Intern. J. Pavement Engineering, 2001, Vol. 2(1), pp. 1-16
Reprints available directly from the publisher
Photocopying permitted by license only

Performance of Asphalt Rubber Mixes in California

SHAKIR SHATNAWI*

California Department of Transportation, 5900 Foslom Boulevard, Sacramento, CA 95819, USA

(Received October 28, 1998; Revised July 19, 1999)

This paper addresses the experience gained in California with asphalt rubber mixes from the performance of field test sections, accelerated pavement tests and laboratory performance tests. Field and laboratory studies have evaluated the performance of asphalt rubber mixes in terms of fatigue, reflective cracking, permanent deformation and moisture sensitivity. The findings have shown that asphalt rubber mixes, when properly designed and constructed, can provide superior performance as compared to conventional dense graded mixes. A proper mix design would be based on performance testing consisting of repetitive permanent deformation testing, fatigue testing, thermal cracking testing and moisture sensitivity evaluation. Mechanistic analysis is necessary so that the structural contribution of asphalt rubber mixes can be quantified. Layer thicknesses will have to be based on fatigue testing accompanied by mechanistic analysis.

Keywords: Asphalt rubber, Fatigue, Permanent deformation, Thermal cracking, Moisture sensitivity

INTRODUCTION

The use of crumb rubber modifier (CRM) in asphalt paving mixes has increased in recent years. The California Department of Transportation (Caltrans) has ranked CRM research at the top of the priority list of the Caltrans Accelerated Pavement Testing (CAL/APT) Program's strategic plan.

Asphalt rubber binders have been successfully used for joint and crack sealers, in chip seals, in stress-absorbing membrane interlayers (SAMIs), and in hot paving mixes. Generally, the field performance of CRM mixes has been positive but short-comings due to poor performance have been reported, which may be attributed in part to poor mix design practices, lack of performance-based physical property tests and poor construction practices. In addition, the properties of CRM mixes have been found to vary with the rubber type and gradation, rubber concentration, asphalt type and concentration, diluent type and concentration, diluent cure time and reaction temperature and time (Epps, 1994).

CRM is incorporated with asphalt paving mixes by one of two production processes, the wet and the dry. In the wet process, the CRM is blended and partially reacted with the asphalt cement prior to mixing with the aggregates in a hot-mix plant. Typically, asphalt cement and the CRM are reacted at high temperatures and diluents, aromatic oils, and polymers may be added. An asphalt cement that has been modified with CRM is called *asphalt rubber* (AR). Two common mixes that use this process are asphalt rubber hot mix

* Corresponding author: Phone: (916) 227 – 7306 Fax: (916) 227 – 7242 E-Mail: shakir.shatnawi@dot.ca.gov

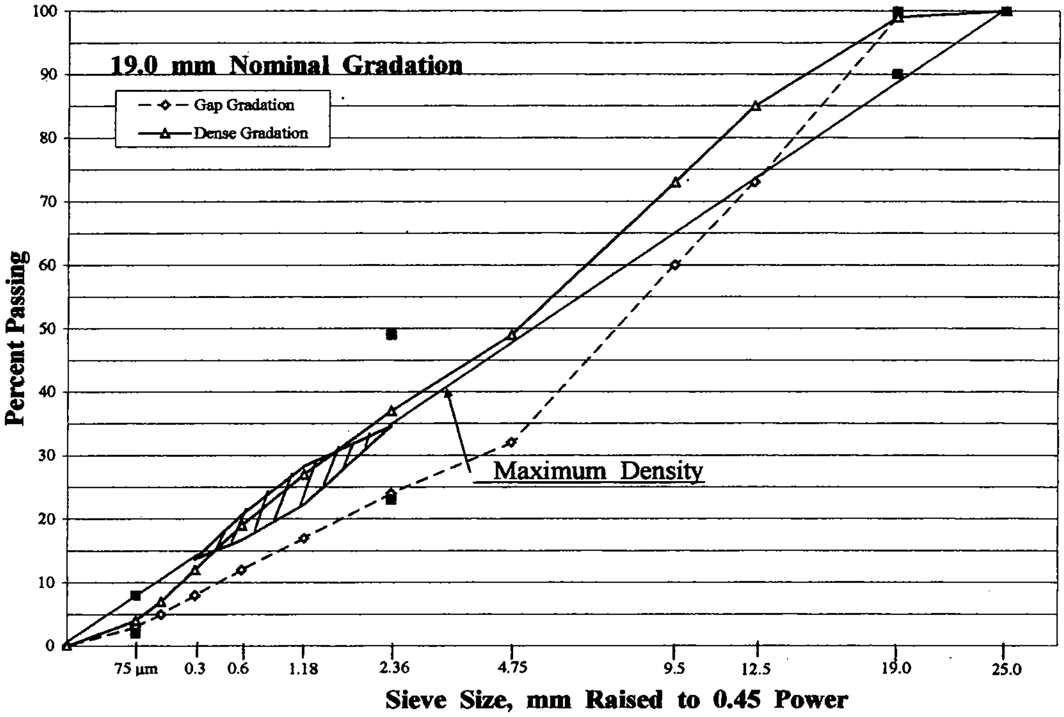

FIGURE 1 Caltrans typical gap and dense gradations

(gap graded) and asphalt rubber hot-mix (dense graded), which are referred to as ARHM-GG and ARHM-DG, respectively. Figure 1 shows typical dense and gap gradations in California.

In the dry process, the CRM is added to the aggregate in a hot-mix central plant operation before adding the asphalt cement. The final mix in this process is often referred to as *rubber modified asphalt concrete* (RUMAC). The CRM may need a pre-treatment with a catalyst to achieve the optimum particle swell (Epps, 1994). In this system, the rubber content should not exceed 3.0% by total weight of mix for surface courses (Epps, 1994). Since the CRM, the asphalt cement, and the aggregate are added at the same time, it is impossible to determine the modified binder properties directly.

The wet process has been the most widely used process in California for which structural and reflective cracking equivalencies have been developed. The terms *asphalt rubber* or *rubberized asphalt concrete* are commonly used interchangeably to refer to both processes of the CRM mix technology.

This paper provides an up-to-date assessment (1999) of the performance of asphalt rubber mixes for which some research and experience have been accumulated in California. The assessment is based on field performance and accelerated pavement testing as well as laboratory testing consisting of fatigue cracking, reflective cracking, permanent deformation, thermal cracking and moisture sensitivity.

ORIGINAL CALTRANS RESEARCH

Caltrans Long-Term Field Test Sections

The Ravendale Project

In the past, Caltrans depended heavily on long-term field test sections to evaluate and validate design procedures. In the late seventies and during the early eighties, Caltrans started experimenting with the use of reclaimed tire rubber in asphalt concrete by constructing field test sections at various sites across the state.

A project that was a turning point in the use of asphalt rubber mixes in California was located near the town of Ravendale on Route 395 in the northeastern part of the state. The project consisted of several test sections of various asphalt-rubber and conventional dense graded asphalt concrete (DGAC) thicknesses with and without stress absorbing membrane interlayers (SAMIs) (Doty, 1988). The asphalt rubber mixes used were ARCO-ARM-R-SHIELD (abbreviated as ARS) and PlusRide. These test sections were constructed in 1983. The annual precipitation in that area is between 200 and 255 mm. The air temperature exceeds 32 Celsius in the summer and drops below freezing in the winter.

Test sections were constructed using several rehabilitation strategies as shown in Table I. These strategies consisted of the following types:

- ARS sections using a 12.5 mm maximum dense gradation with and without SAMIs.
- PlusRide sections using 19 mm maximum gap gradation with and without SAMIs.
- Conventional DGAC sections with 19 mm maximum dense gradation.

The ARS wet process, known as the Arizona refining process, was developed in 1975. With this process, the asphalt rubber blend was composed of 18% rubber, of which 40% was devulcanized and 60% was ground ambient vulcanized, and 78% AR-4000 grade asphalt cement with 4.0% Witco extender oil. All of these percentages were by total weight of binder. The ARS granular rubber gradation had 98.0% passing the 0.60 mm sieve and 8.0% passing the 0.15 mm sieve size. Diluents were not added. The asphalt and the rubber were combined together in a 175 Celsius tank prior to mixing with the aggregate.

The PlusRide was a dry process in which dry ground tire rubber was added as part of the aggregate component. The rubber was not blended with the asphalt cement. The permeabilties according to California Test 341 were between 22.3 and 36.3 ml/min for the ARS, between 6.8 and 11.0 ml/min for the PlusRide and 177.0 ml/min for the conventional DGAC.

Test Section Design and Performance

The required conventional DGAC overlay thicknesses for the project were determined from non-destructive pavement deflection testing. These thicknesses were based on either structural requirements or reflective cracking requirements. After determining the required thickness, the overlays were placed at various thicknesses. Table I shows each segment's, design basis, design strategy, thickness provided, the ratio of the provided thickness over the required thickness and the number of ESALs to failure. The "required thickness" is that needed to provide a design life of 510,000 ESALS over a 10 year period. The data was evaluated in terms of deflections, pre-overlay distress and post-overlay distress. Caltrans engineers concluded that mixes with asphalt rubber modifiers could perform equal to conventional DGAC mixes at reduced thicknesses from that required for conventional DGAC.

Ravendale Laboratory Performance

In 1995, field cores were obtained from the center of the lanes that contained the ARS and the DGAC test segments. The measured air void contents were 6.0% for the ARS and 11.0% for the DGAC segments. The cores were then subjected to reflective cracking testing using the newly developed Caltrans reflective cracking (CRC) device which utilizes both the vertical and the horizontal actuators of the Superpave shear tester (SST) to simulate load-associated crack movement; crack opening-closing (Mode I) and vertical shear movement (Mode II). The reflective cracking testing was conducted at 20 Celsius under controlled-displacement mode of loading. The results showed that the ARS rubber mixes would perform better than the DGAC mixes in terms of reflective cracking resistance (Fig. 2). These results agree with the field performance data. However, emphasis must be placed on the effect of in-place density on fatigue performance, which can be significant.

TABLE I Ravendale Project test sections results

Segment	*Design basis*	*Design strategy*	*Thickness provided*	*Thickness ratio (provided/required)*	*ESALs to failure*
1	Structural	ARS/SAMI	75 mm	0.45	510,000
2	Structural	ARS/SAMI	45 mm	0.30	510,000
3	Reflective	ARS	45 mm	0.60	450,000
4	Structural	PlusRide	45 mm	0.33	450,000
5	Structural	PlusRide/SAMI	45 mm	1.00	510,000
6	Reflective	PlusRide/SAMI	75 mm	1.25	510,000
7	Reflective	DGAC	45 mm	1.00	150,000
8	Structural	DGAC	60 mm	0.40	150,000
9	Structural	DGAC	90 mm	0.50	350,000
10	Structural	DGAC	150 mm	1.25	510,000

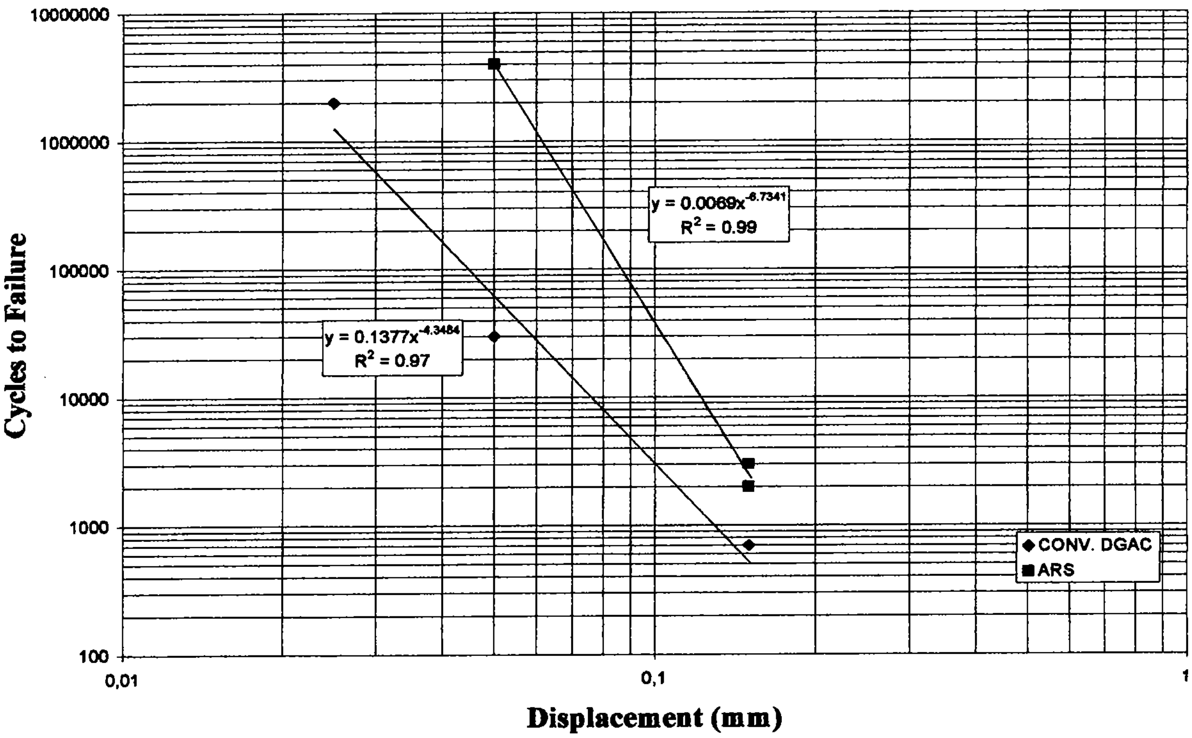

FIGURE 2 Cycles to failure versus shear displacement (reflective cracking)

Recent Field Reviews of Asphalt Rubber Projects

During 1995, Hildebrand and Van Kirk of Caltrans conducted field reviews of 88 asphalt rubber projects throughout the state of California, the majority of which were ARHM-GG and ARHM-DG overlays (Hildebrand and Van Kirk, 1995). The reviews revealed that asphalt rubber mixes would give good performance when properly designed and constructed. The poor performance found in some projects was related to factors such as mix design and compaction problems,

Hildebrand and Van Kirk compared projects constructed using Type I asphalt rubber binder with those constructed with Type II asphalt rubber binder. (Type II binder contains a high natural rubber additive and an extender oil which are not used in Type I binder.) They found that mixes with Type II binder had performed better in reflective cracking resistance than those with Type I binder and they believed that the use of a diluent in Type I and an extender oil in Type II would improve field performance. They mentioned that the rate of cracking and raveling was greatly reduced when compared with conventional DGAC. It should be mentioned here that a physical property specification for asphalt rubber binder has been proposed, which is currently under evaluation by Caltrans (Reese, 1994).

MIX DESIGN PRACTICES FOR ASPHALT RUBBER

Traditional Mix Design Practices

The traditional mix design practices for asphalt rubber mixes have been based on variations of the Hveem and Marshall procedures by using stability tests and weight-volume parameters. In the wet process, the mix design criteria include significant reductions in Hveem stabilities, Marshall stabilities, and Marshall flow and increases in "voids in mineral aggregate" (VMA). In the dry process, the Marshall and Hveem stabilites are reduced, and the mix design properties are largely dependent on the CRM concentration and aggregate gradation.

The mixing and the compaction temperatures for asphalt rubber mixes are higher than those for conventional DGAC. The design air voids and aggregate gradation depend on the CRM content and the production process. It has been found that low asphalt contents in the wet process would have little or no effect on the mix design, whereas the CRM content in the dry process would affect the design air voids and aggregate gradation (Epps, 1994).

Asphalt rubber binder contents are typically 10 to 20% higher than the asphalt content in conventional DGAC mixes. As an example, if 20% CRM is used in the binder, the asphalt rubber binder will be 20% greater than a conventional binder, i.e., 6% versus 5% by dry weight of aggregate (Epps, 1994).

Caltrans' Mix Design Practices

Caltrans' mix design experience with ARHM-GG and ARHM-DG has been based, until recently, on a method that used air voids of 2.0% and 3.0%, respectively, with no stability requirements. The low Hveem stability values associated with asphalt rubber mixes led temporarily to the discontinued use of this parameter in the design of asphalt rubber mixes (Van Kirk, 1989).

The lack of a performance-based test that can adequately assess the stability of asphalt rubber mixes has resulted in some rutting failures. These failures have led Caltrans pavement engineers to include additional requirements and to modify the criteria to consider variations of traffic and environment. The latest requirements for ARHM-GG and ARHM-DG include a Hveem stability of 23 minimum, voids in mineral aggregate (VMA) of 18% minimum and a design air void content that varies with traffic and climate as shown below.

Traffic Index	*Region*			
	Mountain	*Valley*	*Coastal*	*Desert*
<6	3.0	3.0	3.0	3.0
6–10	3.0	4.0	4.0	4.0
>10	4.0	4.0	4.0	5.0

The traffic index is an indicator of the traffic volume in terms of equivalent 80 kN single axle loads (ESALs) according to the following formula:

$$\mathrm{TI} = 9.0 \times (\mathrm{ESAL}/10^6)^{0.119} \qquad \text{Equation 1}$$

Where TI is the traffic index.

The requirements call for the use of 4.0% air voids when the ambient temperature exceeds 35 Celsius in mountain regions with a traffic index greater than 6. In addition, the optimum binder content must fall between the limits of 7.0 and 9.5% for ARHM-GG and between the limits of 6.5 and 8.5% for ARHM-DG based on weight of aggregate. These prescriptive requirements are currently being re-evaluated relative to the inclusion of performance-based specification requirements.

Performance-Based Mix Design and Specifications

Research using the Strategic Highway Research Program (SHRP) tests is being conducted in Caltrans to develop performance-based tests that can be used to design a variety of mixes including asphalt rubber. The proposed specification is based on determining the optimum binder content using the repetitive simple shear test at constant height (RSST-CH) (AASHTO TP7–94), conducting fatigue testing using either the flexural bending beam test (AASHTO TP8–94) or the Caltrans direct tension test, and conducting mechanistic analysis to determine the critical strains in the pavement and comparing the results to a standard mix with known fatigue performance. In addition, the specification requires screening the mix for moisture sensitivity using AASHTO T 283 and performing thermal cracking testing using the thermal stress restrained specimen test (TSRST, AASHTO TP10–93).

CALTRANS' STRUCTURAL DESIGN FOR OVERLAYS

Caltrans' structural design procedure for overlays is based on non-destructive deflection testing of existing pavements. The maximum deflection below the load is used to determine the thickness requirements of an overlay for a design life of 10 years. This procedure uses the maximum deflection criteria to obtain the required thickness according to Caltrans Test 356. The required overlay thickness is selected to account for structural or reflective cracking requirements. The structural requirements are based on deflections that are higher than certain tolerable criteria. When the pavement experiences severe cracking but the deflections are below the tolerable limits, the reflective cracking requirements prevail. In general, design to meet reflective cracking requirements is achieved for by providing an overlay thickness equivalent to 50% of the thickness of the existing wearing course.

Caltrans' Structural Design Guidelines for ARHM-GG

The performance from the Ravendale sections and from other asphalt rubber sections resulted in the development of a design guide for flexible pavement overlay rehabilitation using ARHM-GG (CALTRANS, 1992–3). This guide has recently been used for overlaying "cracked and seated" Portland cement concrete (PCC) pavements. The guide recommends reducing thicknesses of ARHM-GG overlays by as much as 50% of the required conventional DGAC design thicknesses. However, thicknesses of ARHM-GG overlays may not exceed 60 mm in order to prevent rutting problems. If a thickness greater than 60 mm was indicated prior use of conventional DGAC is required so as to keep the ARHM-GG thickness within the permitted limits. Caltrans has been using these guidelines since 1992 in all rehabilitation projects involving ARHM-GG overlays.

TABLE II California structural equivalencies (mm)

DGAC	*ARHM-GG*[a]	*ARHM-GG/SAMI*
45	30[b]	–
60	30	–
75	45	30
90	45	30
105	60	45
120	60	45
135	45[c]	60
150	45[d]	60
165	60[c]	45
180	60[d]	45

a. The maximum allowable non-experimental equivalency for ARHM-GG is 2:1.
b. The minimum allowable ARHM-GG lift thickness is 30 mm.
c. Place 45 mm of new DGAC first.
d. Place 60 mm of new DGAC first.

TABLE III California reflective crack retardation equivalencies (mm)

DGAC	*ARHM-GG*	*ARHM-GG/SAMI*
45	30[a]	–
60	30	–
75	45	–
90	45	–
105[b]	45[c]	30[d]

a. The minimum allowable ARHM-GG lift thickness is 30 mm.
b. A DGAC thickness of 105 mm is the maximum thickness recommended by Caltrans for reflection cracking.
c. Use 45 mm if the crack width is less than 3 mm and 60 mm if the crack width is equal to or greater than 3 mm.
d. Use if the crack width is equal to or greater than 3 mm. If less than 3 mm, use another strategy.

The thickness requirements according to the Caltrans design procedure are shown in Tables II and 3. The procedure begins, first by, determining the thickness requirements for a conventional DGAC based on deflections and structural section stiffening requirements. Secondly, the conventional DGAC thickness required to retard reflection cracking is determined. Thirdly, Tables II and III are used to determine the required thicknesses for ARHM-GG. If the ride score is greater than the allowable minimum and there is no structural need, then two 30 mm thick lifts of ARHM-GG are placed or a depth of 30 mm is cold planed before placing the ARHM-GG as determined by the procedure.

Basis Behind Caltrans' Structural Design Guidelines for ARHM-GG

Caltrans' structural design guidelines have been based largely on the results from the Ravendale project. Some field test sections in California have supported the conclusions drawn from the Ravendale project but additional evaluation efforts are necessary. For example, a project located on Route 139 containing several test segments with ARHM-GG and conventional DGAC exhibited early distress. This project was constructed in 1991. On this project, reduced thicknesses were used on segments containing ARHM-GG and conventional DGAC mixes along with segments of conventional DGAC and polymer-modified DGAC at the normal required thicknesses. The data showed early fatigue failures in all of the reduced thicknesses within 5 years after construction. This project is currently under investigation to determine the causes of failures. The results from this investigation are likely to result in a mechanistic design-based approach to thickness adjustments.

Assumptions Used During the Development of Caltrans' Structural Design Guidelines for ARHM-GG

The following assumptions were made during the development of the guidelines:

- The most promising form of asphalt rubber is ARHM-GG.
- ARHM-GG is recyclable.
- Cracking in the overlays is caused by a combination of traffic loads and movement of the underlying pavement.
- Even thinner layers (higher equivalencies) of ARHM-GG may be appropriate but, to limit risk, higher equivalencies should be considered experimental.
- ARHM-GG may be little or no better than DGAC in preventing cold weather induced transverse cracking.
- The degree of stiffening provided by a specific thickness of ARHM-GG is less than the amount of stiffening provided by the same thickness of DGAC. Thus, after the overlay the ratio of tolerable deflection to the actual deflection for ARHM-GG may become less favorable when the ARHM-GG thickness is greater than 60 mm.
- ARHM-GG can withstand considerably higher deflection than the same thickness of DGAC without cracking.
- The mild climate structural equivalency of a SAMI is less than or equal to 15 mm of ARHM-GG (i.e. less than or equal to 30 mm of DGAC; assuming that the SAMI reduces that portion of the total overlay stress caused by reflection of underlying cracks/joints).

- The reflection crack retardation equivalency of ARHM-GG is considerably greater than that of DGAC.
- The reflection crack retardation equivalency of a SAMI is 30 mm of ARHM-GG which is approximately 60 mm of DGAC.
- There may be stability problems if ARHM-GG is placed thicker than 60 mm, even if multiple lifts are used.

CALTRANS' RECENT RESEARCH ON ASPHALT RUBBER MIXES

Fatigue

CAL/APT Pilot Project in South Africa

To gain additional validation for the reduced thickness design of ARHM-GG, Caltrans undertook a cooperative effort with the Republic of South Africa to perform accelerated pavement testing using the South African Heavy Vehicle Simulator (HVS). This cooperative effort constituted a pilot research project in South Africa. As part of the experiment, a 75 mm thick DGAC overlay section and three 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, which has a climate similar to that found in California. The overlays were constructed using materials and mix design procedures conforming to Caltrans specifications (Rust et al., 1993). This study did not, however, account for the effects of binder age hardening and its effect on fatigue life.

The HVS test results indicated that a reduction of at least 50% in layer thickness to obtain similar fatigue performance over flexible pavements can be justified when conventional DGAC is replaced with ARHM-GG. These test results served to tentatively validate Caltrans' design guide for ARHM-GG overlays over flexible pavements. This study recommended checking the subgrade rutting criteria when reducing the required thickness based on fatigue performance.

CAL/APT HVS Tests at the Richmond Field Station

Additional accelerated testing was conducted in California. In March 1997, a DGAC overlay and an ARHM-GG overlay were constructed side-by-side at the CAL/APT HVS test site at the Richmond Field Station of the University of California at Berkeley. The thickness of the DGAC overlay was 72 mm. The design thickness of the ARHM-GG overlay was half that of the DGAC overlay, following Caltrans design guidelines. The constructed thickness of the ARHM-GG averaged 36 mm. A small section of the ARHM-GG overlay was constructed to a thickness of 67 mm as well.

Both overlays were constructed over an existing flexible pavement consisting of approximately 150 mm of DGAC over an aggregate base and subbase, and a stiff subgrade. The overlaid area included four HVS test sections that were trafficked by the HVS as part of an earlier experiment. The upper lift of asphalt concrete in those four sections was cracked, the lower lift was uncracked, and the sections had some rutting in the mix and the underlying layers (Harvey et al., 1998).

The constructed binder content of the ARHM-GG mix was found to be about 1% less than the design asphalt content of 7.6 to 7.9% by mass of aggregate, on average. The binder content of the DGAC mix, and the gradations of both mixes met specifications. Both mixes were compacted following Caltrans method specifications. The ARHM-GG mix arrived at the site cooler than the DGAC mix, and cooled faster after placement. Despite the same rolling pattern on both mixes, the average air-void contents were 5.4% for the 72 DGAC overlay, 8.9% for the 67 mm ARHM-GG and 14.4% for the 36 mm ARHM-GG overlay (Harvey et al., (1999).

The HVS trafficking was performed at 20 C using 100 kN loads on a dual-radial wheel at the rated inflation pressure with a one meter wide wander pattern and bidirectional loading. The overlays were trafficked until substantial cracking was observed on the surface. The results indicated that the DGAC and the ARHM-GG at half thickness had similar cracking performance. Trenching, and comparison of digitized crack patterns from the surface of the original asphalt concrete and the overlays showed that the cracking in the overlays was reflected through from the underlying asphalt concrete. Better compaction of the ARHM-GG would be expected to improve its cracking and rutting performance beyond that seen in these HVS tests.

Flexural Bending Beam Fatigue

Flexural fatigue tests conducted in Alaska have supported Caltrans' structural thickness adjustments for ARHM-GG overlays. Controlled-strain laboratory flexural beam fatigue tests and multi-layer elastic analysis were conducted at the University of Alaska by Raad et al. (1993). Their analysis indicated that a reduction in the thickness would become more significant with increasing foundation support (higher base and subgrade moduli). Raad et al. developed thickness equivalencies between DGAC and ARHM-GG based on the remaining fatigue life of pavement sections with similar initial fatigue life. By assuming base and subgrade moduli of 550 kPa and 140 kPa, respectively, they demonstrated that DGAC layer thicknesses of 150 mm and 255 mm would be equivalent to ARHM-GG layer thicknesses of 50 mm and 125 mm, respectively. They rationalized that the equivalent ARHM-GG would be significantly smaller in the case of overlays as a result of increased support of the existing pavement structure. In addition to the Alaskan study, controlled-strain flexural fatigue tests were conducted at the University of California for Caltrans as part of the CAL/APT South African pilot project (Harvey and Monismith, 1994). The findings indicated that ARHM-GG would provide considerably longer fatigue life when compared with the same thickness of DGAC.

Repetitive Direct Tension Test

Fatigue tests were conducted on beams taken from two SHRP SPS-5 sections using the Caltrans repetitive direct tension test with a test temperature of 20 Celsius and a frequency of 10 Hz under controlled-strain mode of loading. The SPS-5 sections are located on Interstate 40 near Newberry Springs, which is in a desert environment with a 7-day maximum pavement temperature of 60 Celsius 50 mm below the pavement surface. These sections were constructed in 1992. One section consisted of a rehabilitation strategy composed of an ARHM-GG layer at a reduced thickness over a new conventional DGAC layer, and another section consisted of a rehabilitation strategy composed of 3 layers of conventional DGAC. Two asphalt sources, Valley and Coastal, were used on this project. The fatigue results revealed that the asphalt rubber mix containing the Valley asphalt source performed better in fatigue than the conventional mixes containing either Valley or Coastal binders (Fig. 3) (Shatnawi, 1997). In this figure, S2L1 stands for an ARHM-GG (top lift), S2L2 stands for DGAC with Valley asphalt (second lift). These two mixes are from a section designated as Section 2. S4L1 and S4L2 are DGAC mixes with Coastal asphalt placed at the top and second lifts of Section 4, respectively. S4L3 is a DGAC with Valley asphalt placed as the third lift in Section 4. The Valley asphalt produced DGAC mixes with higher stiffness values than the Coastal asphalt and it resulted in mixes having less fatigue resistance than mixes with Coastal asphalt in the controlled-strain repetitive direct tension test. Even with these properties, the asphalt rubber mix containing Valley asphalt outperformed the DGAC mixes containing both asphalt sources in the fatigue test. In addition, Fig. 3 shows two distinct fatigue curves for the coastal mixes, possibly indicating the effect of aging on the top lift as compared to the second lift. Field reviews after 5 years of traffic showed comparable fatigue performance in both the DGAC and the asphalt rubber sections.

Reflective Cracking

Three laboratory mixes (ARHM-GG, ARHM-DG and DGAC) with air voids of 7.0 % were subjected to the reflective cracking test at a temperature of 20 Celsius to assess their reflective cracking resistance (Fig. 4). The results showed that in terms of reflective cracking resistance ARHM-GG ranked first, ARHM-DG ranked second, and DGAC ranked third. The reflec-

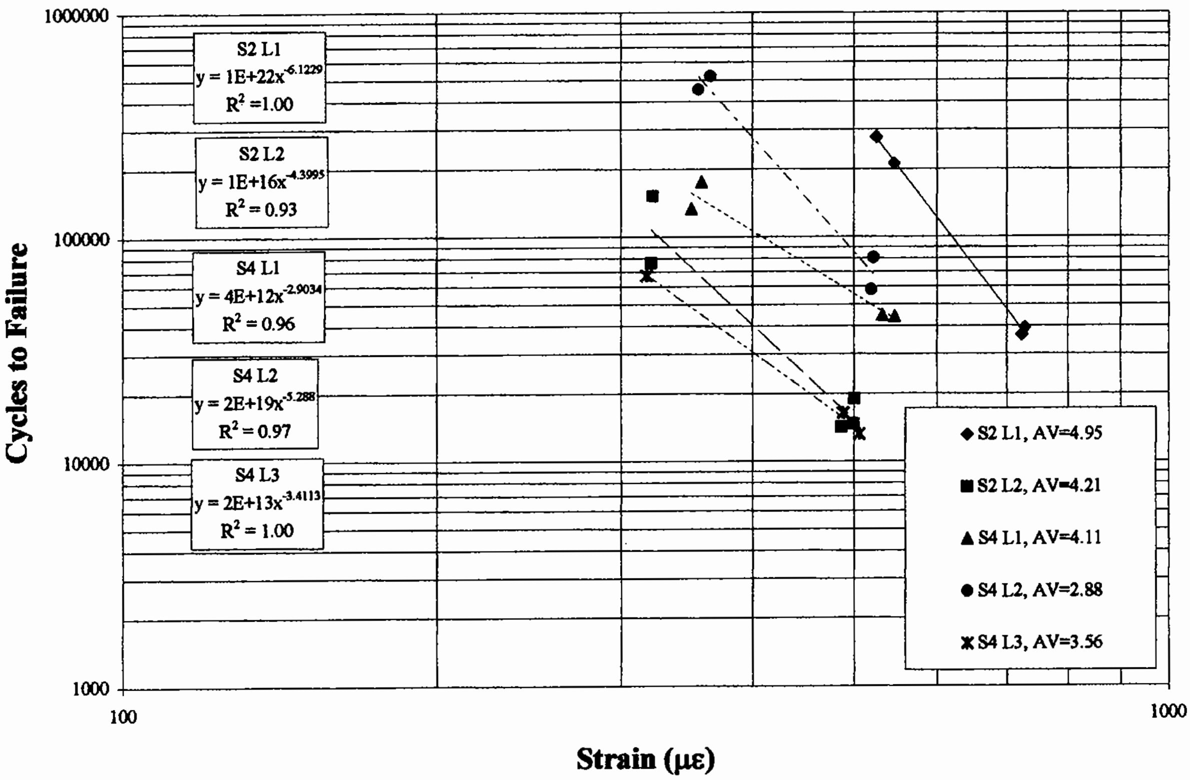

FIGURE 3 SPS-5 repetitive direct tension fatigue results

tive cracking tests simulated crack movement in two modes (Mode I and Mode II) in PCC pavements. These results show that asphalt rubber mixes could provide better reflective cracking resistance than conventional DGAC when used as overlays on top of PCC pavements. The results from these tests could possibly be applied to alternative strategies using ARHM-GG (with and without SAMI) on cracked and seated PCC pavements. These alternatives would provide additional resistance to reflective cracking and would allow placement of thinner layers.

It should be indicated here that field experience with asphalt rubber overlays over PCC pavements has been limited. In 1993, Caltrans constructed for the first time a unique PCC pavement rehabilitation project where the contractor warranted for 5 years an overlay consisting of 45 mm ARHM-GG on 45 mm DGAC leveling course (incorporating a Performance Based Asphalt (PBA-6) over a cracked and seated PCC pavement (Harvey et al., 1995). This project is located north of Redding, California on Interstate 5 in Shasta County. The asphalt rubber binder consisted of AR-4000 blended with 17.0% ground tire rubber and 2.0% natural rubber. The project consisted of both northbound (NB) and southbound (SB) sections which were constructed by two contractors that used two different aggregate sources. The binder contents used were 7.7% and 8.7% for the NB and SB sections, respectively. Reviews of this project so far have indicated good performance in both directions with some minor surface abrasion.

Permanent Deformation

Results from Caltrans field sections and laboratory performance tests have revealed that asphalt rubber

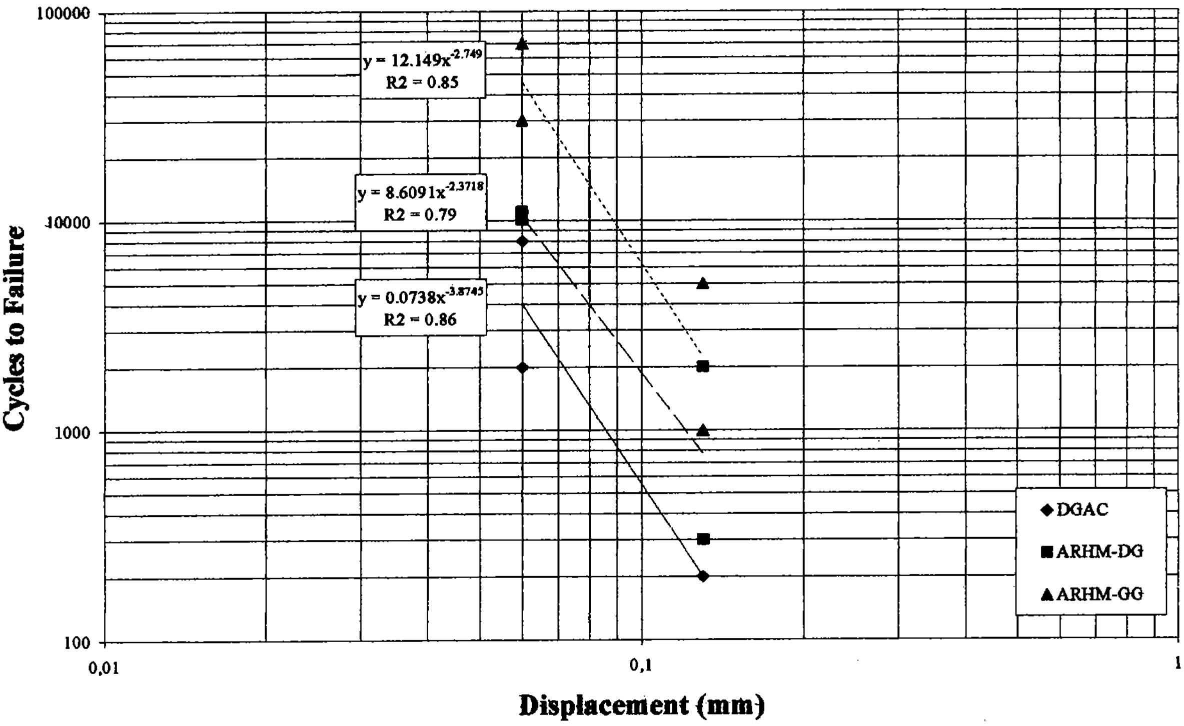

FIGURE 4 Cycles to failure versus displacement (reflective cracking)

mixes could produce adequate resistance to permanent deformation when properly constructed and designed. Recent work has supported field observations regarding the resistance to permanent deformation. The following are brief descriptions of some of these studies.

CAL/APT Pilot Project

During the CAL/APT pilot project, the permanent deformation resistance was assessed by conducting companion laboratory tests utilizing the repetitive simple shear test at constant height (RSST-CH) (Harvey and Monismith, 1994). These tests were conducted at a temperature of 19 Celsius. This medium temperature is not typically used to assess rutting resistance. It was selected, however, to simulate the temperature of the controlled environment of the HVS test sections in South Africa. The shear stress used was 70 kPa with 0.1 seconds loading and 0.6 seconds rest periods. The data were compared at 4.5 percent permanent shear strain which corresponds to 13 mm rut depth according to the following relationship developed as part of the SHRP A-003A project:

$$\text{Rut Depth (mm)} = 279 \times \gamma_p \qquad \text{Equation 2}$$

where γ_p = the permanent shear strain.

The tests indicated that at high air voids (10.0%), ARHM-GG would have higher permanent shear than conventional DGAC, and at low air voids (5.0%), ARHM-GG would have less permanent shear than DGAC. It is worth emphasizing that permanent deformation testing should be conducted at elevated temperatures where mixes have less resistance to permanent deformation.

CAL/APT HVS Tests at the Richmond Field Station

Rutting tests using the HVS were conducted at the Richmond Field Station test sections on both ARHM-GG and DGAC. The construction of the test sections and the layer thicknesses were as described

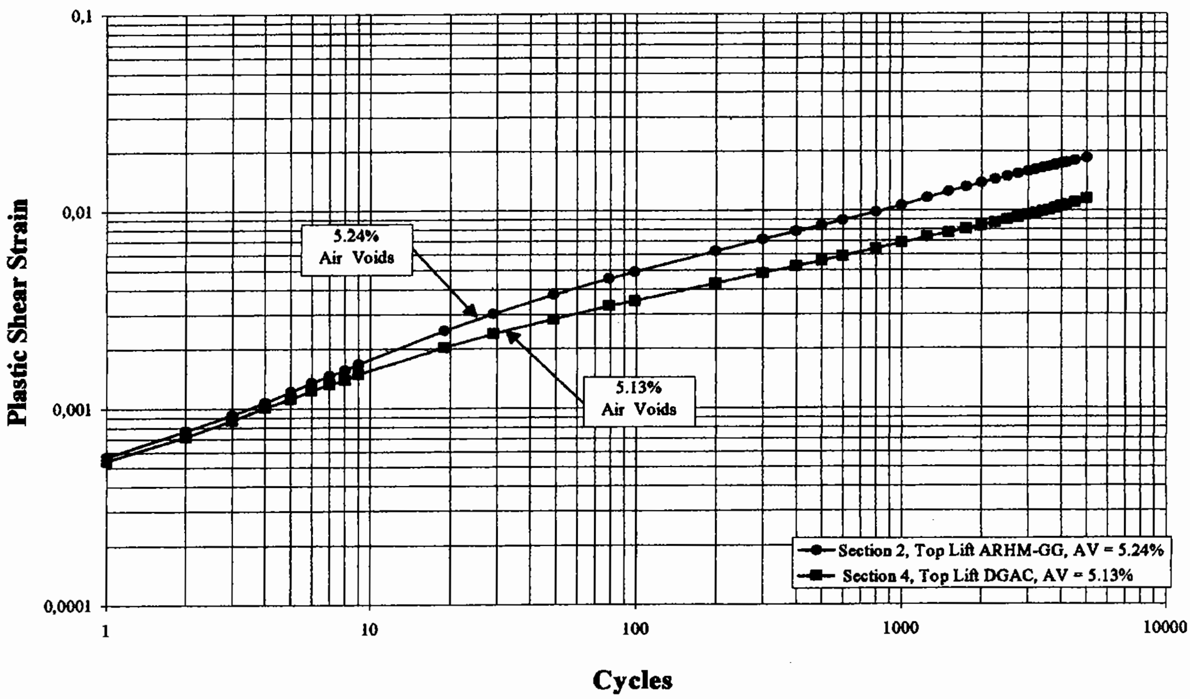

FIGURE 5 Plastic shear strain versus cycles (RSST-CH)

before in the fatigue portion of this paper. The target pavement surface temperature for the rutting tests was a constant 55 C. The rutting testing of the two thicknesses of ARHM-GG and DGAC was conducted in one direction only, using both dual-radial tires and a wide-base single tire with the rated inflated pressures at 40 kN loads in a channelized traffic mode.

The results indicated that the DGAC overlay and both thicknesses of the ARHM-GG overlay had nearly identical performance under the dual-radial wheel. Under the wide-base single wheel, the DGAC and the thick ARHM-GG overlay had similar performance. The thin ARHM-GG overlay had somewhat better performance than the DGAC, although the test temperature was 2 to 3 C higher than that of the other two tests.

Newberry Springs SPS-5 Project

Laboratory tests consisting of RSST-CH and the LCPC wheel-tracking device were conducted on field cores from the aforementioned SPS-5 project on Interstate 40. These tests were conducted at a temperature of 60 Celsius which corresponds to the 7-day maximum pavement temperature at 50 mm pavement depth. The shear stress used was 70 kPa with 0.1 seconds loading and 0.6 seconds rest periods. The data were compared at 4.5 percent permanent shear strain which corresponds to 13 mm rut depth according to Equation 2. The results show that the DGAC mix has more resistance to permanent deformation than the ARHM-GG mix but this does not mean that the ARHM-GG is prone to rutting (Figs 5 and 6). Field reviews of the two test sections showed that both DGAC and ARHM-GG mixes had comparable performance. The measured rut depth in both sections was less than 2 mm after 5 years of traffic with 40 percent trucks under high desert temperature.

I-5 Warranty Project

In the aforementioned 1993 warrantied pavement project, two mixes were designed for the overlay of a "cracked and seated" PCC pavement, one DGAC

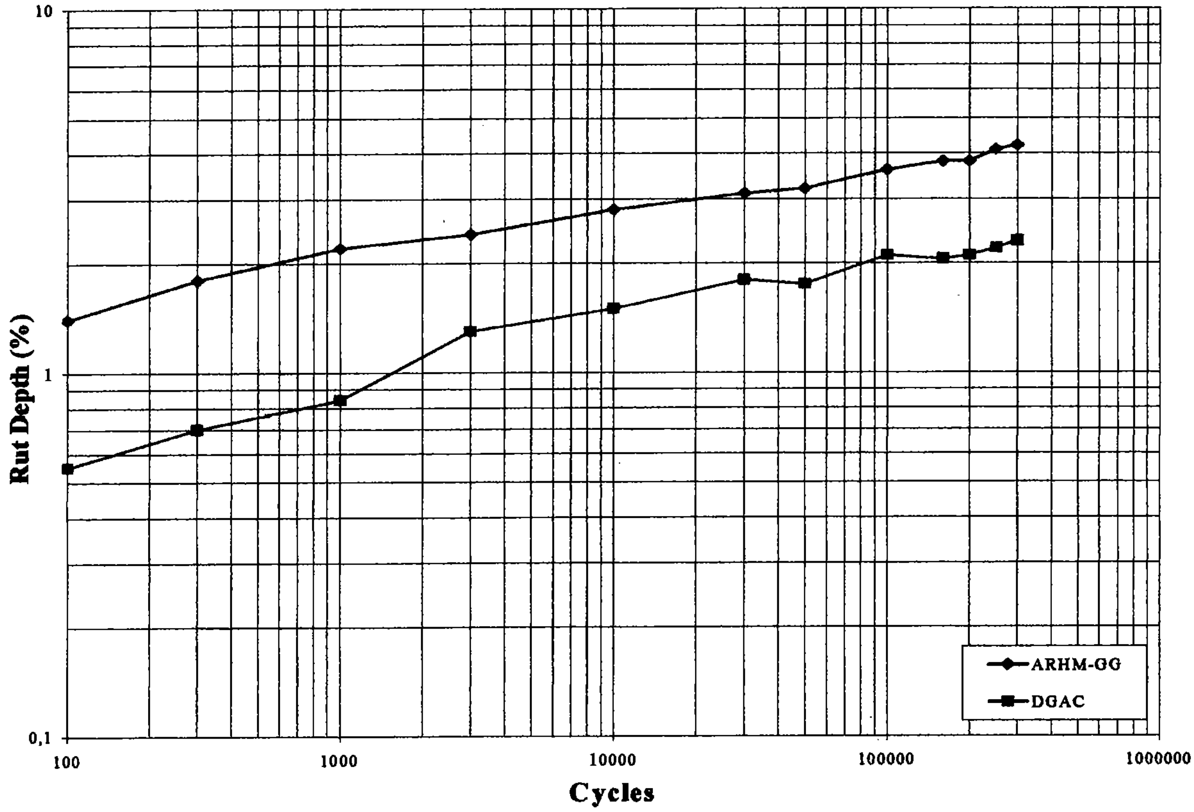

FIGURE 6 Rut depth versus cycles (LCPC wheel tracking)

with PBA-6 binder and the other ARHM-GG (Harvey et al., 1995). The mix design methods were based on mix performance using the RSST-CH, traffic, site-specific temperature, and reliability. The optimum binder contents were found to be 5.2% and 6.5%, for DGAC-PBA6 and ARHM-GG, by dry weight of aggregate. The optimum binder content based on the air void method was compared to that obtained with the performance-based mix design. It was found that the recommended binder content for the ARHM-GG using the performance-based method was much lower than the binder content determined through the air void method which was 8.5%. On this project, a compromise between the 8.5% and the 6.5% binder contents was made before construction, which resulted in using a binder content of 7.5%. Field reviews of this project to date showed good performance on both sections with only minor raveling.

Thermal Cracking

Recent research conducted by Epps at the University of California showed that asphalt rubber mixes would have superior thermal cracking performance as compared with conventional DGAC (Epps, 1997). The tests conducted included thermal strength using the thermal stress restrained specimen test (TSRTS) and thermal fatigue using the flexural fatigue tests at low frequencies. She concluded that asphalt rubber modification would improve the resistance to both types of thermal cracking. In addition to this work, Raad et al. (1993) conducted a thermal cracking study using the TSRST and concluded that thermal cracking would generally be enhanced by using crumb tire modifiers. They emphasized that the magnitude of improvement would depend on the rubber modification process. It should be emphasized that the above conclusions are

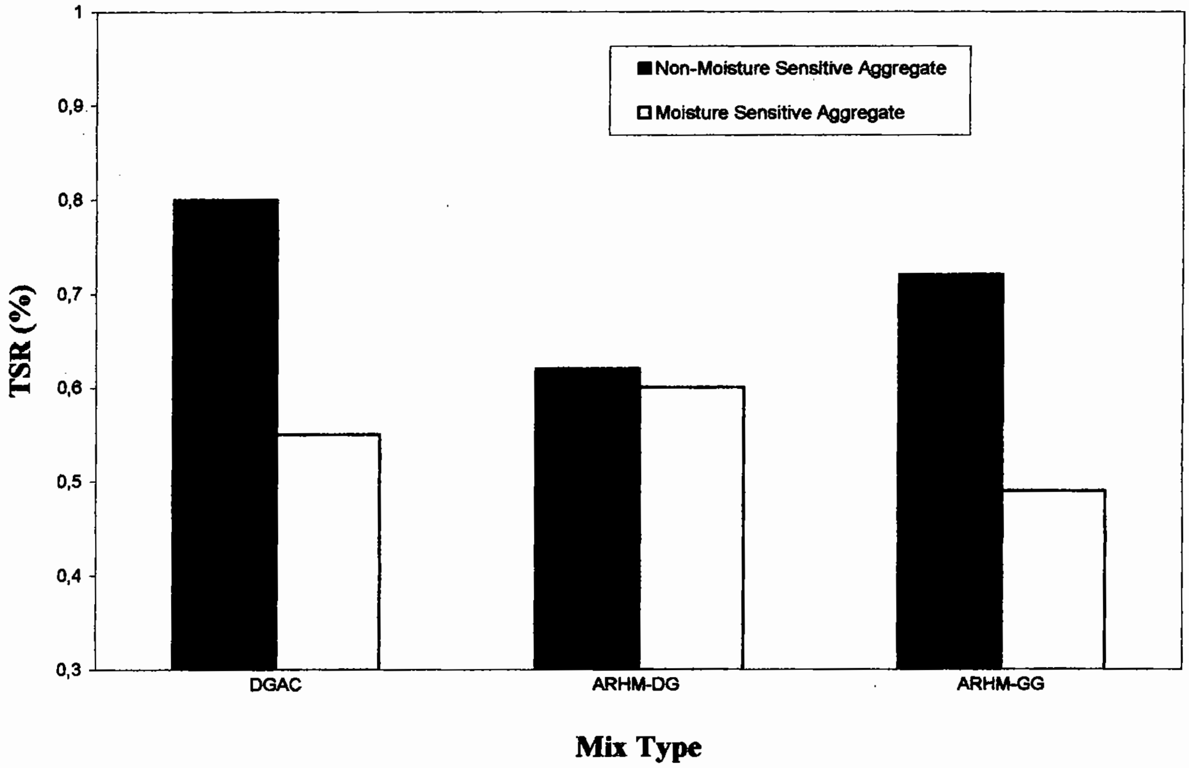

FIGURE 7 Tensile strength ratio (TSR) versus mix type (AASHTO T 283)

dependent on the grade of asphalt used in the DGAC mixes studied.

Moisture Sensitivity

The moisture sensitivity resistance of asphalt rubber mixes has been documented by several research efforts. For example, Maupin used the AASHTO T 283 test method to compare asphalt rubber mixes with conventional DGAC mixes (Maupin, 1992). He showed that asphalt rubber mixes could be more resistant to moisture damage than DGAC mixes containing the same aggregate. Epps (1994) indicated that substantial strength loss was shown to occur after moisture conditioning in both the wet and dry processes Recent studies in California indicated that there could be moisture sensitivity problems with asphalt rubber mixes (Shatnawi, 1994). Therefore, it is essential that moisture sensitivity evaluations of these mixes be conducted during the mix design process. In cases where the potential for moisture sensitivity is detected, a treatment with an anti-stripping additive or the use of a different mix may be necessary. Below are brief descriptions of two moisture sensitivity studies in California.

Moisture Sensitivity Evaluation Using AASHTO T 283

Caltrans conducted testing using the AASHTO T 283 test method on asphalt rubber and conventional DGAC mixes (Shatnawi, 1994). The results showed that lower tensile strength ratios (TSRs) for asphalt rubber mixes (ARHM-GG and ARHM-DG) could occur as compared with conventional DGAC mixes containing the same aggregate type (Fig. 7). Field performance indicated that moisture damage occurred early in the service life of some asphalt rubber pavement projects.

TABLE IV ECS moisture sensitivity results for the I-5 Warranty Project

Mix	*Binder Content (%)*	*0.5% Additive*	*Moisture Sensitive?*
DGAC – PBA6	4.5	No	Yes
	4.5	Yes	No
	5.0	No	Borderline
	5.0	Yes	No
ARHM-GG	7.0	No	No
	7.0	Yes	No
	7.0	Yes	No
	8.0	No	No
	8.0	Yes	No

Environmental Conditioning System (ECS, AASHTO TP34–93)

On the warrantied pavement, moisture sensitivity testing using the Environmental Conditioning System (ECS) was conducted on the mixes with binder contents of 4.5% and 5.0% for DGAC-PBA6 and 7.0% and 8% for ARHM-GG. These two mixes were tested at air voids that approximated in-place field air voids of around 8.0% and 11.0%, respectively. The tests revealed low resistance to water damage in the DGAC-PBA6 mix but not in the ARHM-GG mix (Table IV). An anti-stripping additive was added to selected mixes to increase the resistance to moisture damage.

DISCUSSION

Caltrans' experience with asphalt rubber mixes has demonstrated that asphalt rubber mixes such as ARHM-GG can have superior fatigue performance as compared with DGAC mixes. This experience has also shown that asphalt rubber mixes, when properly designed and constructed, can provide adequate resistance to permanent deformation. The lack of a performance-based mix design has contributed to premature rutting failures.

It has been demonstrated that the current mix design practice, which uses the air void method, could result in higher binder contents when compared to a performance-based mix design. In the warrantied pavement project, which used a performance-based mix design, the optimum binder content was considerably lower (2%) than the optimum obtained using the air void method. Consequently, this could influence field performance. With a reduced binder content, a reduction in fatigue life is likely but at the same time the risk of premature rutting failures is minimized. Thus a reduction in binder content may result in modifications to the reduced thickness guidelines.

Since the development of the structural and reflective cracking equivalencies was based mainly on the long-term performance of pavement test sections, an approach based on engineering properties is under consideration. A new approach based on repetitive simple shear testing and fatigue testing accompanied by mechanistic analysis has been proposed. This approach may result in modifications to the guidelines because mechanistic analysis and fatigue testing would be used as the basis for any thickness adjustments.

CONCLUSIONS AND RECOMMENDATIONS

- Generally, the fatigue performance of ARHM-GG has been demonstrated to be superior to conventional DGAC mixes with unmodified binders.
- Asphalt rubber mixes can have adequate permanent deformation resistance if properly designed and constructed. A proper design must be based

on laboratory performance tests with limiting criteria validated through field performance.

- Thermal cracking properties can improve when asphalt rubber binder is used. This conclusion is dependent on the grade of asphalt used in the DGAC.
- Moisture sensitivity can be a problem for ARHM-GG mixes and must be evaluated during the mix design process. Anti-stripping additives may be necessary to minimize moisture damage.
- Structural and reflective thickness equivalencies for asphalt rubber mixes must be based on laboratory fatigue and reflective cracking tests as well as mechanistic analysis.

References

CALTRANS (March 1992, October 1993) *Internal Memorandums*. Office of Pavement, 5900 Folsom Boulevard, Sacramento, CA 95819.

Doty, R.N. (1988) Flexible pavement rehabilitation using asphalt-rubber combinations – a progress report. In *Transportation Research Record 1196*, TRB, National Research Council, Washington, D.C., pp. 212–223.

Epps, J. (1994) *Uses of Recycled Rubber Tires in Highways*. National Cooperative Highway Research Program Synthesis of Highway Practice 198, TRB, National Research Council, Washington, D.C.

Epps, A. (1997) *Thermal Behavior of Crumb-Rubber Modified Asphalt Concrete Mixtures*. Ph.D. Dissertation, University of California, Berkeley.

Harvey, J. and Monismith, C. (1994) *Accelerated Pavement Testing-Phase 1, Laboratory Evaluation of Dense-Graded Asphalt Concrete (DGAC) and Asphalt-Rubber Hot Mix Gap-Graded (ARHM-GG)*. Institute of Transportation Studies, University of California at Berkeley.

Harvey, J., Vallerga, B.A. and Monismith, C.L. (1995) Mix design methodology for a warrantied pavement: case study. In *Transportation Research Record 1492*, TRB, National Research Council, Washington, D.C., pp. 184–192.

Harvey, J., Louw, L., Guada I., Hung, D. and Scheffy, C. (1998) Performance of CAL/APT Drained and Undrained Pavements Under HVS Loading. In Transportation Research Record 1615, Transportation Research Board, National Research Council, Washington, D.C., pp. 11–20.

Harvey, J., Coetzee, N. and Louw, L. (1999), Construction of Asphalt-Rubber Hot Mix Gap-Graded and Dense Graded Asphalt Concrete Overlays for CAL/APT Goal 3. Draft Report for the California Department of Transportation, Institute of Transportation Studies, University of California, Berkeley.

Hildebrand G. and Van Kirk, J. (1995) *Asphalt-Rubber Performance Evaluation*. The California Department of Transportation, 5900 Folsom Boulevard, Sacramento, California 95819.

Maupin, G.W. (1992) Virginia's experimentation with asphalt rubber concrete. In *Transportation Research Record 1339*, Transportation Research Board, National Research Council, Washington, D.C.

Raad L., Saboundjian, S. and Corcoran J. (1993) Remaining fatigue life analysis: A comparison between conventional asphalt concrete – dense graded (CAC-DG) and asphalt-rubber hot mix – gap graded (ARHM-GG). In *Transportation Research Record*, TRB, National Research Council, Washington, D.C.

Reese, R. (1994) Development of a physical property specification for asphalt-rubber binder. *Journal of the Association of Asphalt Paving Technologists*, 63, 373–413.

Rust, F.C., Du Plessis, J.L., Verhaeghe, B.M.J.A. and Grobler, J.E. (1993) *Heavy Vehicle Simulator Testing of Trial Sections for Caltrans*. Division of Roads and Transport Technology, CSIR, South Africa.

Shatnawi, S. (1994) *Premature Pavement Distress – District 2 Investigation*. California Department of Transportation, 5900 Folsom Boulevard, Sacramento, CA 95819.

Shatnawi, S.R. (1997) *Fatigue Performance of Asphalt Concrete Mixes Using a New Repetitive Direct Tension Test*. California Department of Transportation, 5900 Folsom Boulevard, Sacramento, CA 95819.

Sousa, J.B. (1994) Asphalt-aggregate mix design using the repetitive simple shear test (constant height). *Journal of the Association of Asphalt Paving Technologists*, 63, 298–345.

Van Kirk, J. (1989) Caltrans experience with rubberized asphalt concrete – an overview and future direction. Asphalt Rubber Producers Group, Proceedings, National Seminar on Asphalt Rubber, Kansas City, MO, pp. 311–327.