the HMA overlays. Reflective cracking is considered a major pavement distress which occurs as a result of cracks that reflect through an HMA overlay from cracks or joints of an existing pavement. Another additional benefit of an interlayer is its ability to prevent water intrusion into the lower layers of the pavement structure; thus protecting the structural integrity of the pavement system.

Asphalt rubber chip seals have been used effectively as interlayers over distressed flexible and rigid pavements, and as a surface treatment [1]. In California, these interlayers are known as rubberized stress absorbing membrane interlayers (SAMI-R) or asphalt rubber aggregate membrane interlayers (ARAMI) [2,3], and are often used interchangeably in the pavement technical literature and throughout this white paper. A schematic of a pavement section showing a typical ARAMI is shown in Figure 1. When used as a surface layer such as rubberized open graded friction course, it is called asphalt rubber aggregate membrane (ARAM) or simply a rubberized chip seal.

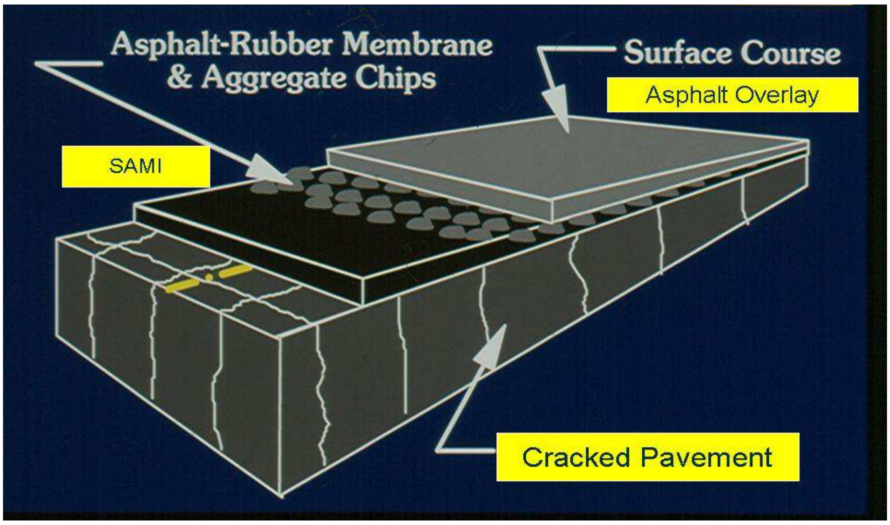

Figure 1. Schematic of a cracked pavement receiving an ARAMI prior to an HMA overlay.

Interlayers can extend the life of preservation and rehabilitation strategies. The magnitude of life extension depends on many factors including existing pavement condition, traffic loading, climatic and environmental conditions, and the type and engineering properties of the interlayer used [1]. The excellent performance of these interlayers is primarily due to the (1) unique elastic properties, and (2) superior aging characteristics of the asphalt rubber binder which can withstand as much as five times more strain than the unmodified asphalt binder [4].

Performance of Interlayer Systems

The merits of ARAMI's have been proven both in the field and the laboratory. Additionally, a number of analytical studies using Finite Element Methods (FEM) have demonstrated the efficacy of interlayer systems in minimizing the potential of reflection fatigue cracking in HMA surface courses. In the following, a brief discussion of some related performance studies is presented.

Field performance of many projects in California and Arizona, since the 1970's. has shown the significant benefits of SAMI-R in retarding reflective cracking on HMA overlays [5-12]. These studies concluded the effectiveness of SAMI-R in reflective cracking retardation and the superiority of the pavement systems incorporating SAMI-R's to those without SAMI-R's.

Many laboratory experiments were conducted to investigate the effectiveness of SAMI-R's in retarding reflection cracking in new HMA overlays. Recently, Bin et al. [13] conducted a laboratory simulation study using the Hamburg wheel tracking test to compare the relative reflective cracking performance of various types of interlayers that were placed below a hot mix asphalt overlay over an existing cracked pavement. These interlayers included SBS modified asphalt sand, Asphalt rubber sand, Fiber glass polyester mat and SAMI-R in addition to a control section without an interlayer. Note, the SAMI-R is the interlayer type modeled in this paper. The tests were conducted at a rate of 52 cycles per minute to simulate the development of reflective cracking under a moving load. The test specimens were simply supported beams conditioned at -20 ºC for 5 hours prior to load conditioning by the application of 8000 loading cycles to stabilize the deflection. The specimens were then subjected to loading cycles until failure; which was described as the first appearance of a crack at the bottom of the surface layer. It was found that the use of an interlayer would extend pavement life significantly when compared with the option of not using an interlayer. In addition, the SAMI-R interlayer was superior to the other types of interlayers tested in these experiments in retarding reflective cracking and extending the life of the overlay.

Additionally, a number of analytical studies have been conducted using finite element analysis to theoretically investigate the contribution of SAMI-R's to the performance of rigid and flexible pavement systems. Among the early studies are those conducted by Coetzee and Monismith [14] and Chen et al. [15]. In Coetzee and Monismith [14], 48 simulations representing various configurations of cracked concrete pavements overlaid with a rubberized stress absorption membrane followed by an asphalt overlay. In the simulations, the effect of many variables was studied including the asphalt concrete overlay modulus (varied between 100,000 psi to 1,500,000 psi) and thickness (varied between 2 to 4 inches). The modulus of the interlayer was assumed between 1,000 and 20,000 psi with a thickness between 0.125-0.5 inch. The concrete layer modulus was varied between

1,000,000 and 4,000,000 psi and its thickness between 4 and 8 inches. A crack in the concrete layer 0.25-0.5 inch wide was assumed. Finally, the base layer was assumed 12 inch thick and 20,000 psi modulus and the subgrade modulus was varied between 5000-10,000 psi. A general purpose 2-D finite element program was used in the analysis. The analysis confirmed the effectiveness of the low-modulus interlayer in reducing the crack tip effective stress (described by the Von Mises criterion), and the inhibition of reflection cracking resulting from both load (traffic loading) and temperature changes (thermal loading). The study found a significant reduction in crack tip stress with the use of the rubber asphalt interlayer. This was found to be more pronounced in those cases where the overlay modulus is 0.1-0.25 that of the cracked PCC layer. The study has also shown that crack width, interlayer modulus, and overlay thickness have significant effect on the crack tip stress, but that the ratio of overlay modulus to cracked layer modulus appears to be more influential.

Chen et al. [15] analyzed the Arizona three-layer thin-overlay system with the use of a 2-D finite element program in which an asphalt rubber concrete is placed in two lifts each 5/8 inch thick and a low-modulus asphalt rubber interlayer 3/8 inch think placed in between. The bottom lift may be considered as a leveling course. This system, also called SAMI-R in Arizona, was commonly placed on top of cracked Portland cement concrete pavements prior to overlaying with hot mix asphalt. In the analytical studies, a 9 inch PCC layer with a crack 0.3 inch wide was assumed. An HMA overlay of various thicknesses placed over the interlayer system was analyzed under the effect of both moving traffic and thermal loadings. The results of the analysis indicated the significant benefits of using the interlayer system in reducing the critical stresses and strains and in dissipating the stress concentrations at the crack tip for HMA overlays placed over rigid pavements. The study demonstrated a significant reduction in both the effective stress and shear stress above the crack tip upon using an interlayer due to both temperature changes and traffic loading. It was also observed that upon incorporating an interlayer, the effect of overlay thickness becomes less critical leading to more economical designs.

Finite Element Analysis

Two dimensional finite element analyses was conducted to study a number of factors and their influence on the performance of rigid and flexible pavement systems incorporating ARAMI's (SAMI-R's) in comparison with systems that did not include these interlayers. Table I provides a summary of the parameters used in the analysis. A total of 36 scenarios involving various variables pertaining to concrete pavements overlaid with HMA were analyzed. Cracks 3 mm wide with a 60 cm spacing were assumed. The finite element models studied consisted of an HMA overlay with or without ARAMI layer, with or without leveling course on top of a rigid cracked pavement; thus representing four types of configurations.

Two types of ARAMI’s, varying in their stiffness, were used in the analysis. The ARAMI was assumed to be orthotropic with regard to its modulus. The “Soft” ARAMI has a modulus of 7 MPa in the horizontal direction and 100 MPa in the vertical direction. The “Hard” ARAMI was assumed to have a modulus of 35 MPa in the horizontal direction and 100 MPa in the vertical direction. Whenever used, the ARAMI thickness was assumed to be equal to 1.0 cm.

The 2-D finite element model used in the analysis represents an HMA overlay with or without ARAMI layer, with or without leveling course on top of a rigid cracked pavement which, in turn, rest on top of a granular base layer and a subgrade layer. The model was designed considering the existence of full friction between the old and new pavement layers. The materials were modeled assuming a linear elastic behavior.

The mesh of the model was designed as a plain strain problem, by using quadrilateral, two-dimensional structural-solid elements, with eight nodes, with two degrees of freedom at each node. The mesh was designed to apply a load with a dual wheel configuration representing a standard axle wheel of 80 kN, applied on the pavement surface in a representative area of the tire-pavement contact. The finite element model used in the numerical analysis was developed in a general finite elements code, ANSYS(R) Academic Teaching Introductory, V12.1. The 2-D finite element model used in the analysis considers typical values for thickness and stiffness as indicated in Table I. Many strains and stresses (X, Y, and XY) were determined with the finite element models analyzed at a number of locations; both within the interlayer and in the overlays, as shown in Figure 2.

Input parameter	**Values**
HMA overlay thickness (cm)	2.0, 6.0, 12.0
HMA overlay stiffness (MPa)	2000, 4000
ARAMI thickness (cm)	0 (none), 1.0
ARAMI stiffness (MPa) (Horizontal, Vertical)	Case 1 (Soft interlayer): (7,100) Case 2 (Hard interlayer):(35,100)
Leveling course thickness (cm)	0 (none), 3.0
Leveling course stiffness (MPa)	Equal to that of the HMA overlay
Existing PCC thickness (cm)	20.0
Existing PCC stiffness (MPa)	20,000
Existing PCC crack spacing (cm)	60.0
Existing PCC crack opening (cm)	0.3
Aggregate base layer thickness (cm)	20.0
Aggregate base layer stiffness (MPa)	270
Subgrade stiffness (MPa)	35

Table I – Material properties used in the finite element analysis of rigid pavements.

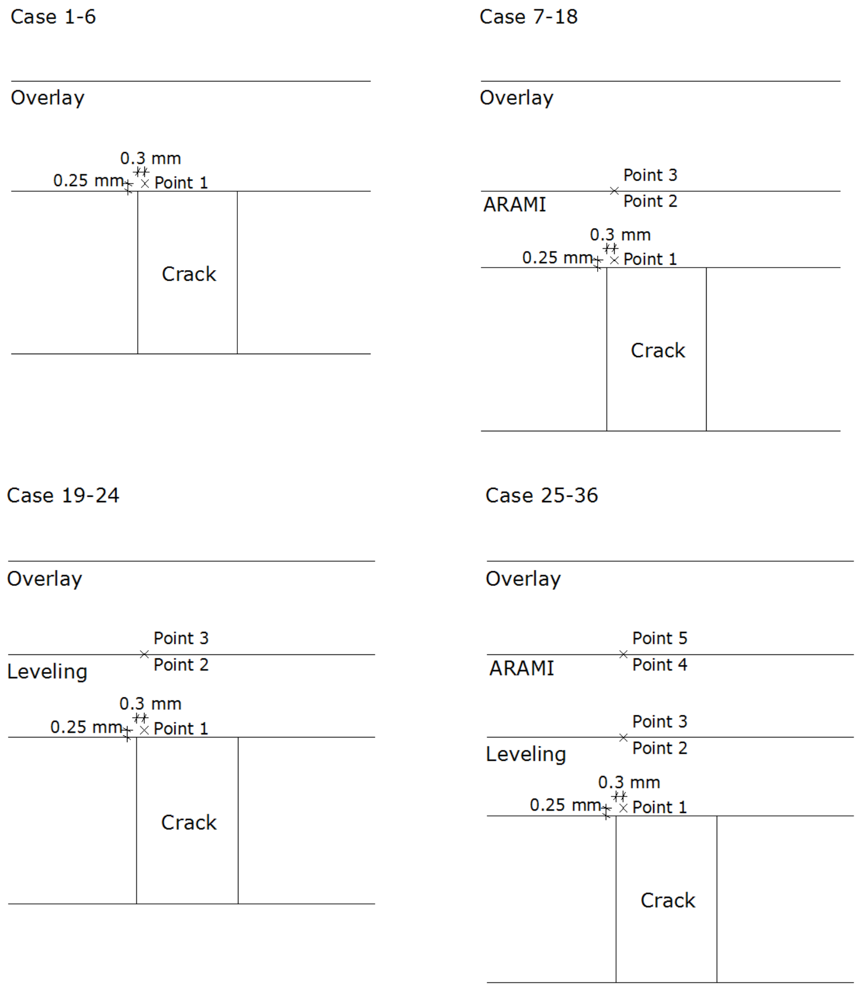

Figure 2. Location of the points used in the analysis of rigid pavements.

In cases where a leveling course may be used prior to placement of the interlayer and subsequently the HMA overlay, the Von Mises strain was calculated at the interface between the leveling course and ARAMI and between the ARAMI and the overlay. Also, Von Mises stresses were calculated in the same locations as for strains. Also included for the analysis is the configuration where a rigid pavement receives only a leveling course without any interlayer then an HMA overlay, as shown in Case 19-24 of Figure 2.

In this paper, only the effective stresses and strains defined by Von Mises criterion will be used in evaluating the benefits of the interlayers. The Von Mises stresses and strains have been used by many researchers in evaluating pavement systems [9, 14, 15]. The Von Mises stress is calculated from the principal stresses according to the following equation:

$$\sigma_{VM} = \sqrt{\frac{(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_2)^2}{2}}$$

where σ_{VM} is the Von Mises stress, and σ_1 , σ_2 , and σ_3 are the major, intermediate, and minor principal stresses, respectively. A similar equation may be written for the Von Mises strain as follows:

$$\varepsilon_{VM} = \frac{1}{1+\upsilon}\sqrt{\frac{(\varepsilon_1-\varepsilon_3)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_1-\varepsilon_2)^2}{2}}$$

where ε_{VM} is the Von Mises strain, and ε_1 , ε_2 , and ε_3 are the major, intermediate, and minor principal strains, respectively. For a 2-D system, the above two equations are reduced by assuming $\varepsilon_3=0$ and $\sigma_3=0$. In order to study the benefits of interlayers in extending the fatigue life of the HMA overlay, the Von Mises stresses and strains were calculated at the underside of the HMA overlay for all the systems with and without interlayers. Once these stresses and strains are calculated, they may be used with appropriate transfer function to calculate fatigue life.

Figure 3 shows the Von Misses stress that develops at the underside of the HMA overlay in the various overlay configurations studied. Similarly, Figure 4 shows the calculated Von Mises strain at the bottom of the HMA overlay.

In order to study the effect of using ARAMI on the fatigue reflective cracking performance of HMA overlays placed over cracked rigid pavements, a transfer function would be required to describe the rate of deterioration as function of the strain at the bottom of the overlay. Since a Von Mises type of strain was used, it would be necessary to have a transfer function with such a strain in its statement. Sousa et al. [9] provided such equations for HMA and gap graded rubberized hot mix asphalt (RHMA-G) as shown in Figure 5. In these equations, the fatigue life represents the number of loading cycles until crack initiation and it does not consider crack propagation. In this study, the overlay is made of HMA (dense graded asphalt concrete) and therefore, the corresponding transfer function shown in Figure 5 will be used in computing the fatigue life of the overlay in terms of repetitions of the 80-kN axle load (1 ESALs). Figure 6 shows the calculated fatigue life for three HMA thicknesses (2, 6, and 12 cm) and the 12 pavement configurations used in the analysis (total 36 cases).

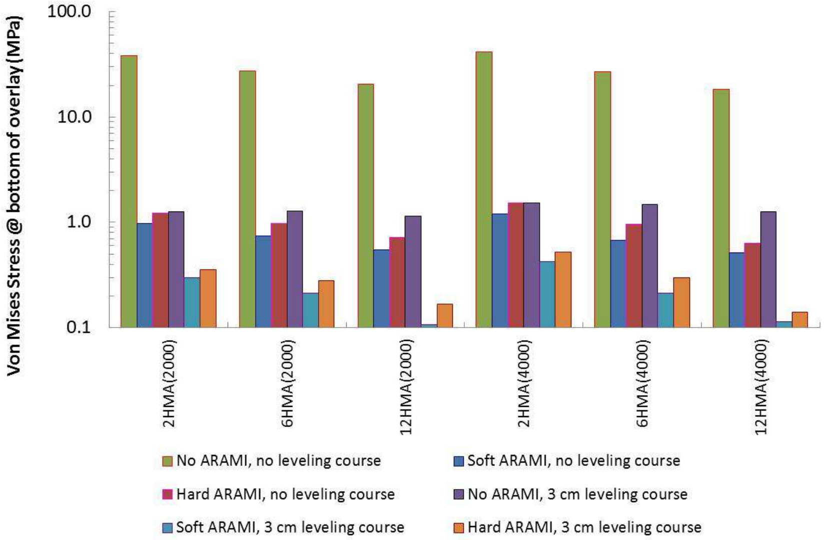

Figure 3. Von Mises stress at the bottom of the HMA overlay for the rigid pavement configurations.

The notation used to describe the configurations in Figure 6 consists of the HMA overlay thickness in cm followed by the HMA stiffness, in parentheses, in MPa. For example, 2HMA(2000) represents the cases where the HMA overlay is 2 cm thick and of 2000 MPa modulus. In each group, a number of cases is considered as described in the legend of Figure 6. The control case is with no ARAMI and no leveling course and represented with the green bar in Figure 6. The soft and hard interlayers are described by their modulus as shown in Table I. Inspection of Figure 6 reveals the following:

- Strains and stresses are largest for the control cases (i.e., pavement structures without ARAMI or leveling course).
- Using a soft ARAMI results in reduced levels of stress and strain compared to using hard ARAMI.
- The use of a 3 cm leveling course tends to significantly reduce the stresses and strains compared to similar cases without the leveling course. The additional leveling course provides a structural layer that reduces the strain and stress at the bottom of the HMA overlays.

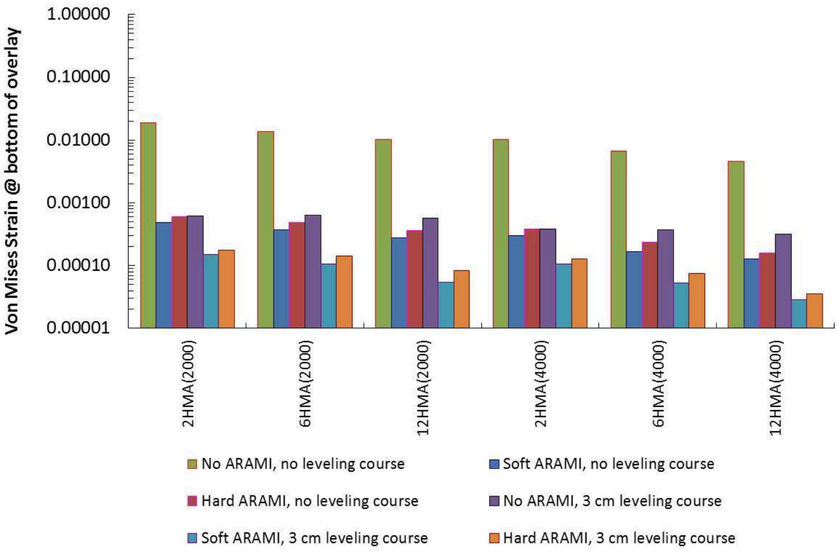

Figure 4. Von Mises strain at the bottom of the HMA overlay for the rigid pavement configurations.

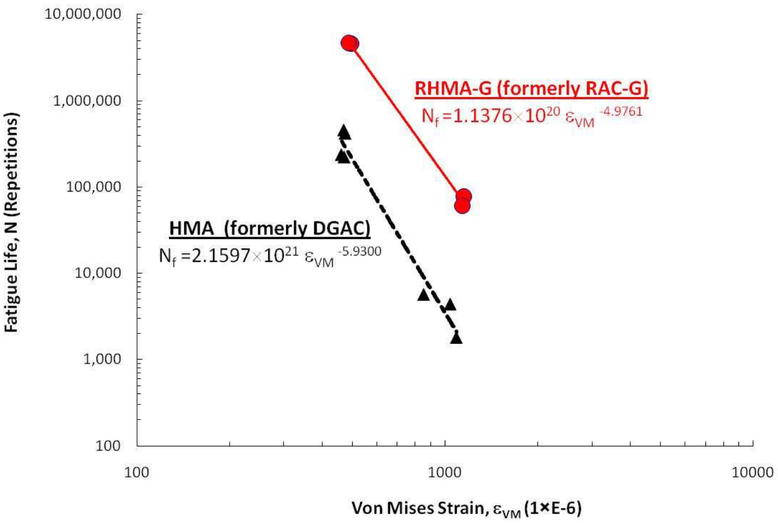

Figure 5. Fatigue transfer function for HMA and ARHMA mixes (from Sousa et al. [9]).

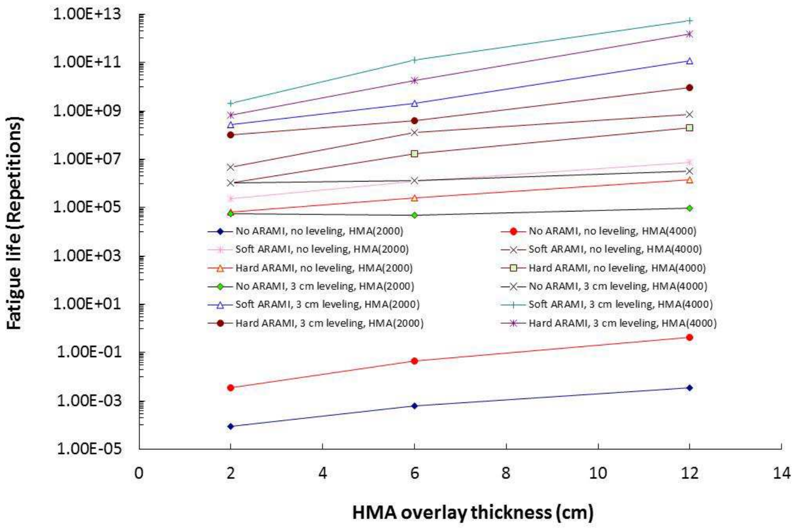

Figure 6. Fatigue life as function of overlay thickness for the 12 concrete pavement configurations analyzed.

- Increasing the HMA overlay thickness up to 12 cm (when used without ARAMI or leveling course) was not able to reduce the strain and stress to the levels achieved when using ARAMI even with the thinnest HMA of 2 cm. A similar trend was observed in the studies by Coetzee and Monismith [14] and Chen et al. [15]. For example, considering the 2000 MPa modulus HMA, a 12 cm overlay without ARAMI or leveling course would produce a stress of ~20 MPa whereas using an ARAMI with a 2 cm HMA overlay resulted in a stress of only 1 MPa. Similar trends were observed with the Von Mises strains shown in Figure 4. The use of a leveling course tends to diminish the benefits of using thicker overlays by always producing nearly same level of stress and strain regardless of HMA thickness. As an example, for the 2000 modulus HMA, the use of 3 cm leveling course without ARAMI always produced about 1 MPa of stress regardless whether a 2 cm, 6 cm, or 12 cm HMA overlay was used.
- Without ARAMI or leveling course, the HMA overlays exhibit shorter life than when an interlayer or a leveling course was used.
- The use of soft ARAMI resulted in greater extension in overlay life compared to hard ARAMI.
- Without an ARAMI, the HMA overlay tends to fail immediately upon loading due to experiencing “exceptionally high” levels of Von Mises strain in the range of 0.01-0.02 (see Figure 6). It is questionable, however,

if the transfer function (Figure 5) used in calculating the fatigue life is valid for this level of strain.

As can be seen, there is significant increase in the life of the overlay with the use of ARAMI. This is due to reduced level of strain upon using these interlayers. It is believed that the interlayers absorb a great amount of the stress and strain and as such only small amount of these stresses and strains arrives at the underside of the overlay.

Conclusions

This white paper has demonstrated the benefits of using overlay systems with asphalt rubber interlayers. The ARAMI (or SAMI-R) has consistently been shown to reduce reflective cracking when used as part of preservation and rehabilitation strategies. Field studies, accelerated wheel tracking experiments, laboratory testing, and analytical studies have all confirmed the significant contribution of these interlayers in extending pavement life and in minimizing reflective cracking in hot mix asphalt overlays. In this paper, 36 rigid pavement configurations representing a variety of cases were modeled and analyzed using the finite element method (FEM) to quantify the benefits of the interlayers in these systems when subjected to loading. The FEM analysis validated the outstanding performance of these composite systems when interlayers were incorporated, and further quantified the benefits of these ARAMI's in terms of critical stress and strain reduction and related pavement life extension. A stress reduction ranging from 92% to 98% was achieved with the use of ARAMI compared to non-ARAMI system. Soft ARAMI's were found to be more effective in reducing stress and strain levels compared to hard ARAMI's. It was also found that the use of leveling course below the interlayers was very beneficial in lowering the strain levels and in increasing pavement life.

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