Reduced Thickness Design of Asphalt Rubber – Myth or Reality?

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ABSTRACT. *The use of asphalt rubber in the rehabilitation of flexible and rigid pavement systems has been shown to improve the performance of these systems and extend their service life. This has been demonstrated in the laboratory, field, and using analytical tools such as finite element method (FEM).*

The California Department of Transportation (Caltrans) has been implementing reduced thickness design standards of asphalt rubber overlays since 1992. These standards call for a reduction in the thickness of the overlay when rubberized hot mix asphalt is used in lieu of conventional hot mix asphalt.

This paper explores the background and basis behind the reduced thickness design concepts and further provides validation to this approach. Additionally, this paper will discuss the benefits of using various asphalt rubber strategies in lieu of using conventional asphalt.

KEYWORDS: *Asphalt Rubber, Reduced Thickness, Structural Design, Asphalt Rubber Design Standards, Asphalt Rubber Performance, Fatigue, Stiffness, Frequency Sweep, Accelerated Pavement Testing, HVS, ALF, Mechanistic-Empirical, Composite Pavements, Composite Layering Systems, Interlayers*

1. Introduction

Asphalt rubber been successfully used for over 35 years in the United States and in many countries. The success of rubberized asphalt strategies have led many highway departments to develop design standards that take into account its superior performance. One example highway entity is the California Department of Transportation (Caltrans) which developed reduced thickness guidelines in 1992 for Asphalt-Rubber Hot Mix-Gap Graded (ARHM-GG) (known today as RHMA-G) as compared to dense graded asphalt concrete (DGAC) (also known as hot mix asphalt or HMA) involving both structural and reflective crack thickness equivalencies (Shirley, 1992). The reduced thickness design of rubberized hot mix asphalt (RHMA) has been a well-accepted standard for many years in California. The sense of the use of RHMA has been heightened to a higher degree. Some other public entities have followed suit with this reduced design concept. Since California was one of the pioneering states in the asphalt rubber technology implementation, it will be sited in various sections of this paper. California has taken great strides in both the technical and the political arenas.

From a political perspective, a 2005 California Assembly Bill (AB338) called for progressive amount of usage of tire rubber in paving materials over several years. The Bill mandates increased usage of rubber in paving materials from 20 percent in 2007 to 35 percent in 2013. By 2010, Caltrans reached an amount of over 30 percent of the total hot mix asphalt projects.

The California Public Resources Code 42703 requires Caltrans to use 11.58 pounds of crumb rubber modified (CRM) per metric ton of total asphalt paving material placed for calendar 2013 and beyond. The 11.58 pounds of CRM per metric ton equates to the requirement that Caltrans must use CRM in 35 percent of the total hot mix asphalt (HMA) placed on the California state highway system. A 2013 crumb rubber report noted that Caltrans did not meet the goal of 35 percent usage of the rubberized HMA (RHMA) when compared with HMA where Caltrans only achieved 22.9 percent (Sutliff and Takigawa, 2015). As a result of this fact of not meeting the requirements, Caltrans issued a memorandum on February 10, 2015 requiring that all HMA projects to be screened for the appropriate application of RHMA and that each Caltrans district was required to ask for an approval if it wanted an exception to using RHMA on its project (Sutliff and Takigawa, 2015). This indicates that RHMA has become the standard mix for the state highways and that conventional HMA is the exception that requires justification.

Asphalt rubber is defined by ASTM as: “A blend of asphalt binder, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt binder sufficiently to cause swelling of the rubber particles” (ASTM, 2005). This product been successfully used for over 35 years in Arizona, California and other states. As a result of its success, Caltrans developed reduced thickness guidelines in 1992 for asphalt rubber hot mix-gap graded (ARHM-GG) as compared to dense graded asphalt concrete (DGAC) involving both structural and reflective crack thickness equivalencies (Shirley, 1992). Table 1 is an example showing reflective crack thickness equivalencies.

There are two types of asphalt rubber binder (known as “wet process”); Type I and II. Type I is mainly used in Arizona and Texas. It contains asphalt binder and 18 to 20 percent tire rubber that meets a specific gradation requirement. Type II is used in California and consists of about 20 percent rubber (75 percent ground tire rubber and 25 percent natural rubber, both are used with suitable grading). In addition heavy aromatic oils (asphalt modifier) may be added up to 6 percent. The asphalt rubber binder is blended using a low shear system for a minimum of 45 minutes (Shatnawi and Holleran, 2003).

There are other asphalt rubber products that have been used such as the dry process, terminal blend, pelletized rubberized-asphalt systems. For example terminal blend binders have been used since the middle of 1980s in Florida and Texas and later on in California, Colorado, Louisiana, Arizona and Nevada. Additionally, terminal blend products have been used in slurry seal applications. The amount of rubber used in this process may vary anywhere between 5 to 20 percent. The specifications for terminal blend binders have recently adopted the PG grading system which can be met with polymer modifies. This binder comes with several grades such as PG64-28TR, PG70-22TR, MAC-10TR, MAC-15TR and also as an emulsified product. Terminal blends utilize a fine mesh of crumb rubber derived from 100% tire rubber and blended in the refinery or a stationary asphalt terminal with asphalt binder where the component materials are heated over an extended period of time which can result in dissolving the rubber particles.

This paper discusses the basis behind the reduced thickness design standards for asphalt rubber and the reasons behind the increased interest in using it as a standard pavement strategy.

2. Asphalt Rubber Pavement Standards

The Caltrans Highway Design Manual (HDM) states that RHMA-G is generally specified to retard reflective cracking, resist thermal stressed created by wide temperature variations and add flexibility to a structural overlay (HDM, 2010). Currently, Caltrans specifies RHMA-G (gap graded) and RHMA-O (open graded). The difference between these two strategies is the aggregate gradation. RHMA-O is normally considered a non-structural pavement preservation treatment, whereas RHMA-G can be used either as non-structural pavement preservation treatment or as a structural layer. The HDM states that RHMA should be considered the strategy of choice when evaluating various rehabilitation alternatives. If RHMA is not selected as the strategy for a specific project, then justification for not using it must be documented in the scoping document, the project initiation document and in the project report. It should be noted that these documents are elements in the Caltrans project development stages. This clearly shows the standardization of the use of asphalt rubber in California as a main strategy preferred over conventional HMA strategies. It should be mentioned here that the minimum thickness for RHMA used by Caltrans is 30 mm for new construction and rehabilitation. For pavement preservation, asphalt rubber can be placed in a 30 mm or 25 mm thickness as well as in spray applications such as in asphalt rubber chip seals. These chip seals may be used as interlayers part of alternative rehabilitation design strategies.

Although higher thicknesses have been used, the maximum thickness for RHMA-G by Caltrans standards is 60 mm. Additionally, these standards call for a maximum thickness of 45 mm for RHMA-O. The standards state that if a thicker surface layer or overlay is called for, then an HMA layer should be placed prior to placing the RHMA. Caltrans HDM states that RHMA should only be placed over a flexible or rigid surface course and not on a granular layer, and that RHMA-O may be placed on top of new RHMA-G. The standards call for not placing conventional HMA or open graded friction course (OGFC) over new RHMA pavement. The standards state that it is undesirable to place RHMA-G or RHMA-O in areas that will not allow surface water to drain.

Reduced thickness design standards have been developed for both flexible and composite pavement systems. These systems have utilized the use of interlayers as an integral part of the design philosophy since interlayers provide significant benefits in improving their performance cost-effectively.

2.1. *Rubberized Stress Absorbing Membrane Interlayers (SAMI-R)*

Strategies utilizing SAMI-R has been widely used for the rehabilitation of flexible and rigid pavements using asphaltic overlays. A SAMI-R may be placed between layers of new flexible pavement, such as on a leveling course, or on the surface of an existing flexible pavement. SAMI-R can be placed prior to placement of an overlay, a slurry seal, or microsurfacing. When used as a surface layer, it provides a flexible, waterproof, skid resistant, and durable surface that resists oxidation. When used in combination with an overlay as an interlayer, SAMI-R provides a further reduction in the overlay thickness in addition to the reduction attributed to the use of RHMA. SAMI-R provides the additional great benefit of retarding reflective cracks from propagating up into asphalt concrete overlays. SAMI-R application consists of the following steps:

- Spraying hot asphalt rubber binder over the pavement surface at a rate of 0.55-0.65 gallons per square yard (2.29-2.71 liters per square meter),
- Application of 35-45 pounds per square yard (19-24 kilogram/square meter) of clean 3/8 inch (9.5 mm) aggregate size chips over the asphalt rubber,
- Rolling chips with pneumatic tire rollers,

- Sweeping the rolled down chips surface to remove loose chips, and finally
- Placement of the surface course.

Caltrans specifies SAMI-R in flexible layer rehabilitation as a means to retard reflective cracks, prevent water intrusion, and enhance pavement structural strength. When a SAMI is placed on an existing pavement, surface preparation must be performed prior to SAMI placement. This may include repairing potholes and localized failures as well as sealing cracks wider than 6 mm (HDM, 2010).

2.2. *Reflective Crack Retardation Equivalencies*

Caltrans developed reflective crack retardation equivalencies for the use of asphalt rubber overlays and SAMIs as in Table 1 (HDM, 2010). The table shows the thickness equivalencies of asphalt rubber in comparison to conventional HMA overlay thickness. As shown in the table, the maximum thickness equivalency for RHMA-G is 1:2.

Table 1 – *Reflective Crack Retardation Equivalencies*

HMA	RHMA-G	RHMA-G over SAMI-R
45 mm	30 mm	N/A
60 mm	30 mm	N/A
75 mm	45 mm	N/A
90 mm	45 mm	N/A
105 mm	45 mm (for crack width < 3 mm)	N/A
105 mm	60 mm (for crack width ≥ 3 mm) (if untreated underlying layer is used)	30 mm
105 mm	60 mm (for crack width ≥3 mm) (or if CTB, LCB or PCC underlying layer is used)	45 mm

When a SAMI-R is used to resist reflective cracking and placed under a conventional HMA, the equivalency of a SAMI-R is considered a function of the type of base material beneath the existing pavement. When the base is a treated material, a SAMI-R placed under HMA or OGFC is considered to be equivalent to 30 mm of HMA. When the base is an untreated material, SAMI-R is equivalent to 45 mm of HMA. In comparison, when a SAMI-F (fabric) is placed beneath an HMA layer for reflective cracking resistance it is considered to provide 30 mm of HMA (HDM, 2010).

Recent efforts have shown that the cost effectiveness of using SAMI-R in rehabilitating existing flexible pavements to be greater than what is currently used in the Caltrans equivalencies (Shatnawi, 2012), (Pais, 2012). These efforts which utilized finite element analysis showed that the use of an equivalency of 30 mm to 45 mm HMA for SAMI-R to be conservative, and as such, the use of such interlayers could impart greater benefits to rehabilitated flexible pavements either in reducing life cycle costs and/or extending their service life. It was demonstrated that the use of RHMA and SAMI-R provide significant improvements in the performance of rehabilitation and preservation strategies and impart lower life cycle cost than conventional strategies.

2.3. *Composite Layering System*

In California, SAMI-R has been used in a number of applications; collectively referred to as Composite Layering Systems I, II, III, and IV (Shatnawi, 2012). A brief description of these four systems is listed below:

- **System I** consists of SAMI-R Cape Seal. The SAMI-R (9.5 mm) is applied directly on existing HMA surface followed by a Type II slurry seal.
- **System II** consists of SAMI-R Cape Seal with a leveling course. In this system, an HMA leveling course (19 mm minimum) is placed on top of existing pavement followed by SAMI-R (9.5mm), then Type II slurry seal.
- **System III** consists of cold milling existing pavement (25 mm minimum), placing an HMA leveling course (19 mm), then SAMI-R, then HMA or RHMA-G overlay.
- **System IV** consist of cold milling existing pavement (25 mm minimum), placing SAMI-R, then placing HMA overlay or RHMA-G.

2.4. *Flexible Pavement Structural Section Design*

This section provides an example of pavement rehabilitation design that was designed based on the Caltrans deflection reduction method (HDM, 2010). This design provides four alternative rehabilitation strategies that are considered to have equal design lives of 20-years using the Caltrans reflective cracking retardation criteria:

- **Strategy I**: 105 mm HMA overlay.
- **Strategy II**: SAMI-R followed by 60 mm HMA.

- **Strategy III**: 60 mm RHMA.
- **Strategy IV**: SAMI-R followed by 30 mm RHMA.

Although these designs are equal in terms of the existing standards, the life cycle analysis of the strategies revealed that the RHMA strategies would provide the most cost-effective options especially when combined with a SAMI-R (Shatnawi, 2012). Additionally, finite element analysis of such strategies showed that the use of SAMI-R would significantly reduce the reflective cracking potential and that Caltrans reflective cracking equivalencies for SAMI-R were found to be conservative.

2.5. *Composite Pavement Structural Section*

There are standards for using asphalt rubber in composite pavements. An example composite pavement is the crack, seat and overlay strategy. In this strategy, the existing distressed rigid pavement slab is cracked into smaller pieces, then seated using heavy rollers to ensure against any potential rocking motion, then overlaid by a hot mix asphalt (HMA) leveling course (LC), followed by a stress absorbing membrane interlayer (SAMI), then another HMA layer or alternatively with a gap graded (RHMA-G) overlay. Table 2 shows a table with minimum standard thicknesses for crack, seat and overlay projects (HDM, 2010). Note, the table uses criteria for two traffic indices (TI) around the TI of 12 which is equivalent to around 11 million equivalent single axle loads (ESALs).

Table 2 – *Minimum Standard Thicknesses for Crack, Seat, and Asphalt Overlay*

Criteria	Conventional HMA Strategy	Equivalent RHMA-G Strategy
TI < 12.0	105 mm HMA over SAMI-F or SAMI-R over 30 mm HMA LC	60 mm RHMA over SAMI-R over 30 mm HMA LC
TI ≥ 12.0	150 mm HMA over SAMI-F or SAMI-R over 30 mm HMA LC	60 mm RHMA-G over 45 mm HMA over SAMI F or SAMI-R over 30 mm HMA LC

In this table, HMA LC referred to hot mix asphalt leveling course. SAMI-F refers to a fabric interlayer. All other terms have been previously defined. The standards state that if the existing rigid pavement is not cracked and seated, an additional 30 mm minimum HMA thickness is required above the SAMI to ensure against reflective cracking. An open graded layer may be placed over any of the strategies listed in Table 2 as a non-structural layer.

3. Structural versus Reflective Cracking

Although standards by Caltrans only consider the use of asphalt rubber in the rehabilitation of existing pavements (by providing reflective cracking equivalencies), as well as in pavement preservation, there is no reason as to why they cannot be used on new construction as long as certain criteria are met. From a mechanistic-empirical (ME) design perspective, these criteria include:

1) Limiting the compressive strain on top of the subgrade to a tolerable level to ensure adequate structural bearing capacity.
2) Limiting the tensile strain below the asphalt rubber and the asphalt layers with the appropriate transfer functions to ensure adequate fatigue life.
3) Limiting stresses at the crack tips below the overlay to overcome the problem of reflective cracking.

ME design procedures have been employed for the structural design pavements with the use of transfer functions that were developed based on the field performance of asphalt rubber pavements. Additionally, accelerated pavement tests have been used to develop and validate such transfer functions.

4. Mechanistic-Empirical Rehabilitation

4.1. *Design*

Recently a new mechanistic-empirical (ME) overlay design method that specifically addressed RHMA overlay have been developed. This procedure can be used for both RHMA and HMA overlays over existing, cracked bituminous-bound pavements (Sousa et al, 2001). Through this effort, the effect of thickness and stiffness (increased with the date) of an overlay on crack activity was determined (Figure 1). A graph showing the relationship between the predicted traffic loading and overlay thickness was developed for both RHMA and HMA overlays (Figure 2).

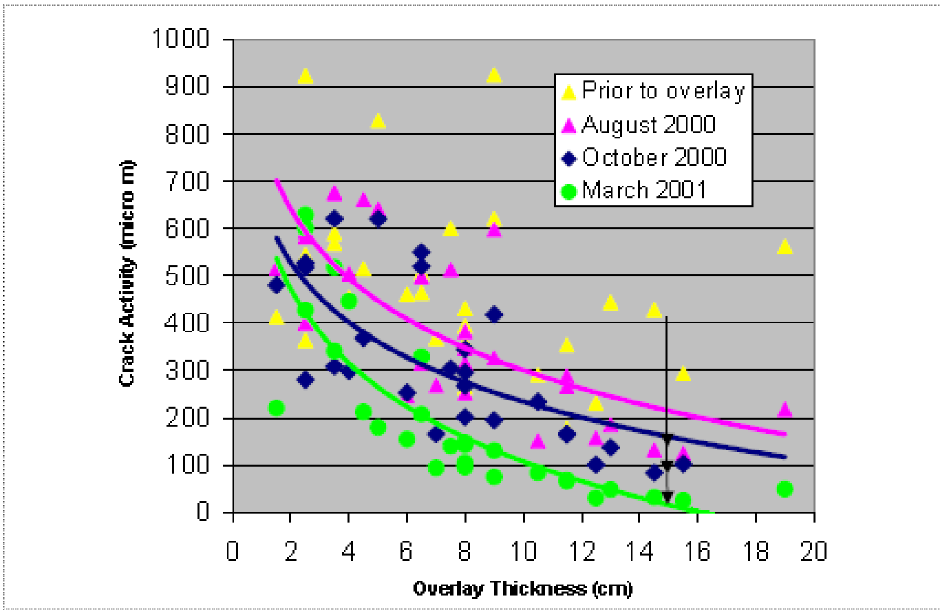


Figure 1 – *Crack activity versus overlay thickness*

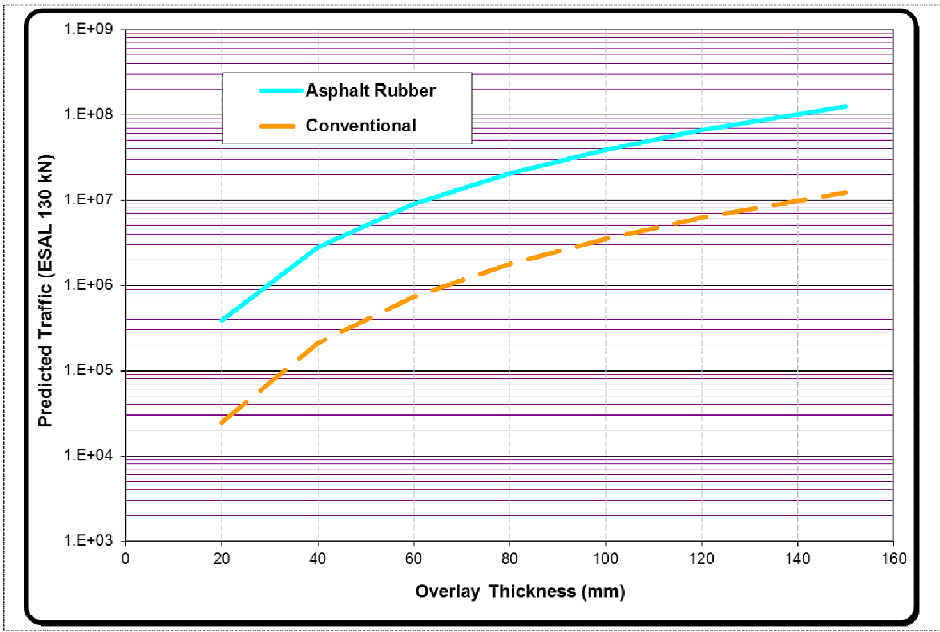


Figure 2 – *Predicted traffic versus overlay thickness for RHMA and HMA*

4.2. *Engineering Properties*

Measured engineering properties are used in the ME procedure to determine the strain levels. One of the studies was conducted on California mixes on conventional HMA mixes using a Valley Asphalt and a Coastal Asphalt as well on RHMA asphalt rubber mixes (Shatnawi, 1997) (Table 3).

Table 3 – *Frequency sweep test results*

Mix	Frequency (Hz)	Uniaxial Stiffness Compression	Uniaxial Stiffness Tension	Shear Stiffness	Uniaxial Phase Angle Compression	Uniaxial Phase Angle Tension	Shear Phase Angle	Computed Poisson's Ratio
S2L1								
	10	4.386E+9	4.373E+9	1.844E+09	12.65	12.74	16.68	0.19
	5	3.974E+9	3.958E+9	1.660E+09	14.63	14.79	17.08	0.19
	2	3.420E+9	3.405E+9	1.420E+09	17.40	17.55	18.77	0.20
	1	3.002E+9	2.991E+9	1.245E+09	19.52	19.73	20.49	0.20
	0.5	2.595E+9	2.581E+9	1.075E+09	21.77	22.04	22.30	0.20
	0.2	2.088E+9	2.075E+9	8.672E+08	24.90	25.37	25.21	0.20
	0.1	1.741E+9	1.725E+9	7.198E+08	27.42	27.91	27.42	0.20
	0.05	1.427E+9	1.408E+9	5.923E+08	30.60	31.29	29.81	0.20
	0.02	1.071E+9	1.052E+9	4.476E+08	33.45	34.23	32.76	0.19
	0.01	844.710E+6	826.357E+6	3.565E+08	35.56	36.09	34.52	0.17
S2L2								
	10	6.773E+9	6.783E+9	3.093E+09	8.82	8.82	15.59	0.10
	5	6.302E+9	6.325E+9	2.858E+09	10.70	10.60	16.33	0.10
	2	5.633E+9	5.664E+9	2.495E+09	13.37	13.30	18.52	0.13
	1	5.088E+9	5.120E+9	2.227E+09	15.66	15.57	20.85	0.15
	0.5	4.518E+9	4.549E+9	1.945E+09	18.38	18.33	23.99	0.17
	0.2	3.736E+9	3.766E+9	1.546E+09	22.60	22.70	29.30	0.21
	0.1	3.143E+9	3.175E+9	1.239E+09	26.51	26.52	33.72	0.27
	0.05	2.577E+9	2.599E+9	9.519E+08	31.15	31.43	38.44	0.36
	0.02	1.891E+9	1.907E+9	6.293E+08	36.31	36.67	44.38	0.51
	0.01	1.449E+9	1.455E+9	4.378E+08	40.08	40.66	48.13	0.66
S4L1								
	10	5.163E+9	5.134E+9	2.412E+09	10.31	10.41	15.14	0.07
	5	4.758E+9	4.734E+9	2.209E+09	11.87	11.99	15.17	0.07
	2	4.207E+9	4.178E+9	1.940E+09	13.89	14.08	16.15	0.08
	1	3.791E+9	3.765E+9	1.752E+09	15.53	15.76	17.28	0.08
	0.5	3.375E+9	3.343E+9	1.557E+09	17.25	17.50	19.03	0.08
	0.2	2.837E+9	2.811E+9	1.295E+09	19.70	20.28	21.76	0.09
	0.1	2.451E+9	2.424E+9	1.104E+09	21.79	22.30	24.17	0.10
	0.05	2.092E+9	2.059E+9	9.265E+08	24.36	25.00	26.41	0.12
	0.02	1.657E+9	1.627E+9	7.177E+08	26.96	27.79	29.67	0.14
	0.01	1.365E+9	1.336E+9	5.755E+08	28.88	29.77	31.99	0.17
S4L2								
	10	4.937E+9	4.951E+9	2.248E+09	12.70	12.70	15.94	0.10
	5	4.477E+9	4.493E+9	2.031E+09	14.57	14.66	16.31	0.10
	2	3.861E+9	3.877E+9	1.745E+09	17.28	17.27	17.88	0.11
	1	3.398E+9	3.413E+9	1.529E+09	19.38	19.41	19.43	0.11
	0.5	2.944E+9	2.956E+9	1.320E+09	21.60	21.61	21.39	0.12
	0.2	2.383E+9	2.397E+9	1.066E+09	24.57	24.73	24.28	0.12
	0.1	2.000E+9	2.008E+9	8.943E+08	27.12	27.17	26.35	0.12
	0.05	1.653E+9	1.660E+9	7.389E+08	30.22	30.37	28.57	0.12
	0.02	1.257E+9	1.259E+9	5.625E+08	32.97	33.15	31.47	0.12
	0.01	1.009E+9	1.009E+9	4.505E+08	34.97	35.04	33.31	0.12
S4L3								
	10	6.471E+9	6.546E+9	2.646E+09	9.69	9.50	15.23	0.23
	5	5.997E+9	6.079E+9	2.425E+09	11.68	11.55	15.77	0.25
	2	5.317E+9	5.400E+9	2.114E+09	14.67	14.33	17.83	0.27
	1	4.759E+9	4.845E+9	1.874E+09	17.20	16.81	20.07	0.28
	0.5	4.175E+9	4.275E+9	1.624E+09	20.38	19.75	22.77	0.30
	0.2	3.392E+9	3.490E+9	1.295E+09	25.20	24.45	26.93	0.33
	0.1	2.804E+9	2.893E+9	1.060E+09	29.43	28.73	30.41	0.34
	0.05	2.244E+9	2.318E+9	8.438E+08	34.94	34.49	34.33	0.35
	0.02	1.581E+9	1.643E+9	5.957E+08	41.28	40.84	39.29	0.35
	0.01	1.168E+9	1.211E+9	4.440E+08	45.68	45.48	42.63	0.34

The testing was conducted on field cores taken from a 5-year old pavement located in the California Mojavi desert (I-10 Freeway). As part of this study, frequency sweep tests were conducted at 20 C using both the uniaxial and shear testing modes. The frequency sweep tests were conducted at 100 microstrains using a sinusoidal wave form with the following frequencies: 0.01 Hz, 0.02 Hz, 0.05 Hz, 0.1 Hz, 0.2 Hz, 0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz and 10.0 Hz.

The terms in Table 3 are defined as S2L1: Section 2 (RHMA-Valley Asphalt), Lift 1 (top lift -surface layer), S2L2: Section 2 (HMA-Valley Asphalt), Lift 2 (second lift down), S4L1: Section 4 (HMA-Coastal Asphalt), Lift 1 (top lift – surface layer), S4L2: Section 4 (HMA-Coastal Asphalt), Lift 2 (second lift down), and S4L3: Section 4 (HMA-Valley Asphalt), Lift 3 (third lift down)

This study showed that the stiffness of rubber mixes (RHMA) to be around 65% of the stiffness of conventional HMA (Table 3) with the same base asphalt. This lower stiffness provides more flexibility and longer life. Additionally, this table shows measured poison ratios and phase angles.

5. Performance Studies

5.1. *Fatigue Studies*

After the frequency sweep tests that were discussed in the previous section, fatigue direct tension tests were conducted at 10 Hz using two strain levels; low and high (Shatnawi, 1997) (Table 4). The fatigue tests were controlled strain tests with a constant amplitude.

Table 4 – *Summary of Stiffness and Fatigue Life Results*

Mix	Lift	Stiffness (kPa) X 10^6	Fatigue Life at 500 $\mu\varepsilon$ (Cycles)
RHMA-Valley	Top	4.386	150,000
HMA-Valley	Second	6.773	15,000
HMA-Valley	Third	6.471	14,000
HMA-Coastal	Top	5.163	40,000
HMA-Coastal	Second	4.930	40,000

Table 4 compares the frequency sweep stiffness at 10.0 Hz with the fatigue test results for the various mixes. This table shows the stiffness results and the results of the fatigue tests based on the dissipated energy failure criteria. These results show that asphalt rubber improves fatigue by 10 times over HMA (Table 5). The flexibility of asphalt rubber for these mixes was determined to be 65% to 68% of the flexibility of HMA. These mixes were compared using the same base asphalt.

Table 5 – *RHMA/HMA Stiffness and Fatigue Ratios for same base asphalt*

Mix	Lift	Stiffness Ratio	Fatigue Ratio
RHMA-Valley	Top	-	-
HMA-Valley	Second	65%	10
HMA-Valley	Third	68%	10

Another example is shown in Figure 3. The Figure clearly shows the significant fatigue superiority of various rubberized mixes over the non-rubberized mixes

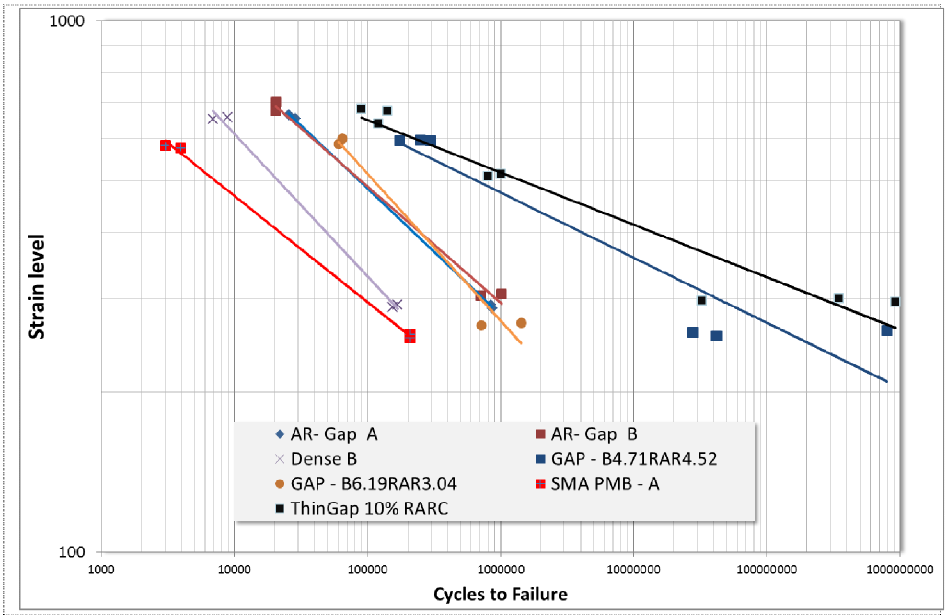


Figure 3 – *Fatigue comparison between various mixes*

In Figure 3, AR-Gap A and B refers to two types of ARHM-G, whereas Dense B refers a conventional HMA mix. SMA PMB refers to a stone matrix mix. GAP-

B6.19RRAR3.04 and GAP-B4.71RAR4.52 refer to asphalt mixes made with reacted and activated rubber (RAR) placed directly into the pug-mill (not reacted in the bitumen like regular AR- asphalt rubber).

Ample other studies have confirmed the above findings. One of these studies is cited here in Figure 4 (Kaloush et al, 2003). The figure shows the results of flexural fatigue beam tests where it is shown that asphalt rubber mixes were better than conventional asphalt mixes by a factor of 10.

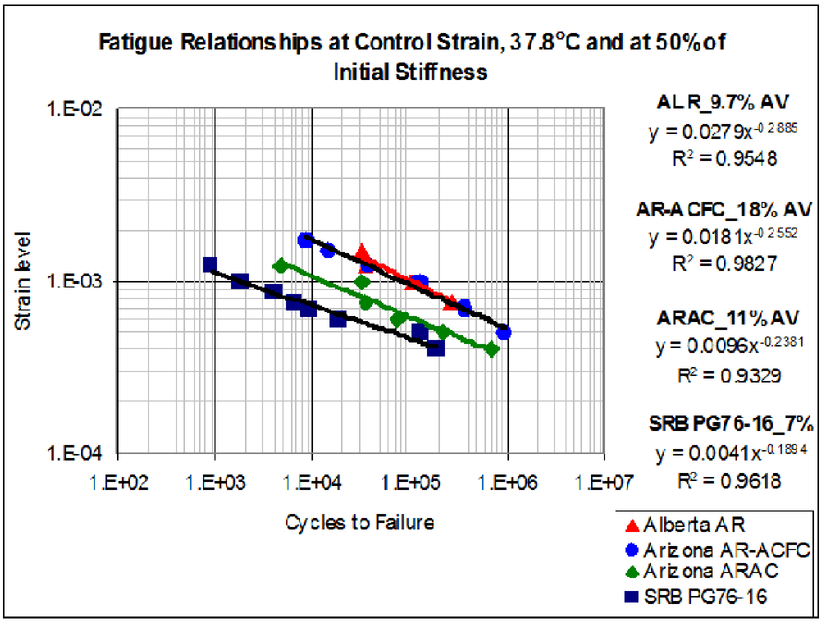


Figure 4 – *Comparison of flexural fatigue lives under strain control for conventional and asphalt rubber binders (Kaloush et al, 2003)*

5.2. *Accelerated Pavement Testing*

5.2.1. *HVS Study in South Africa (1992)*

Accelerated pavement testing (APT) using the Heavy Vehicle Simulator (HVS) on asphalt rubber overlays was conducted in South Africa to validate the Caltrans 1992 reduced thickness guidelines of gap graded asphalt rubber hot mix (ARHM-GG) which are known today by the term RHMA-G (Figure 5). Those guidelines were the first to use reduced thickness equivalencies for asphalt rubber which were based on field performance of test sections and on in-service projects in California. The HVS testing was conducted through a cooperative effort between Caltrans and the Council of Scientific and Industrial Research (CSIR) of South Africa. As part of the experiment, a 75 mm thick DGAC overlay section and three thinner ARHM-GG overlay sections consisting of 50 mm, 38 mm and 25 mm thicknesses were placed on an existing distressed flexible pavement in South Africa where the climate is similar to California. The overlays were constructed using materials and mix design procedures conforming to Caltrans specifications (Rust, 1993).

Figure 5 – *HVS Test Section Distress (Rust, 1993)*

Using a 40kN load, the test results showed that the conventional dense graded HMA (DGAC) test section failed at 200,000 repetitions (Table 6). The 38 mm ARHM-GG section showed no cracking at 175,000 repetitions, so the load was increased to 80kN and still no cracking occurred up to 237,000 repetitions. The temperature was then lowered to -5ºC and only one half the section cracked at 250,000 repetitions. The 25 mm ARHM-GG section showed no cracking at 175,000 repetitions, so the load was increased to 80kN and the section finally showed fine cracks at 200,000 repetitions. The section completely cracked at 237,000 repetitions (Table 6).

These results showed that 25 mm of ARHM-GG outperformed the 75 mm section of conventional DGAC in regards to fatigue. This is a 3:1 reduction in thickness. Also, these test results indicated that a reduction of at least 50 percent in layer thickness to obtain similar fatigue performance over flexible pavements could be justified when conventional DGAC was replaced with ARHM-GG.

Table 6 – *Results of the HVS Experiment in South Africa (Rust, 1993)*

Repetitions Phases	**Load (KN)**	**Temp (Celsius)**	**HMA 75 mm**	**RHMA-G 38 mm**	**RHMA-G 25 mm**
0 to 100,000	40	10	Fine Cracks	No Cracking	No Cracking
100,000 to 175,000	40	10	Block Cracking	No Cracking	No Cracking
175,000 to 200,000	80	10	100% Cracking	No Cracking	Fine Cracks
200,000 to 237,000	80	10	Test Stopped	No Cracking	100% Cracking
237,000 to 250,000	80	-5	Test Stopped	50% Cracking	Test Stopped

This experiment served to validate Caltrans' design guide for ARHM-GG overlays over flexible pavements. It should be noted that this study recommended checking the subgrade rutting criteria (compressive strain) when reducing the required thickness based on fatigue performance.

5.2.2. *ALF Test Sections (2002)*

Further accelerated testing using the accelerated load facility (ALF) was conducted in 2002 at Turner-Fairbank Highway Research Center in McLean, Virginia as part of pooled fund study (Figure 6). This effort consisted of testing twelve lanes of dense graded HMA with various modified asphalts. Two of the test lanes used crumb rubber material technology. Lane 1 employed the Arizona wet process (CR-AZ) which is Type I, and Lane 5 employed the Texas Terminal Blend process (CR-TB). Lane 2 was constructed with an unmodified asphalt binder as the control section. Other lanes included air-blown, polymer and fiber modified asphalt binders. Note that all sections were dense graded with full thickness and only the CR-AZ was gap graded at 50 percent reduced thickness.

Figure 6 – *Accelerated Loading Facility (ALF)*

The test sections underwent accelerated pavement testing using the Accelerated Pavement Facility (ALF) machine at 19ºC. The results showed that the CR-AZ test performed the best in terms of fatigue and reflective cracking (Figure 7) (Qi et al, 2006).

Post-mortem evaluation was conducted 10 months later by taking core samples to investigate the conventional HMA dense graded layer (control mix) below the asphalt rubber CR-AZ mix. It was found that all cores in this layer exhibited bottom-up cracks after 300 loading applications, and that most cracks did not reflect through the asphalt rubber CR-AZ gap graded layer. This finding is an indication of the reflective cracking resistance of the asphalt rubber gap graded layer. This important finding further validates Caltrans reduced thickness design for asphalt rubber gap graded overlays as compared with conventional dense graded overlays.

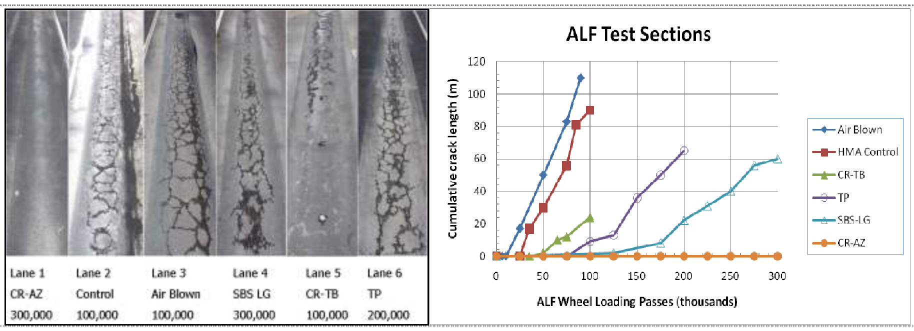


Figure 7 – *Results of the FHWA ALF test section investigation. (a) Pavement cracking condition after completion of loading at 19oC and 74 kN wheel load, and (b) surface crack length accumulation with load passes (Qi et al, 2006).*

5.2.3. *California HVS Test Sections (2001)*

Heavy Vehicle Simulator (HVS) tests were conducted to evaluate the performance of several rubberized HMA mixes in 2001 at the University of California Richmond Field Station (Bejarano et al, 2005), (Steven et al, 2007), (Jones, et al, 2007) (Figure 8). The following mixes were used in the evaluation: 1) MB4-G: terminal blend gap graded mix with 7 percent ground tire rubber, 2) MB4-15-G:Terminal blend gap graded mix with 15 percent minimum ground tire rubber, 3) MAC-15TR-G:terminal blend gap graded mix with 15 percent minimum ground tire rubber, 4) RAC-G: asphalt rubber hot mix gap graded mix Type II, and 5) AR 4000-D: dense graded asphalt concrete mix. The rubberized sections were placed at 45 mm while the DGAC sections were placed at 90 mm thickness.

Figure 8 – *Heavy Vehicle Simulator (HVS)*

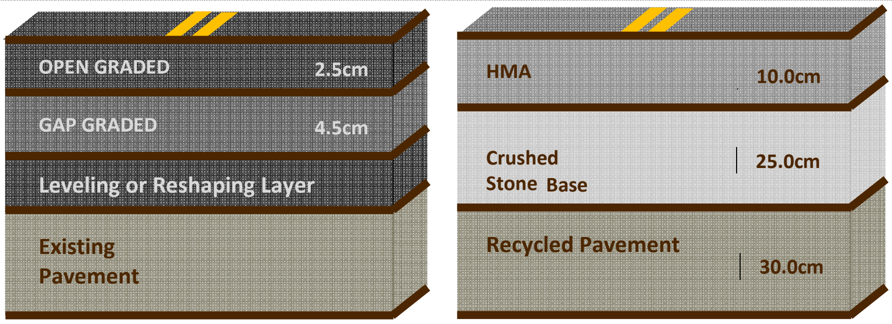
The results showed the reflective cracking performance of all of the rubberized overlays to be superior to the conventional mix, and further validated the reduced thickness design standards.

5.2.4. *Brazil HVS Test Sections (2001)*

In 2001, Departamento Estradas Rodagem (DER- RJ) in Brazil constructed a 40 km long two-layer overlay with asphalt rubber on RJ-122 (Figure 9) (Ângelo and Sousa, 2001). The asphalt rubber strategy used in place of the equivalent conventional HMA strategy is show in Figure 10.

(a) (b)

Figure 9 – *a) RJ-122 before rehabilitation, and b) after rehabilitation*



(a) (b)

Figure 10 – *a) Asphalt rubber strategy equivalent to b) conventional HMA strategy used on RJ-122 for a 20-year design life*

To predict the future performance of this strategy, accelerated pavements tests (APT) were conducted at RJ-122 using the Large Scale Traffic Simulator (Figure 11). The large scale accelerated pavement tests consisted of applying a controlled axle load equal to or larger than the legal maximum allowable load to determine the response and performance of this structure under controlled, accelerated conditions in a limited time span. The traffic simulator consists of a highway half-axle with dual wheel and loads up to 15 tons, which corresponds to a total single wheel axle load of 30 tons, which moves longitudinally along an axis with displacements of up to 9 meters, with a transversal displacement of up to 1 meter. The traffic simulator may perform up to 1,000 passages of the load per hour in a given test section. In this way, by combining the longitudinal displacement speed of the half-axle with the other resources of the equipment, like transversal displacement or applied load, the consequences of the expected local traffic loading on the existing pavement structure can be reproduced in a short period of time with a high accuracy.

Figure 11 – *Large Scale Traffic Simulator at RJ-122*

The large-scale traffic simulator was placed on two test sections for evaluating the pavement´s performance. The first test section was located at approximately the 28 kilometer mark, whereas the second test section was at the 12 kilometer mark. The pavements exhibited a behavior that satisfied all project parameters for the 20 year design period during the APT tests, even though a significant load was applied (Table 7).

In the first test section, the design life in terms of the equivalent single-axle load traffic was surpassed with the combination of 113,063 passages of the 6.7 ton single load (13.4 ton axle loads) followed by 79,017 passages of the 8.6 ton single load (17.2 ton axle loads). Similarly, in second section, the design service life in terms of the equivalent single-axle load traffic was surpassed with the combination of 100,007 passages of the 8.64 ton single load (17.2 ton axle loads) followed by 49,993 passages of the 8.95 ton single load (17.9 ton axle loads) for the second test section.

Table 7 – *Accelerated pavement testing results for RJ-122 two test sections*

Parameter	Test-Section 1		Test-Section 2		Limits
	Initial	Final	Initial	Final	
Deflection	38x0.01mm	49x0.01mm	48x0.01mm	58x0.01mm	< 64 x0.01mm
Cracking	0%	0%	0%	0%	< 20 %
Permanent Deformation	0 mm	2.1 mm	0 mm	5.0 mm	< 7 mm
Microtexture – British Pendulum	55	51	52	52	VRD > 47
Macrotexture – Sand Patch	0.70	0.65	0.70	0.66	0.6 – 1.2 mm

A cost comparison between the two alternative designs is presented in Table 8 and Table 9. These tables show that the asphalt rubber alternative to be more cost-effective where the cost of the asphalt rubber solution was about 62% of the conventional HMA strategy.

Table 8 – *Cost Analysis of the conventional rehabilitation solution (service life 10 years)*

Layer	Cost (US$/m^3)	Layer Height (cm)	Cost (US$/m^2)	Total (US$/m^2)
HMA	298.69	10	29.87	59.74
Crushed Store Base	29.87	25	7.47	
Recycling	74.67	30	22.40	

Table 9 – *Cost Analysis of proposed rehabilitation solution*

Layer	Cost (US $/m^3)	Layer Height (cm)	Cost (US $/m^2)	Total (US $/m^2)
Open graded	398.25	2.50	9.96	36.84
Gap graded	398.25	4.50	17.92	
Leveling	298.69	varies	8.96	

6. The Use of Asphalt Rubber in Various Climates

To ensure satisfactory performance, asphalt rubber binder must be designed to accommodate the climate conditions. Generally, a performance grading (PG) of binders has addressed this issue for conventional, polymer modified and terminal blend binder. Currently, PG grading development efforts of asphalt rubber are underway. Although these efforts have not been completed, tables for the use of base stock asphalt have been prepared to accommodate various climatic conditions where asphalt rubber may be utilized. Table 10 shows the PG grading for various climatic regions (HDM, 2010).

Table 10 – *Performance Graded (PG) Binders*

Binder / Climatic Region	Conventional Hot Mixed Asphalt				Rubberized Asphalt
	Dense Graded HMA		Open Graded		Base Stock for Gap and Open Graded
			Placement Temperature		
	Typical	Special(1)	> 70°F	≤ 70°F	
South Coast Central Coast Inland Valleys	PG 64-10	PG 70-10 PG 64-28 PM	PG 64-10	PG 58-34 PM	PG 64-16
North Coast	PG 64-16	PG 64-28 PM	PG 64-16	PG 58-34 PM	PG 64-16
Low Mountain South Mountain	PG 64-16	PG 64-28 PM	PG 64-16	PG 58-34 PM	PG 64-16
High Mountain High Desert	PG 64-28	PG 58-34 PM(2)	PG 64-28	PG 58-34 PM	PG 58-22
Desert	PG 70-10	PG 64-28 PM	PG 70-10	PG 58-34 PM or PG 64-28 PM(3)	PG 64-16

7. Discussion

The reduced thickness design of asphalt rubber is a reality that has been supported by facts on the road as well as by laboratory and accelerated pavement testing. Additionally, mechanistic-empirical procedures can be used to design rubberized asphalt pavements using appropriate transfer-functions that relate the primary response parameters to actual field performance.

Reduced thickness standards of asphalt rubber can be applied to both structural and reflective cracking design as long as the criteria for compressive strain on top of the subgrade and the lateral strain below the asphalt rubber and asphalt layers are satisfied, as well as the crack-tip stresses below the overlay are minimized.

Rubberized stress absorbing membrane interlayers have been shown to provide significant benefits in increasing the life of pavements. These benefits have been quantified in terms of thickness equivalencies. Their contribution to performance have been attributed to the dissipation of stresses on the tips of the existing cracks as well as to their water proofing properties that protect the unbound layers below the pavement surface.

8. Conclusions

The following are some of the conclusions that can be derived from this paper:

• The reduced thickness design standards for asphalt rubber is not a myth but a reality. Reduced thickness design standards are being used on many roads with great success.

• Field performance of in-service roads and ample studies have validated the reduced thickness design standards.

• Accelerated pavement testing and laboratory performance testing have validated the reduced thickness standards of asphalt rubber.

• The reduced thickness standards can be applied to both structural and reflecting cracking design provided that there is adequate pavement support to minimize the compressive strain on top of the subgrade, and that the fatigue and reflective cracking criteria are satisfied.

• Rubberized stress absorbing membrane interlayers (SAMI-R) are an integral part of the reduced thickness design standards as they have been shown to provide structural contribution in pavement design.

9. References

ASTM, 2005, ASTM International Annual Book of Standards, D 8 Definitions, 2005.

Bejarano, M., Jones, D., Morton, B. and Scheffy, C., 2005, "Reflective Cracking Study: Initial Construction, Phase 1 HVS Testing, and Overlay Construction," University of California Pavement Research Center, Report UCPRC-RR-2005-03, October 2005.

HDM, Highway Design Manual, 2010, Highway design manual. California Department of Transportation, 1120 N Street, Sacramento, California 95716.

Jones, D., Harvey, J., and Monismith, C., 2007, "Reflective Cracking Study: Summary Report," University of California Pavement Research Center, Report UCPRC-SR-2007-01, December 2007.

Pais, J., Minhoto, M. and Shatnawi, "Multi-Cracks Modeling in Reflective Cracking," Proceedings, 7th RILEM International Conference on Cracking in Pavements, Delft, The Netherlands, June 2012.

Pinto Ângelo, Sousa Jorge B. , "The First Brazilian Experience with In Situ Field Blend Rubber Asphalt", Proceedings, Asphalt Rubber 2012 Conference, Munich, Germany, October 2012.

Qi, X., Shenoy, A., Al-Khateeb, G., Arnold, T., Gibson, N., Youtcheff, J., and Harman, T., 2006, "Laboratory Characterization and Full-Scale Accelerated Performance Testing of Crumb Rubber Asphalt and other Modified Asphalt Systems," Proceedings of AR2006 Conference, Palm Springs, 2006.

Rust F., Du Plessis J., Verhaeghe B., Grobler J., 1993, Heavy Vehicle Simulator Testing of Trial Sections for Caltrans. Division of Roads and Transport Technology, CSIR, South Africa, 1993.

Kaloush, K, Zborowski, A., Sotil, A. Abojaradeh, M., and Way G., "Material Characteristics of Asphalt Rubber Mixtures"/ Proceedings Asphalt Rubber 2003 Confernece, Brasilia, Brazil, December 2003.

Sousa, J., Pais, J., Saim R., Way, G. and Stubstad, R., "Development of a Mechanistic Overlay Design Method Based on Reflective Cracking Concepts". Report developed under contract with Rubber Pavements Association, August 2001.

Shatnawi, S., and Holleran, G., 2003, "Asphalt-Rubber Maintenance Treatments in California," Proceedings of AR2003 Conference, Brasilia, Brazil, 2003.

Shatnawi, S. "Life-Cycle Cost Analysis of Flexible Pavement Systems Rehabilitated with the Use of Asphalt Rubber Interlayers," Proceedings, Asphalt Rubber 2012 Conference, Munich, Germany, October 2012.

Shatnawi, S., Pais, J., Minhoto, M., “Asphalt Rubber Inerlayer Benefits on Reflective Crack Retardation of Flexible Pavement Overlays,” Proceedings, 30th Southern African Transport Conference (SATC), Pretoria, South Africa, July 2011.

Shatnawi, S., “Fatigue Performance of Asphalt Concrete Mixes Using a New Repetitive Direct Tension Test,” California Department of Transportation, Sacramento, California 95819, 1997.

Shirley, E., 1992, “Design Guide for ARHM-GG”, Memorandum, California Department of Transportation, Feb. 28.

Steven, B., Jones, D., Harvey, J., 2007, “Reflective Cracking Study: First Level Report on the Rutting Experiment,” University of California Pavement Research Center, Report UCPRC-RR-2007-06, April, 2007.

Sutliff, K. and Takigawa, S., “Crumb Rubber Usage in Hot Mix Asphalt (HMA) Pavements”. Memorandum, California Department of Transportation, February 10, 2015.