PAVEMENT TECHNOLOGY UPDATE

TECHNOLOGY TRANSFER PROGRAM SEPTEMBER 2009, VOL. 1, NO. 2

Rubber Roads: Waste Tires Find a Home

This Technology Transfer Program publication is funded by the Division of Research and Innovation at the California Department of Transportation. Content is provided by the University of California Pavement Research Center.

The University of California Pavement Research Center

Using innovative research and sound engineering principles to improve pavement structures, materials, and technologies.

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The University of California Pavement Research Center (UCPRC) conducts research on pavements of all types, including concrete and asphalt. It has operated facilities at UC Berkeley since 1948 and at UC Davis since 2002, and also conducts research on California highways. Primary funding for the UCPRC is provided by Caltrans. Most of the UCPRC's work is done through the Partnered Pavement Research Center contract, whose mission is to apply innovative research and sound engineering principles to improve pavement structures, materials, and technologies through partnership between academia, Caltrans, and industry.

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Introduction

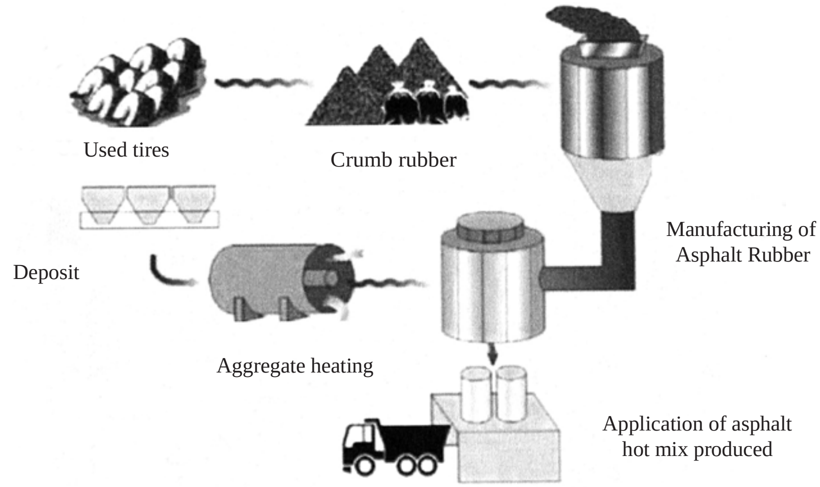
Most of us have heard the phrase "Where the rubber meets the road." In recent years, increasing amounts of crumb rubber from recycled tires have been added into the road in the form of thin rubber modified hot mix asphalt (HMA) surface courses or rubber modified spray applications used as pavement interlayers or surface treatments. Several states and local agencies are now using rubber modified pavement systems as a significant part of their pavement preservation strategy. California actually has a legislated mandate calling for the use of increasing amounts of reclaimed rubber in pavements over future years. This trend has resulted in rubber modified products that have performed well in reducing crack reflection, improving wet weather safety, and reducing pavement noise. It has also helped solve the very serious problem of waste tire disposal.

Waste tires are commonly used in rubber modified roads.

Historic Review

Rubber modification of asphalt has a long history. Natural rubber was used in bitumen (asphalt) as early as the 1840s [1]. In the 1950s, tire manufacturers and polymer suppliers such as Goodyear, Firestone, U.S. Rubber, and DuPont promoted the use of various rubber modifiers, or elastomers, as a way to improve the performance of asphalt pavements. Proprietary products such as Rubarite, Pliopave, Rub-R-Road, and certain neoprenes appeared on the market. They generally came in dry powder or latex form. The rubber additives were normally added to the asphalt binder in concentrations ranging from 2 to 7 percent. Lewis and Welborn reported the results of a laboratory study to evaluate binders made with 14 types of rubber powders and 3 asphalts in a 1954 issue of *Public Roads* [2]. A companion mixture study examined a wide range of rubber materials including tread from scrap tires, styrene-butadiene rubber (SBR), natural rubber, polybutadiene, and reclaimed rubber using both wet and dry methods of adding them to HMA [3]. Although these rubber modifiers showed promise in reducing the temperature susceptibility of the asphalt binder and conceivably improving the high temperature and low temperature performance of the mix, they never received widespread acceptance. This was likely due to the economics of the time, when asphalt was very low cost relative to the rubber modifiers. Many agencies found it difficult to justify the increased cost in light of marginal improvement in pavement performance. Some agencies also concluded that the rubber modified mix was more difficult to apply and had an objectionable odor [4].

FIGURE 1 Production of Asphalt Rubber and Asphalt Rubber mix



SOURCE: RUBBER PAVEMENTS ASSOCIATION

Interest in rubber modified asphalt systems did not surface again until the mid 1960s, when Charlie McDonald, an engineer for the City of Phoenix, Arizona, developed a process for blending rubber from waste tires with hot asphalt [5]. His formula produced a binder that used about 20 percent tire rubber. Based on positive performance experiences over ensuing years, the Arizona Department of Transportation (ADOT) adopted the use of this material in pavement interlayers, seal coats, and later as a binder in open and gap graded HMA. Subsequently these products have been evaluated in roughly 40 states in the United States and over 25 countries worldwide.

Methods of Rubber Modification

As concerns over the environmental problem of waste tire disposal escalated, various techniques for incorporating rubber into asphalt pavements emerged. The three basic methods for modifying asphalt with reclaimed tire rubber are referred to as the **wet process**, the **dry process**, and the **terminal blend process**[6].

Wet Process

The binder produced from the McDonald process, or wet process, is called Asphalt Rubber. It has been defined by ASTM as:

"A blend of asphalt cement, 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 cement sufficiently to cause swelling of the rubber particles."[7]

In the wet process, asphalt is blended with a crumb rubber modifier in a specialized blending unit at elevated temperatures (190-225°C) for a minimum of 45 minutes to promote the chemical and physical bonding of the components. During the blending process, the crumb rubber swells and softens as it reacts with the asphalt. This reaction is influenced by the blending temperature, the time the temperature remains elevated, the type and amount of mechanical mixing, the size and texture of the crumb rubber, and the aromatic component of the asphalt. The rubber modifier typically ranges from 18 to 22 percent by weight of the asphalt. Extender oils are sometimes used to reduce viscosity and promote workability of the Asphalt Rubber as well as to increase the compatibility between the asphalt and crumb rubber. The diagram in Figure 1 shows how Asphalt Rubber mixes are produced using the wet process [8]. Asphalt Rubber is used primarily in open graded and gap graded HMA. It is also used in spray applications for seal coats and pavement interlayers and as a crack sealant. Where Asphalt Rubber is used as a seal coat, it is commonly referred to as a Stress Absorbing Membrane (SAM). When it is used as an interlayer under HMA surfacing, it is called a Stress Absorbing Membrane Interlayer (SAMI). The overall performance of Asphalt Rubber systems has been good. Benefits include thinner overlays, reductions in reflective cracking, improved wet weather safety, and reduced traffic noise.

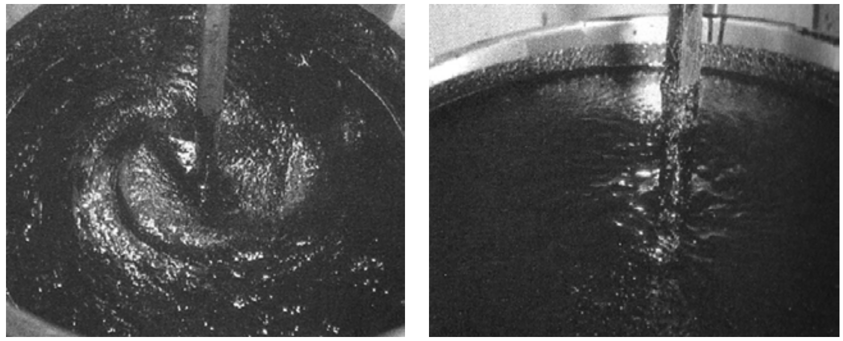
Dry Process

In the dry process, crumb rubber is added to the aggregate in a hot mix plant operation prior to adding the asphalt. There is relatively little reaction between the asphalt and crumb rubber in the dry process. In essence, the crumb rubber replaces a portion of the aggregate. The dry process can be used in dense graded, open graded, or gap graded HMA. The most commonly used dry process was developed and patented in the late 1960s in Sweden under the trade name "Rubite." This technology was later patented for use in the United States in 1978 under the trade name "PlusRide." The performance of pavements using this process has met with mixed reviews and, as a result, the dry process is not widely used for modifying asphalt pavements. However, dry crumb rubber or rubber chips from recycled tires are being used in other applications, such as landscaping and lightweight backfill for retaining walls.

Terminal Blend

The terminal blend is a wet process inwhich a fine mesh crumb rubber is blended with asphalt at a refinery or terminal. Terminal blends use anywhere from 5 to 18 percent crumb rubber depending on their final application. Terminal blends can be held in storage tanks for extended periods of time with proper agitation. The binder produced from terminal blends can be used in dense graded, open graded, or gap graded HMA. The manufacturing process for terminal blends is similar to that used for polymer modified asphalts. Terminal blends were initially introduced in the mid 1980s and, hence, they have less performance history than Asphalt Rubber. However, they are being successfully used by several states and are being evaluated in trial field applications by other states [9,10]. Terminal blends and Asphalt Rubber are completely different products as illustrated by the photographs in Figure 2 [11]. Terminal blends often use less rubber than Asphalt Rubber but they can be produced as a finished product at a refinery or terminal rather than in a specialized blending unit at the hot mix plant. Unlike Asphalt Rubber, terminal blends can be used in dense graded mixes, which may open up a new opportunity for the disposal of additional waste tire rubber. In this regard, terminal blends are more likely to compete with polymer modified asphalts than Asphalt Rubber.

FIGURE 2 Asphalt Rubber versus terminal blends



Continuous Blend — Terminal Blend

SOURCE: RUBBER PAVEMENTS ASSOCIATION

Accelerated Pavement Testing

The University of California, through its Partnered Pavement Research Center program with the California Department of Transportation (Caltrans) and industry, conducted accelerated pavement testing using a Heavy Vehicle Simulator (HVS) and laboratory testing to evaluate the performance of several rubberized asphalt mix overlays [12]. The HVS, shown in Figure 3, was used to apply very high traffic loads on 6 parallel test sections monitored for rutting and reflective cracking. A total of more than 15 million load applications, or about 400 million equivalent single axle loads (ESALs), were applied to the test sections. A description of the binders used in the study is given in Table 1 and a layout of the test sections is shown in Figure 4.

The test road for this study was constructed in 2001 at the University of California, Berkeley's Richmond Field Station using a commercial contractor. It was designed using

FIGURE 3 Heavy Vehicle Simulator (HVS)

SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

TABLE 1 Overlay mixes used in HVS accelerated pavement testing

Mix Identification	General Description	Supplier	Actual Binder Content*, %
MB4-G	Terminal Blend Gap Graded Mix with 5% Ground Tire Rubber	Valero	7.77
MB4-15-G	Terminal Blend Gap Graded Mix with 15% min. Ground Tire Rubber	Valero	7.52
MAC-15TR-G	Terminal Blend Gap Graded Mix with 15% min. Ground Tire Rubber	Paramount	7.55
RAC-G	Asphalt Rubber Gap Graded Mix	FNF/Valero	8.49
AR 4000-D	Dense Graded HMA Control	Valero	6.13
* by mass of dry aggregate.			

SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

standard Caltrans procedures and consists of a 410 mm Class 2 aggregate base on a clay subgrade with a 90 mm dense graded HMA surface. Design thickness was based on a subgrade R-value of 5 and a Traffic Index of 7 (~131,000 ESALs).

The completed pavement structure was then trafficked with the HVS between February 2002 and April 2003 to induce fatigue cracking on each of the 6 test sections. A total of about 3.3 million load repetitions (roughly 17.7 million ESALs) were applied.

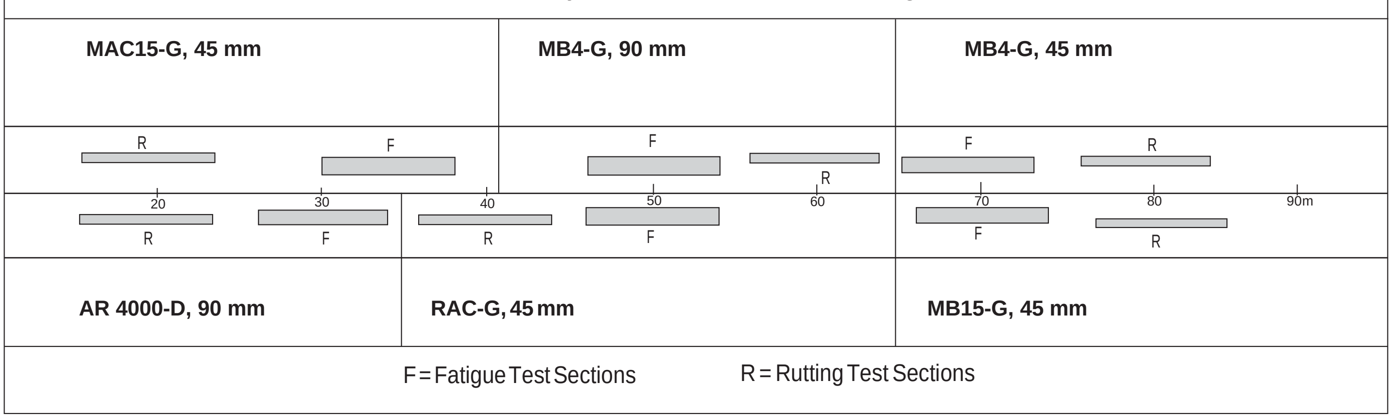
Upon completion of the HVS loadings, the road was overlaid with six different mixes. The thickness for the control HMA overlay was determined according to Caltrans Test Method 356 [13]. The other overlay thicknesses were either the same or half that of the HMA overlay. The overlay mixes tested were:

- 45 mm thick MB4 gap graded overlay
- 90 mm thick MB4 gap graded overlay
- 45 mm thick MB4 gap graded overlay with minimum 15 percent recycled tire rubber
- 45 mm thick MAC-15TR gap graded overlay
- 45 mm Asphalt Rubber gap graded overlay (RAC-G)[1]
- 90 mm thick AR 4000 dense graded HMA overlay included as a control

HVS testing of the overlay sections to determine the susceptibility of the mixes to early rutting at high pavement temperatures was carried out over a 4-month period (September 2003 through December 2003). A total of 80,000 channeled, unidirectional 60 kN wheel loadings (455,000 ESALs) were applied using dual truck tires at 720 kPa tire pressure. Pavement temperature was maintained at 50°C ± 4°C at a 50 mm depth below the surface using a temperature control chamber.

The next series of HVS tests was conducted over a 3½ year period (January 2004 through June 2007) on overlay sections positioned precisely above the cracked sections on the original pavement and adjacent to the sections tested for rutting. This testing assessed the effectiveness of the overlays in limiting reflective cracking from the underlying pavement. A total of 12.5 million repetitions, varying between 60 kN and 100 kN wheel loads, were applied to the test sections. This equates to approximately 385 million ESALs. Pavement temperature was maintained at 20°C ± 4°C for the first 1 million load applications on each section, then at 15°C ± 4°C for the

FIGURE 4 Layout of test sections for HVS testing



SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

[1] Now called RHMA-G. Refer to Table 7.

remainder of the test. Dual truck tires (720 kPa pressure) in a bidirectional loading pattern with lateral wander were used.

Reflective cracking performance for each of the overlays in the HVS study is reported in Table 2. The terminal blend mixes (MB4, MB4-15, and MAC-15TR) had similar results and performed the best, followed by the Asphalt Rubber section (RAC-G). The dense graded HMA control showed the poorest performance. Laboratory beam fatigue tests on the overlay materials and a simulation study of reflection crack initiation and propagation verified the ranking order of the overlays from the HVS tests. The simulation studied crack initiation and propagation for a pavement structure with identical cracking pattern and density, climate, and traffic.

Rutting performance for each of the mixes under HVS testing is presented in Table 3. In this case, the dense graded HMA control showed superior rutting resistance followed by the 45 mm MB4 terminal blend mix and the Asphalt Rubber section (RAC-G). The remaining terminal blend sections (90 mm MB4, 45 mm MB4-15, and 45 mm MAC-15TR) showed poor rutting resistance. Trenches were cut transversely through the pavement sections to conduct a forensic investigation into the cause of the rutting distress (Figure 5). As shown in Figure 6, most of the rutting occurred in the underlying HMA layer and not in the overlays. It should be noted that the original pavement underlying the rutting sections received no traffic and was relatively "new" when the overlays were constructed. Laboratory shear testing and simulation studies across various California climate regions and traffic levels generally supported the ranking order of the HVS tests. Namely, the dense graded HMA was predicted to perform the best while the terminal blend sections were expected to perform poorly in rutting behavior.

The results from the HVS testing program are encouraging for terminal blend mixes and Asphalt Rubber mixes, both of which performed much better than the dense graded HMA overlay in resisting reflective cracking from the underlying distressed pavement. It appears that the terminal blend mixes can be used in appropriately designed half-thickness overlays for reflection cracking applications where Asphalt Rubber mixes are normally applied. However, there is some potential for rutting with these mixes when used under slow moving, heavy truck traffic in hot climates. Therefore, field projects exposed to these conditions should be evaluated prior to widespread use of terminal blend mixes. Mix design issues associated with dense graded terminal blend mixes should also be addressed in light of the low stiffness and shear resistance found in laboratory tests on these mixes [14] when compared to dense graded HMA.

The Federal Highway Administration (FHWA) has also conducted pavement testing using an Accelerated Loading Facility (ALF) at its Turner Fairbanks Highway Research Center, near Washington, D.C. The loading is done by repeated passes of a truck tire attached to a beam with an automated rolling mechanism as shown in Figure 7. Several test sections were constructed in 2002 at the Turner Fairbanks site to compare the performance of modified asphalt pavements to a PG 70-22 HMA control section [15]. Included in the study was an Asphalt Rubber section built according to Arizona Department of Transportation (ADOT) specifications identified as CR-AZ, and a terminal blend section identified as CR-TB. The 50 mm thick Asphalt Rubber section was placed over a 50 mm HMA section. The terminal blend and HMA control sections were 100 mm thick. There were also some 150 mm thick sections included in the study. All sections were

TABLE 2 Reflective cracking performance from HVS accelerated pavement testing

Rank	Section	Parameter	Finding
1	45 mm MAC-15TR-G	Number of ESALs to 2.5 m/m^2 reflective cracking	None after 91 million
1	45 mm MB4-15-G		None after 88 million
1	45 mm MB4-G		None after 66 million
1	90 mm MB4-G		None after 37 million
5	45 mm RAC-G		60 million
6	90 mm AR 4000-D		18 million

SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

TABLE 3 Rutting performance from HVS accelerated pavement testing

Rank	Section	Parameter	Finding
1	90 mm AR 4000-D	Number of HVS repetitions to 12.5 mm average maximum rut	8,266
2	45 mm MB4-G		3,043
3	45 mm RAC-G		2,354
4	90 mm MB4-G		1,522
5	45 mm MB4-15-G		914
6	45 mm MAC-15TR-G		726

SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

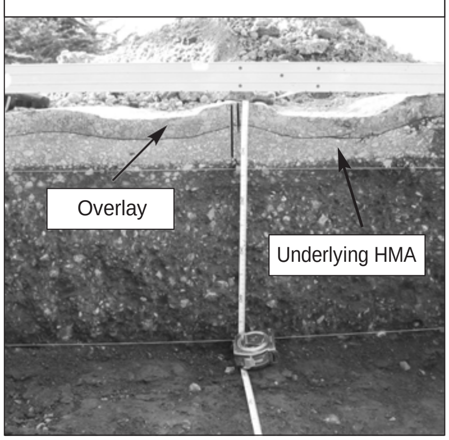
FIGURE 5
Forensic investigation of rutting in HVS test sections

SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

placed on a dense graded, crushed aggregate base (CAB) course over a uniformly prepared AASHTO A-4 subgrade. The total thickness of the test sections and CAB layer was 660 mm.

The Asphalt Rubber section showed no cracking after 300,000 passes of the ALF loading wheel while the 100 mm HMA control section experienced 90 meters of cumulative cracking after 100,000 passes. The 100 mm terminal blend section had about 20 meters of cumulative cracking after 100,000 passes. A pictorial comparison of the sections after fatigue testing is shown in Figure 8. It is interesting to note from this study that the 100 mm terminal blend section exhibited the highest rutting resistance (8.4 mm) while the Asphalt Rubber section (11.6 mm) and the HMA control section (12.2 mm) showed similar but less rutting resistance. These results are contrary to what was found in the HVS study. The discrepancy may be due to the higher binder content of the terminal blends used in the HVS study (see Table 1) of roughly 7.6 percent by mass of aggregate compared to a terminal blend binder content of 5.6 percent by mass of aggregate in the ALF study.

FIGURE 6
Rutting in underlying HMA on the 45 mm MB4-G section



SOURCE: UNIVERSITY OF CALIFORNIA PAVEMENT RESEARCH CENTER

Terminology and Specifications

The term “rubberized asphalt” is often used to describe the binder produced by blending crumb rubber, or more specifically, ground tire rubber with hot asphalt. Both Asphalt Rubber and terminal blends fall under this general description. Ground tire rubber is produced from ambient and/or cryogenic grinding of waste tires. Ambient grinding at or above room temperature is a process that generates irregularly shaped, torn rubber particles with a relatively large surface area that helps promote interaction with the asphalt. Cryogenic grinding is a process that uses liquid nitrogen to freeze the tire rubber until it becomes brittle and then uses a hammer mill to shatter the rubber into smaller particles. If used, cryogenic grinding is usually followed by ambient grinding.

Specifications for rubberized asphalt binders have evolved over the years. The MB4 binders used in the HVS accelerated pavement testing study were designed to satisfy the specifications shown in Table 4 [16]. The MAC-15TR binder is similar to the MAC-10TR binder specified in the Greenbook section 600-5.2.1 [17], except that it uses 15 percent tire rubber rather than 10 percent tire rubber. Caltrans is currently considering performance graded (PG) specifications for terminal blends similar to those adopted for optional use by the Pacific Coast Conference on Asphalt Specifications (PCCAS) in 2008 [18] and shown in Table 5. These specifications are very similar to those adopted by Caltrans for PG polymer modified asphalts in 2007 [19]. The Asphalt Rubber binder used in the RAC-G section satisfied the design profile shown in Table 6 and included in the Caltrans Asphalt Rubber User Guide [20]. The AR 4000 asphalt used in the HMA control satisfied the Caltrans AR specifications in place in 2001.

Terminology used to describe mixes made with rubberized asphalt has also changed over the years. Caltrans, for example, formerly referred to Asphalt Rubber mixes as rubberized asphalt concrete (RAC). In an effort to be more consistent with terminology used nationally, Caltrans now refers to these mixes as rubberized HMA (RHMA). The mix type is further designated as gap graded (G) or open graded (O). The former and current designations for these Asphalt Rubber mixes are shown in Table 7.

Field Performance

Several states and other countries have tested and evaluated the performance of rubberized asphalt mixes as well as SAMs and SAMIs. As with any evolving technology, not all jobs went smoothly. Some agencies that experienced major failures requiring the removal of material were hesitant to pursue the further development of rubberized asphalt systems. Most of these failures were the result of using a rubberized asphalt product for the wrong application, inadequate material quality control, or poor construction practices. Some states lost interest in pursuing rubberized asphalt technology once an unfunded federal mandate on the use of waste tire rubber in pavements expired. Those agencies who persisted in the development and refinement of application procedures found increasing performance successes with rubberized asphalt systems. Thinner

FIGURE 7 ALF testing device and close-up of loading wheel

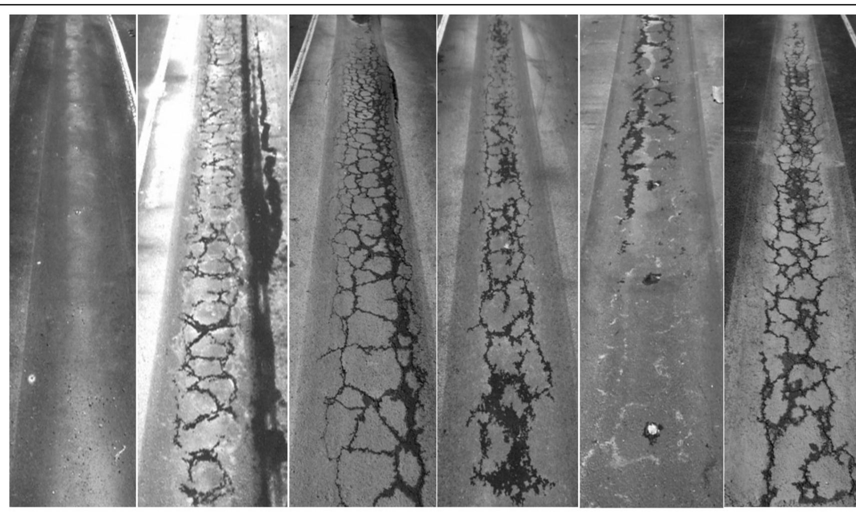
SOURCE: RUBBER PAVEMENTS ASSOCIATION

overlays, reductions in reflective cracking, improvements in wet weather driving safety, and traffic noise reduction were among the benefits realized from rubberized asphalt mix and membrane systems. The following represents a sampling of the experiences of state agencies that have a long history with and extensive use of rubberized asphalt systems.

Arizona. ADOT has over 35 years of experience with rubberized asphalt, specifically Asphalt Rubber [21]. In the early 1970s, ADOT conducted several SAM and SAMI field experiments. From 1974 until 1989, approximately 1100 km (660 miles) of state highways were built using SAM and SAMI technology. In 1989, ADOT documented in a research report [22] on the history, development, and performance of Asphalt Rubber that it "has successfully been used as an encapsulating membrane to control distortion due to expansive soils and to reduce reflective cracking in overlays on both rigid and flexible pavements." In 1985, ADOT began experiments with open graded and gap graded Asphalt Rubber mixes. The open graded Asphalt Rubber mix, typically 12.5 mm to 25 mm thick, is generally used as the final wearing surface over both concrete and HMA pavements. On badly cracked pavements, a gap graded Asphalt Rubber mix, generally 37.5 mm to 50 mm thick, is often used. This may be followed by an open graded Asphalt Rubber application depending on traffic and type of highway. ADOT has monitored pavement performance since 1972. Figure 9 shows a comparison of average percent cracking for conventional HMA overlays and projects built with Asphalt Rubber. More than 28,000 lane-km (16,800 lane miles) of very good performing Asphalt Rubber pavements have been built in Arizona since 1988.

California. Caltrans began using Asphalt Rubber in chip seals in the 1970s and in hot mixes in the 1980s [23]. The first major Asphalt Rubber field experiment was in Ravendale, California in 1982 [24]. Several field projects, laboratory studies, and accelerated pavement testing programs followed that led to the development of design guidelines and specifications for the use of Asphalt Rubber mixes, chip seals, and interlayers (see reference 20). By mid-2001, Caltrans had constructed more than 210 Asphalt Rubber mix projects throughout the state. Several municipalities and counties also use Asphalt Rubber for hot mixes

FIGURE 8 Condition of ALF lanes after completion of loading



Lane 1	Lane 2	Lane 3	Lane 4	Lane 5	Lane 6
CR-AZ	Control	Air Blown	SBS LG	CR-TB	TP
300,000	100,000	100,000	300,000	100,000	200,000

SOURCE: RUBBER PAVEMENTS ASSOCIATION

and surface treatments. Caltrans requires 25 percent natural rubber in its crumb rubber modifier and extender oil in the Asphalt Rubber. In October, 2005, California Assembly Bill 338 was signed into law. This bill originally called for the use of increasing amounts of Asphalt Rubber in HMA—20 percent of total HMA tonnage in 2007, 25 percent in 2010, and 35 percent in 2013. The language of the bill has recently been broadened to allow the use of other types of rubberized asphalt including terminal blends.

The performance of Asphalt Rubber chip seals has generally been good. However, some flushing and bleeding failures have occurred in high temperature locations subjected to heavy, slow moving traffic. The use of extender oil in Asphalt Rubber may have contributed to the distress. Several laboratory and field studies have shown that Asphalt Rubber mixes, primarily gap and open graded mixes, perform better than conventional dense graded HMA with respect to resisting fatigue cracking, reflective cracking, and thermal cracking. Caltrans no longer uses Asphalt Rubber in dense graded mixes due to the limited space available in a dense gradation to accommodate the Asphalt Rubber.

More recently, Caltrans has been evaluating and field testing terminal blends including MB binders [25]. Several field projects in northern and southern California have been constructed and inspected on a regular basis. According to follow-up surveys, these test projects are performing well. Some counties and cities in California have also used terminal blends in chip seal construction. Caltrans is considering the adoption of specifications for two PG terminal blend grades, PG 64-28TR and PG 76-22TR, for use in California (see Table 5). Based on successful field projects and the promising results from the HVS accelerated pavement testing study reported here, the use of terminal blends is likely to increase in California in the future.

Florida. The Florida Department of Transportation (FDOT) began its investigation into the use of Asphalt Rubber as a stress absorbing membrane interlayer and moisture barrier in the late 1970s. In 1988, the Florida legislature passed a bill (Senate Bill 1192) directing the FDOT to determine the feasibility of using ground tire rubber in HMA. FDOT concentrated its efforts on the use of ground tire rubber in open graded friction course mixes. Three major projects were constructed in the period 1989-1990. FDOT took a slightly different approach than other states by including several test sections that used the Rouse continuous wet process [26] for blending fine mesh (80 mesh) ground tire rubber with the asphalt. This, in essence, is a hybrid manufacturing approach between that used to produce Asphalt Rubber and terminal blends. Ground tire rubber concentrations of 5-15 percent by total weight of binder were used. In most cases, extender oil was not added. Based on observations from these test projects, FDOT concluded that the use of rubber significantly improved the cracking resistance of the open graded friction course and that the optimum amount of rubber to add was between 10 and 15 percent.

Texas. The first reported use of Asphalt Rubber in Texas was in 1976 in the Bryan and El Paso Districts of the Texas Department of Transportation (TxDOT) [27]. In Texas, Asphalt Rubber has been used in four applications: chip seal coat or SAM, undercoat or SAMI, hot mix, and open graded porous friction course. Asphalt Rubber chip seal is considered to be a routine rehabilitation strategy in several districts of TxDOT. TxDOT made significant changes in mix design procedure and specifications for crumb rubber modified hot mix in 1992, basically replacing dense graded mixes with gap graded mixes. District personnel of TxDOT reported that Asphalt Rubber HMA projects had significantly better resistance to cracking than conventional HMA [28]. Porous friction courses modified with Asphalt Rubber were also reported to have better performance

TABLE 4 MB specifications for terminal blend asphalt

Specification	Test Method	MB-4	MB-5	MB-6	MB-7
On Original Binder:					
SSD ε30(0.6 + SSV)[3] @ °C	CT 381	25°C	25°C	25°C	25°C
On Residue from RTFO:	AASHTO T240				
Delta δ97 – 6(log G*)	CT 381				
and G*–: sin(delta) ε4.0 kPa					
Both at 10 rad/sec @ °C		64°C	64°C	64°C	70°C
On Residue from either:					
Pressure Aging Vessel[1] @ °C	AASHTO PP1	100°C	100°C	100°C	110°C
Or					
Tilt-Oven @ 113°C for hrs shown	CT 374B	36 hrs	36 hrs	36 hrs	72 hrs
Stiffness:					
300 MPa (max.) at 60 sec[1]	AASHTO TP1				
@°C, with M-value = 0.30 min		- 8°C	- 19°C	- 30°C	- 8°C
Or					
100 MPa (max.) at 10 rad/sec	CT 381				
@°C, with M-value = 0.30 min		9°C	- 2°C	- 13°C	9°C
SSD ε-115 SSV - 50.6 @°C	CT 381	25°C	25°C	25°C	25°C

NOTES: [1]Referee method
California Test (CT)
Shear Susceptibility of Delta (SSD)
Shear Susceptibility of Viscosity (SSV)
Rolling Thin Film Oven (RTFO)

SOURCE: CALIFORNIA DEPARTMENT OF TRANSPORTATION

TABLE 5 PCCAS PG-TR specifications for terminal blend asphalt[a]

Property	AASHTO Test Method	Specification Grade	
		PG 64-28 TR	PG 76-22 TR
Original Binder			
Flash Point, Minimum °C	T 48	230	230
Solubility, % minimum	T 44[b]	97.5	97.5
Viscosity at 135°C, [c] Maximum, Pa-s	T 316	3.0	3.0
Dynamic Shear, Test Temp. at 10 rad/s, °C Minimum G*/sin(delta), kPa	T 315	64 1.00	76 1.00
RTFO Test, Mass Loss, Maximum, %	T 240	1.00	1.00
RTFO Test Aged Binder			
Dynamic Shear, Test Temp. at 10 rad/s, °C Minimum G*/sin(delta), kPa	T 315	64 2.20	76 2.20
Elastic Recovery[e], Test Temp., °C Minimum recovery, %	T 301	25 75	25 65
Multiple Stress Creep Recov. Average % Recov. @100 Pa	TP 70	Report	Report
Multiple Stress Creep Recov. Average % Recov. @3200 Pa	TP 70	Report	Report
Multiple Stress Creep Recov. Non-Recov. Compliance, Jnr	TP 70	Report	Report
PAV[f] Aging, Temperature, °C	R 28	100	100 (110)[d]
RTFO Test and PAV Aged Binder			
Dynamic Shear, Test Temp. at 10 rad/s, °C Maximum G*sin(delta), kPa	T 315	22 5000	31 5000
Creep Stiffness, Test Temperature, °C Maximum S-value, MPa Minimum M-value	T 313	-18 300 0.300	-12 300 0.300

Notes: a. PG-TR grades require a minimum of 10 percent by weight ground tire rubber content.
b. ASTM D 5546 is allowed as an alternative test to AASHTO T 44.
c. This specification may be waived if the supplier certifies the asphalt binder can be adequately pumped and mixed at temperatures meeting applicable safety standards.
d. In desert climates, the PAV aging temperature may be specified as 110 °C.
e. Tests without a force ductility clamp may be performed.
f. “PAV” means Pressurized Aging Vessel.

SOURCE: PACIFIC COAST CONFERENCE ON ASPHALT SPECIFICATIONS

TABLE 6 Typical Asphalt Rubber binder design profile

Test Performed	Minutes of Reaction					45 minutes
	45	90	240	360	1,440	Specification Limits***
Viscosity, Haake at 190°C, Pa-s, (10^{-3}), or cP (*See Note)	2400	2800	2800	2800	2100	1500 - 4000
Resilience at 25°C, % Rebound (ASTM D5329)**	27	—	33	—	23	18 Minimum
Ring & Ball Softening Point, °C (ASTM D36)	59.0	59.5	59.5	60.0	58.5	52 - 74
Cone Pen. at 25°C, 150g, 5 sec., 1/10 mm (ASTM D217)	39	—	46	—	50	25 -70

Notes regarding specified test procedures for Asphalt Rubber Binder:
** The viscosity test shall be conducted using a hand-held Haake viscometer . . . or equivalent.*
*** ASTM D 5329 has replaced ASTM D3407.*
**** Per Caltrans specifications as of September 2006*

SOURCE: CALIFORNIA DEPARTMENT OF TRANSPORTATION RUBBER USAGE GUIDE, SEPTEMBER 2006

with respect to cracking and raveling than conventional or polymer modified mixes. The improvement in resistance was considered to be due to the high amount of binder in the rubber modified friction courses. Asphalt Rubber seal coats showed excellent resistance to reflective cracking but varied in the degree of bleeding/flushing depending on the size of aggregate chip used.

Terminal blends were first used in Texas in the mid-1980s. In a comprehensive study by Texas A&M University in 2000 [29], supported by TxDOT, terminal blends, referred to as "high-cure crumb rubber modified asphalt," were shown to perform well in laboratory tests and field evaluations. Among other things, the researchers concluded that terminal blends are suitable for dense graded mixes and can be produced through a combination of high temperature and high shear. Production in the presence of oxygen can enhance the breakdown of the rubber and the curing process. They also reported that PG test equipment, such as the dynamic shear rheometer and bending beam rheometer can be used to test and monitor the properties of the terminal blend. Field studies were conducted at two Texas locations in 1998 and 2000 that showed terminal blends could be used successfully in dense graded mixes with up to 17.6 percent rubber added.

Nevada. The Nevada Department of Transportation (NDOT) has used polymer modified asphalt in its mixes successfully since 1990. NDOT now specifies two PG polymer modified asphalt grades: PG 64-28NV for northern Nevada and PG 76-22NV for southern Nevada. In recent years, NDOT has been evaluating terminal blend binders as an alternative to polymer modified asphalt. Specification requirements for the terminal blends are very similar to those used for the polymer modified asphalt grades and have been designated as PG 64-28TR and PG 76-22TR [30]. NDOT has also reported on the use of Asphalt Rubber in a major open graded mix project on the I-515 freeway in Henderson, Nevada (near Las Vegas) where the primary objective was to reduce pavement noise [31]. The tire noise of the original concrete pavement was 108.1 decibels. After the Asphalt Rubber overlay was placed, the tire noise level dropped to 97.4 decibels, a 10.7 decibel reduction [32].

There have been two notable research projects conducted at the University of Nevada, Reno (UNR) involving Asphalt Rubber, terminal blends, and polymer modified asphalt mixes. In 1998, UNR evaluated the performance of terminal blend mixes with the performance of Asphalt Rubber mixes [33]. This UNR study compared the performance of laboratory prepared gap graded terminal blend mixes to gap graded Asphalt Rubber mixes. The study also compared the performance of dense graded terminal blend mixes to gap graded terminal blend mixes. In addition, the performance of field produced gap graded terminal blend mixes was compared to the

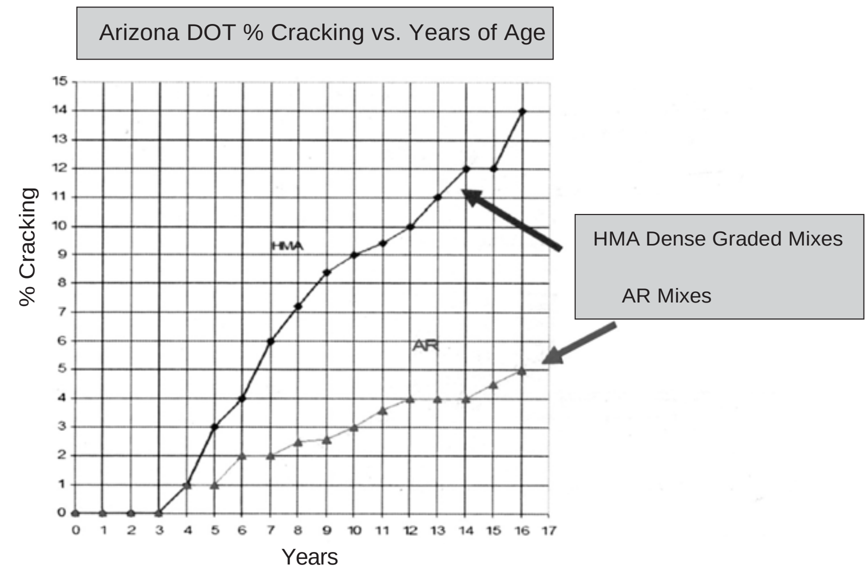
TABLE 7 Caltrans designation for Asphalt Rubber mixes

Former Designation	Current Designation	General Description
RAC	RHMA	Rubberized HMA
RAC-G	RHMA-G	Gap Graded RHMA
RAC-O	RHMA-O	Open Graded RHMA
RAC-O-HB	RHMA-O-HB	High Binder Content RHMA-O

SOURCE: CALIFORNIA DEPARTMENT OF TRANSPORTATION performance of the laboratory mixes. The researchers concluded that there was no statistical difference in rutting or fatigue resistance between the gap graded terminal blend and Asphalt Rubber mixes and that the dense graded terminal blend mixes were more resistant to rutting but less resistant to fatigue cracking than the gap graded terminal blend mixes. The field prepared gap graded terminal blend mixes were found to be resistant to moisture damage, thermal cracking, and rutting. The rutting resistance of the field prepared gap graded terminal blend mix was similar to that of the laboratory prepared gap graded terminal blend and Asphalt Rubber mixes.

In 2006, UNR conducted a research project to evaluate the laboratory performance of HMA mixes made with terminal blend binders and polymer modified binders [34]. Phase two of the study involved mechanistic-empirical analyses of a pavement structure to access the fatigue resistance of the various mixes under traffic loads. It was concluded from the combined findings of the laboratory evaluations and the mechanistic-empirical analyses that terminal blend mixes can perform well regardless of whether they are used in dense or gap graded mixes.

FIGURE 9 Percent cracking versus years of service for HMA and Asphalt Rubber pavements in Arizona



SOURCE: RUBBER PAVEMENTS ASSOCIATION

Summary

Although many techniques have been used to combine rubber and asphalt over the years, two major technologies have emerged for blending ground tire rubber into hot asphalt: the Asphalt Rubber process and the terminal blend process. Both technologies are described as wet processes. The Asphalt Rubber process involves blending ground tire rubber and asphalt in a specialized blending unit on site at the hot mix plant, and then adding the binder to the selected aggregate gradation to produce the final mix. In the terminal blend process, a finer mesh ground tire rubber is blended with the asphalt at a refinery or terminal into a homogeneous binder that is delivered to the hot mix plant for production of the final mix.

By their very nature, Asphalt Rubber and terminal blend binders are different products with a different appearance and different properties. Both Asphalt Rubber and terminal blends can be used in chip seal applications and interlayers. Both binders can be used to produce gap graded and open graded mixes. Terminal blend binders are also suitable for dense graded mixes. Asphalt Rubber technology has a longer proven performance history and uses a higher percentage of rubber than terminal blend technology while terminal blend technology may have manufacturing benefits over Asphalt Rubber technology. Yet, both technologies serve a valuable role in providing highway agencies with useful pavement preservation strategies and, at the same time, addressing the environmental problem of waste tire disposal.

Based on numerous laboratory studies, field installations, and accelerated pavement testing programs, it has been shown that both Asphalt Rubber and terminal blend systems, properly designed and constructed, can perform well in resisting crack reflection, improving driving safety, and reducing pavement noise. Despite the many advantages of these systems, there are situations where these technologies may not be the best choice. For example, Asphalt Rubber and terminal blend mixes should not be used:

- during cold or rainy weather with ambient temperatures below 13°C.
- over pavements with severe cracks.
- where considerable handwork is required.
- where traffic and deflection data are unknown.
- where haul distances are too long to maintain sufficient mix temperature for placement and compaction. (Warm Mix technologies may eventually alleviate this problem.)

Performance history is important in the use of Asphalt Rubber and terminal blend mixes. Terminal blend systems appear to be a likely alternative to polymer modified asphalt applications. Based on the HVS accelerated pavement testing study and laboratory studies at UNR, terminal blend performance may also compare favorably with that of Asphalt Rubber for gap graded mixes. However, mix design and thickness design issues need to be considered with dense graded terminal blend mixes in light of the lower stiffness and shear resistance of these mixes compared to dense graded HMA.

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PAVEMENT TECHNOLOGY UPDATE
SEPTEMBER 2009, VOL. 1, NO. 2

This publication was produced by the Technology Transfer Program at the UC Berkeley Institute of Transportation Studies, with funding from the Caltrans Division of Research and Innovation.

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