Laboratory Characterization and Full–scale Accelerated Performance Testing of Crumb Rubber Asphalts And Other Modified Asphalt Systems

Xicheng Qi* — Aroon Shenoy* — Ghazi Al-Khateeb* — Terry Arnold* — Nelson Gibson — Jack Youtcheff** — Tom Harman ****

** Turner-Fairbank Highway Research Center / SaLUT*
6300 Georgetown Pike, McLean, VA 22101-2296, USA
Xicheng.Qi@fhwa.dot.gov; Aroon.Shenoy@fhwa.dot.gov; Ghazi.Al-Khateeb@fhwa.dot.gov; Terry.Arnold@fhwa.dot.gov

***Federal Highway Administration*
6300 Georgetown Pike, McLean, VA 22101-2296, USA
Nelson.Gibson@fhwa.dot.gov; Jack.Youtcheff@fhwa.dot.gov;
Tom.Harman@fhwa.dot.gov

ABSTRACT: *During the summer and fall of 2002, the Federal Highway Administration (FHWA) in partnership with 16 State Highway Agencies (SHA) and over 30 Industry groups constructed 12 full-scale test sections of pavements with various modified asphalt binders at FHWA's Pavement Test Facility in McLean, Virginia. The 12 test sections were loaded using FHWA's two Accelerated Loading Facility (ALF) machines to evaluate permanent deformation (rutting) and fatigue cracking response. The ALF performance results are linked to a comprehensive laboratory binder rheological, physiochemical, and mixture characterization study. Two of the test sections use crumb rubber material (CRM) technology: Lane 1 employs the Arizona wet process and Lane 5 employs a Texas terminal blend process. This paper explores the ability of laboratory characterization techniques to predict the performance of CRM technology under accelerated loading and compares the performance the two CRM technologies to each other and other modified systems.*

KEYWORDS: *crumb-rubber, modified-binders, lab-characterization, APT, rutting, fatigue.*

1. Background and Introduction

The incorporation of rubber into asphalt paving materials may have its beginning as early as the 1840's. Massucco (1994) Ruth and Roque (1995) both give a summary of rubber modified asphalt history starting with devulcanization experiments by the US Rubber Reclaiming Company in the 1940s then further development by Macdonald, City of Phoenix Engineer, in 1960 of the well known 'wet process'. The first notable trial of this material was in 1968 City of Phoenix, Arizona with Stress Absorbing Membrane application. Early implementation efforts by the FHWA began in 1973. Further development was stimulated by some late 1980s and early 1990s waste material legislation and then the Intermodal Surface Transportation Efficiency Act in 1991 mandated the use of recycled tire rubber in pavements. One of the first demonstrations of open-graded asphalt-rubber friction courses was in 1989 and 1991. However, there were other applications earlier such as reflection cracking mitigation (Way *et al.*, 1981), surface treatments and interlayers membranes (Gupta 1986, Schnormeier 1986). State DOTs began reporting research efforts in the 1990s such as a Florida DOT study of fine and open graded mixtures (Page, 1992) and Kentucky DOT's experiences (Mahboub *et al.*, 1994) with construction and specifications for a wet-process dense-graded overlay. The experiences varied and an almost universal finding was that close attention must be paid to the entire process including mix design, material selection, production and lay down are all critical.

Hicks *et al.* (1995) outlined a national rubber modified asphalt research plan in a follow up study to the FHWA congressional report on recycled materials. The outstanding research topics were identification of appropriate mixture and structural design, evaluation of construction equipment, expected performance, ability to be recycled and development of suitable binder characterization tests for crumb rubber modified asphalt. Conventional viscosity and penetration tests were identified as inappropriate and the SHRP tests were to be investigated. Currently this topic is being studied by the FHWA with the help of Industry and State DOT support in the Transportation Pooled Fund Study TPF-5(19). One of the primary objectives is to determine any recommended changes to the Superpave binder specification such that it is 'blind' to the modifier and accounts for the impact of modification on performance thereby reducing the need for non-standardized addition specifications such as elastic recovery. Various other polymer modifications are being studied as well but both the Arizona wet-process and the 'terminal-blend' process modified asphalts are included.

2. Objectives and Scope

The primary objectives of this study are to test the ability of laboratory characterization techniques to predict the pavement performance of the crumb rubber materials (CRM) under accelerated loading and compare the two CRM technologies (wet process and terminal blend) to each other and other modified asphalt systems. To achieve the objectives, 12 test lanes were constructed at the FHWA's Pavement Test Facility (PTF) in McLean, Virginia. Lanes 1 through 7 were constructed with a 100-mm thick layer of Hot Mix Asphalt (HMA) while lanes 8 through 12 with a 150-mm layer of HMA. Among the 100-mm thick HMA pavements, two of the test lanes used CRM technology: Lane 1 employs the Arizona wet process and Lane 5 employs a Texas terminal blend process. Lane 2 was constructed with a unmodified asphalt as the control lane. Other lanes include air-blown, polymer, and fiber modified asphalt binders.

3. Experimental Design

The experimental design consists of two parts: laboratory binder / mixture characterization and field pavement tests using FHWA's two accelerated loading facility (ALF) machines described as follows.

3.1. Laboratory Characterization

3.1.1. *Binders' description and binder tests*

Seven different types of binders were used, namely, Arizona Crumb Rubber (CR-AZ), control PG 70-22 (Unmodified 72-23), Air-Blown PG 70-28 (AB 74-28), Styrene-Butadiene-Styrene Linear-Grafted PG 70-28 (SBS LG 74-28), Styrene-Butadiene-Styrene Linear-Grafted PG 64-40 (SBS 64-40 / 71-38), Elvaloy PG 70-28 (Terpolymer 74-31), Crumb Rubber - Terminal Blend PG 76-28 (CR-TB 79-28). The numbers in brackets signify the continuous performance grades (PG) based on Superpave grading system. While the goal of the overall ALF experiment was to utilize a common crude source for the various binders this was not always possible. The CR-AZ base was a Citgo binder from Paulsboro, NJ. This is the same crude used to produce the binders for the control, fiber, elvaloy and air blown. The CR-TB base was obtained from Rod Asphalt. The air-blown grade was obtained by noncatalytic air-blowing of a lower grade. The polymer-modified grades were obtained by addition of various amounts of different polymers to lower grades, and were modified to have the same high temperature Superpave performance grade (PG 74-xx) so that the observed laboratory and field performances could be attributed only to the mode of modification. The CR-TB, however, missed the PG target of 74-xx, and the SBS 64-40 was purposely designed to have a PG different from the rest in order to check out whether the performance of binders with high polymer content and soft bases can be captured by the Superpave specification. The intermediate temperature performance grades based on $|G^*| \times \sin\delta = 5$ MPa were found to differ significantly and provided a good opportunity for checking the ability of the current intermediate binder specification to rate asphalt binders according to the fatigue cracking performance.

The CR-TB consisted of less than 3 percent SBS and 5 percent crumb rubber (80 mesh scrap tire rubber). It is made by mixing ground tire rubber with asphalt binder. Hot air at 69 kPa (10 psi), 177-252 °C (350-485 °F) and 62 M^3/min (2200 ft^3/min) is blown through the mixture until the rubber is dissolved. The air blowing process is described in the patent as "abrasive absorption," no high shear milling is involved (Flanigan T. P., 1995). The product is described as a "new composite, which is completely incorporated together." In appearance the material looks like regular asphalt, there are no undissolved rubber particles.

The CR-AZ is different from the CR-TB in that it contains discrete undissolved particle of ground tire rubber. The process, as specified by the Arizona DOT Specification 1009, consists of blending ground tire rubber (minimum 20%) with asphalt at 177-204 °C (350-400 °F) until the asphalt wets the rubber particles. Mixing is then continued for one hour at 163-191 °C (325-375 °F) until the rotational viscosity reaches specification. No MP1a testing is done since the rubber particles would interfere with the DSR. Properties measured include penetration, softening point and resilience.

The Rheometrics dynamic shear rheometer (DSR) was used for generating dynamic data at different temperatures (7° C, 19 °C, 25 °C, 64 °C, 70 °C, 76° C) in the intermediate and high temperature range with a set of parallel plates following the AASHTO T315-02 procedure. The data were generated using frequency sweep. All data were generated within the linear viscoelastic range of response. The samples for the test were prefabricated using a silicone rubber mold. For determination of the high temperature PG, the samples that were aged using the rolling thin-film oven test (RTFOT) following AASHTO T240-00 procedure were used; and for determination of the intermediate temperature PG, samples that were aged in pressurized aging vessel (PAV) following AASHTO R28-02 procedure after RTFOT were used. Such RTFOT and PAV-aged samples were used in the case of all binders except the Arizona crumb rubber modified asphalt (CR-AZ). It was found that when CR-AZ was aged, the obtained aged-binder was not homogeneous and had discrete areas of chunkiness. This made it impossible to generate data on the DSR for the aged CR-AZ in a manner identical to what was used for the other binders. Hence, only in the case of CR-AZ, data was generated on the original unaged binder. From this data, the PG was estimated using the method proposed earlier to estimate the rheological properties of aged asphalt binders without actually aging them (Shenoy, 2002a). The conventional Superpave high temperature PG is determined as the temperature when $|G^*| / \sin \delta = 2.2$ kPa at a frequency $\omega = 10$ radians/s for RTFOT-aged samples. Shenoy showed that adding 6 °C to the temperature at which $(|G^*| / \sin \delta)_{ORIG} = 2.2$ kPa gives the temperature at which $(|G^*| / \sin \delta)_{RTFOT} = 2.2$ kPa (Shenoy, 2002a), and this was thus used to determine the high temperature PG of the CR-AZ. Similarly, the conventional Superpave intermediate temperature PG is determined as the temperature when $|G^*| \times \sin \delta = 5$ MPa at a frequency $\omega = 10$ radians/s for PAV-aged samples. Shenoy showed that adding 6 °C to the temperature at which $(|G^*| \times \sin \delta)_{ORIG} = 5$ MPa gives the temperature at which $(|G^*| \times \sin \delta)_{PAV} = 5$ MPa (Shenoy, 2002a), and this was thus used to determine the intermediate temperature PG of the CR-AZ. The original unaged binder was also used for determining the high temperature PG from the material's volumetric-flow rate (MVR) using the Flow Measuring Device (FMD) (Shenoy, 2001). The bending beam rheometer was used for determination of the low temperature PG in accordance with the AASHTO T313-02 procedure and cracking temperatures determined following the procedure given in earlier work (Shenoy, 2002b).

Laboratory testing of the CR-AZ was also conducted by the Law Gibb Group. This entailed heating a known quantity of asphalt cement to 204 °C (400 °F). The Crumb Rubber was slowly added to the hot binder. The asphalt rubber blend was tested over a range of times--60 minutes (representative of field mixing) and 4 hours (to capture effects of possible job delays). Testing included viscosity measurement at 177 °C (350 °F) (Haake Viscometer Model VT-04 with Rotor 1), resilience at 25 °C (ASTM D 5329), Ring and Ball Softening Point (ASTM D36), and needle penetration at 25 °C (ASTM D5).

3.1.2. *Mixture Design and Tests*

3.1.2.1. Mixture Design

A job-mix formula was submitted by the paving contractor for a Superpave mixture with the unmodified PG 70-22 asphalt binder and the primary 12.5-mm NMAS gradation (Figure 1). The optimum asphalt binder content was 5.3 percent by total mass of the mixture, based on a 4.0 percent design air-void content at 75 gyratory revolutions. Although mixture designs with the other binders suggested slightly higher binder contents, the targets for all except the CR-AZ mixture were also set at 5.3 percent.

The CR-AZ asphalt binder consisted of an unmodified Citgo PG 58-22 asphalt binder from Paulsboro, NJ, with 1.40-mm (14-mesh) scrap tire rubber from Global Tire Recycling, Wildwood, FL. ADOT calls this a Type II asphalt rubber binder. The proportions were 83.0 percent PG 58-22 and 17.0 percent crumb rubber, which means that the asphalt binder consisted of 20.5-percent rubber by mass of the asphalt and 17.0-percent rubber by total mass of the binder.

Law Gibb Group in Phoenix, AZ, designed the CR-AZ mixture according to ADOT's 413 asphalt rubber asphalt concrete design specifications. Five materials were used: No. 68 diabase, No. 78 diabase, No. 8P diabase, No. 10 diabase, and hydrated lime. The aggregate blending percentages were 32.7, 46.5, 8.9, 10.9, and 1.0 percent, respectively. For this design, untreated No. 10 aggregate was used and the 1.0-percent hydrated lime was added separately. The aggregate gradations used in the CR-AZ mixture and other mixtures are shown in Figure 1.

The 75 blow-per-side Marshall Method was used for the mixture design. The compaction temperature was 163 °C (325 °F). The volumetric requirements were that the air voids had to be between 4.5 and 6.5 percent and the void-in-the-mineral aggregate (VMA) had to be a minimum 19.0 percent. Four asphalt binder contents were tried: 6.0, 7.0, 8.0, and 9.0 percent. The optimum asphalt binder content was found to be 7.1 percent.

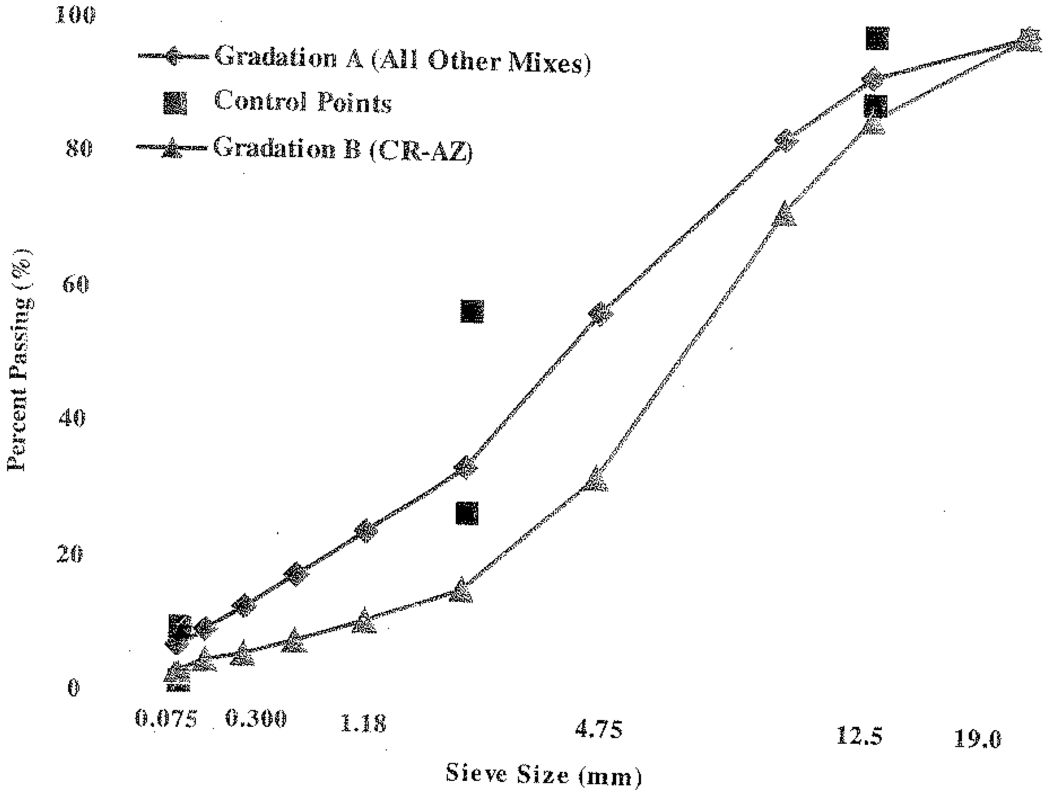


Figure 1 *Aggregate gradations used in the asphalt mixtures*

3.1.2.2. Mixture Tests

Extensive laboratory performance tests were conducted in the FHWA's bituminous mixture laboratory (BML) on the specimens fabricated from plant-produced lab-compacted mixtures used in the full-scale test pavements. These tests were conducted by the simple performance tester (SPT), French permanent rut tester (PRT), Hamburg wheel tracking device (WTD), Superpave shear tester (SST), indirect tensile tester (IDT), and beam fatigue tester.

Mixture dynamic modulus was tested using the simple performance tester according to the NCHRP Report 465 procedure and was conducted at a sweep of frequencies: 20, 10, 5, 1, 0.5, and 0.1 Hz and temperatures of 4, 19, 31, 46, 58, and 64 °C to characterize all evaluated mixtures at a wide range of temperatures and loading frequencies for both rutting and fatigue cracking performance evaluation.

French permanent rut tester was used to evaluate mixture rutting resistance and was conducted on slabs with dimensions of 500x180x100 mm at a temperature of 74 °C. The French PRT applies a vertical load of approximately 5000 N using reciprocating pneumatic smooth tires inflated to 600 kPa. For a tested slab, rut depth at 60,000 wheel passes is measured and averaged over 15 measurements at 15 standard positions.

Hamburg wheel tracking device was used to evaluate the mixture rutting sensitivity at wet conditions and conducted on slabs with dimensions of 320x260x80 mm submerged under water at a temperature of 64 °C. The Hamburg rut test applies a vertical load of 650 N using steel wheels. The wheel passes at 10-mm rut depth and rut depths at 10,000 and 20,000 wheel passes are normally recorded. Slabs are visually checked for any stripping or/and fracture due to moisture. In this way, asphalt mixtures can be evaluated and ranked for rutting susceptibility and moisture damage.

Repeated shear at constant height (RSCH) test using the Superpave shear tester was performed at a temperature of 74 °C according to the AASHTO TP7 procedure. The specimens were fabricated into discs with 50-mm thickness and 150-mm diameter The RSCH test applies a haversine shear stress with rest periods (0.1 sec loading and 0.6 sec rest period). The vertical load is varied to keep the specimen's height constant. The load cycles to 2 percent strain is recorded either from measured values or by predicting from the best-fit curve of the measured data.

Frequency sweep at constant height (FSCH) test using the SST was also conducted according to the AASHTO TP7 procedure at a temperature of 74 °C. The FSCH test applies a sinusoidal shear strain. The vertical load is varied to keep the specimen's height constant. The shear modulus (G*) of the material is estimated from this test.

Tensile strength tests were conducted using the indirect tensile tester according to the AASHTO TP9 procedure. The test was conducted using a constant ram rate at a temperature of 19 °C. The tensile strength as well as the tensile strain at failure were determined.

Mixture fatigue performances are being evaluated using the laboratory beam fatigue tester at multiple levels of temperature and strain. The testing data are not available at the time of the paper preparation and will be reported in the future.

3.2. *Field ALF tests*

3.2.1. *ALF Machines*

FHWA's PTF consists of two ALF machines (Figure 2), to simulate traffic loading at controlled loading and pavement temperatures, and about 3420 m^2 (0.83 acres) of grounds that provide space for 12 pavement test lanes.

The ALF machines are 29 m (95-ft) long frames with rails to direct rolling wheel loads. Each ALF machine is capable of applying an average of 35,000 wheel passes per week from a half-axle load ranging from 33 to 84 kN (7,500 to 19,000 lbf). The load is applied unidirectionally at 18 km/h (11 mi/h) to a 14 m (45-ft) length of

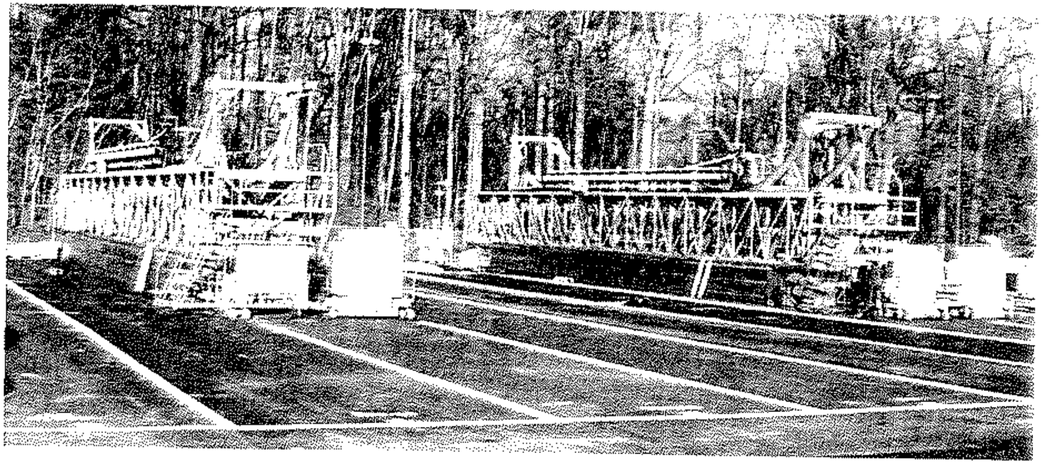


Figure 2. *The FHWA two ALF machines loading pavements at PTF site.*

pavement. The machines allow testing with conventional dual truck tires or wide-based, "super-single" tires and simulation of the real-world, lateral distribution of truck loadings using programmed transverse wheel wander. In the current experiment, both machines are equipped with super-single (425/65R22.5 wide base) tires.

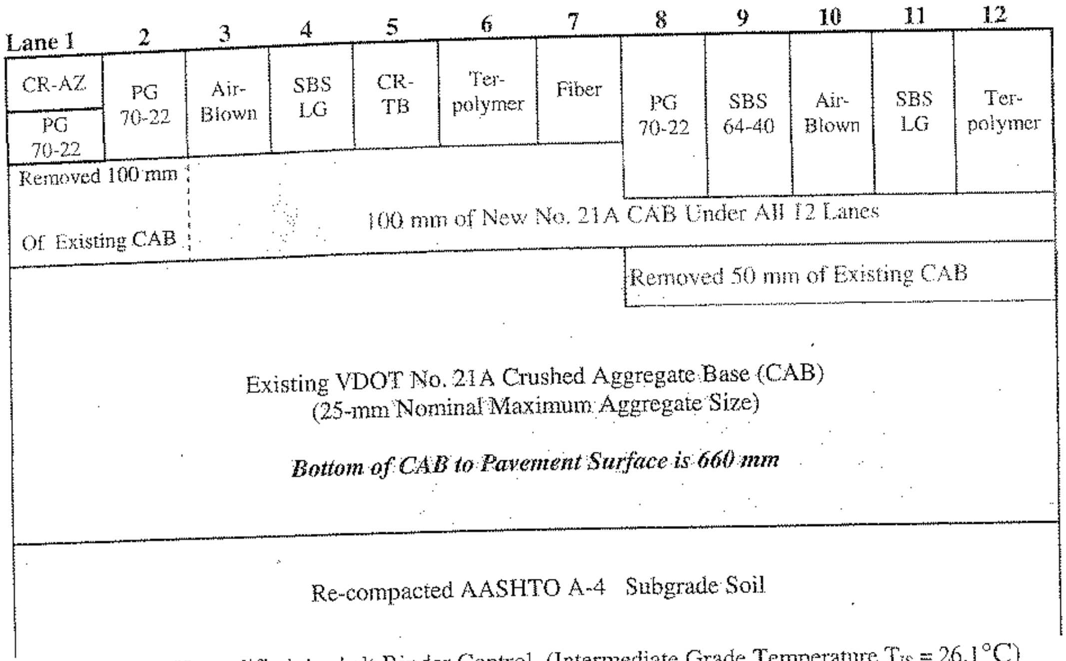
3.2.2. *Pavement test lanes*

The current layout of the 12 as-built pavement lanes is presented in Figure 3. Each pavement lane is 4 m (13 ft) wide and 50 m (165 ft) long, and is divided into four test sites. All lanes consist of a HMA layer and a dense-graded, crushed aggregate base (CAB) course over a uniformly prepared, AASHTO A-4 subgrade soil. The total thickness of the HMA and CAB layers is 660 mm (26 in.). The binders used in each lane are also listed in Figure 4. Note that Lane 1 HMA layer consists of a 50-mm Arizona ARM in the top lift and a 50-mm control mix in the bottom lift. Also note that the control binder (PG 70-22) and three modified binders (Air-Blown, SBS-LG, and Terpolymer) are used in both 100-mm and 150-mm thick lanes to see the effect of thickness of HMA layer.

3.2.3. *Pavement construction*

The pavement test lanes were constructed in the summer and fall of 2002. The mixtures were produced in a counter flow drum plant located in Sterling, Virginia, 27 km (17 mi) from the PTF site. After transport, trucks unloaded the HMA into a material transfer device (MTD), which fed a Blaw-Knox PF3200 rubber tire paver. Use of an infrared camera during construction indicated the MTD was very effective in eliminating temperature and aggregate segregation.

All of the test lanes were constructed in two lifts, each 50-mm (2-in.) or 75-mm (3-in.) thick, as appropriate. A 12.3-Mg (13.5-ton) vibratory roller was used for the breakdown, followed by a 9.1-Mg (10-ton) static steel roller for the finish rolling.



PG 70-22 = Unmodified Asphalt Binder Control (Intermediate Grade Temperature T_{IS} = 26.1°C)
CR-AZ = Crumb Rubber Asphalt Binder, Arizona DOT Wet Process
CR-TB = Crumb Rubber Asphalt Binder, Terminal Blend (T_{IS} =17.9°C)
Terpolymer = Ethylene Terpolymer Modified Asphalt Binder (T_{IS} = 14.3°C)
SBS LG = Styrene-Butadiene-Styrene Modified Asphalt Binder with Linear Grafting (T_{IS} = 18.1°C)
SBS 64-40 = Styrene-Butadiene-Styrene Modified Asphalt Binder Graded PG 64-40 (T_{IS} =8.6°C)
Air-Blown = Air-Blown Asphalt Binder (T_{IS} = 22.6°C)
Fiber = Unmodified PG 70-22 Asphalt Binder with 0.2 Percent Polyester Fiber by Mass of the Aggregate.

Figure 3. *Layout of the 12 as-built pavement lanes (not to scale)*

An extensive quality control/quality assurance (QA/QC) test program was conducted during the construction of both the crushed aggregate base and the HMA. The detailed testing results have been reported elsewhere (Qi *et al.*, 2004).

The hydrated lime was add to the No. 10 diabase aggregate to produce each asphalt mixture by the paving contractor. The lime and No. 10 aggregate were mixed together in the hot-mix drum plant without asphalt. The lime-treated aggregate was then stockpiled. This method of lime addition resulted in the formation of some lime nuggets as observed during the pavement construction. The actual lime contents distributed in the pavement test lanes are now under investigation.

A blender was delivered to the hot mix plant for the CR-AZ production, whereas the CR-TB was trucked to the hot mix plant from Rod Asphalt's terminal in Texas. The recommended mixing temperature for the CR-AZ was slightly higher than that of the CR-TB; these were 157-163 °C (315-325 °F) and 154-157 °C (310-315 °F), respectively. The recommended compaction temperatures were the same for the two materials, 135 °C (275 °F).

3.2.4. *ALF loading and data collection*

Since each pavement lane has four test sites available, the full-scale pavement testing is being conducted at two failure modes, rutting tests (sites 1 and 2) at 64 and 74 °C (selected lanes), and fatigue cracking tests (sites 3 and 4) at 19 and 28 °C. According to the results of "shakedown" rutting and fatigue cracking tests early in 2003, it was decided that all rutting tests use a wheel load of 44 kN (10,000 lb) without transverse wander while all fatigue tests use a wheel load of 74 kN (16,600 lb) with transverse wander. This will fit the project schedule and provides results in a reasonable length of time. An infrared heating system and thermocouples in the pavements provide the required pavement temperature.

During loading, pavement layer rutting data are collected through differential rod and level surveys on eight sets of reference plates installed at the time of construction along the centerline of the test section. The plates are located at the surface of the pavement and on top of the aggregate base in order to measure permanent displacement at these two locations at predetermined ALF loading passes. The difference between these two measurements yields the permanent vertical deformation (rutting) in the asphalt layer.

For fatigue test sections, cracks were manually traced onto clear plastic Mylar sheets as they formed at the surface of the pavements. Different color pens were used to correspond to the number of load repetitions. Two approaches were used to process the data. One was to measure the total crack length and the other was to measure the percentage of area cracked in the loaded area.

4. Results and discussions

4.1. *Laboratory test results*

4.1.1 *Binder characterization*

Tables 1 and 2 give the rheological characteristics of the binders used in the ALF lanes and of the base binders before modification, respectively

4.1.2. *Mixture tests*

The laboratory performance testing results and their statistical rankings are summarized in the tables 3 though 9. As observed from these tables, the different laboratory tests did not provide the same rankings for all mixtures evaluated. However, three laboratory tests (the French PRT, the SST, and the SPT) did consistently indicate that CR-TB mixture performed the best rutting resistance while the CR-AZ mixture performed poor rutting resistance. (SST showed the lowest rutting resistance and French PRT and SPT showed the lower rutting resistance than CR-TB, air-blown, and control PG 70-22 mixtures). Hamburg WTD tests at wet conditions showed the same rankings for the CR-TB and control mixtures while the

Table 1. *Performance Grades and Rheological Characteristics of ALF Binders*

Binder Code	B6269	B6267	B6272	B6298	B6281	B6289	B6295	B6280	B6286
Binder Type	CR-AZ	Control	Control	Control	Air-Blown	Ter-polymer	SBS LG	SBS 64-40	CR-TB
ALF Lane	*1 (top)*	*1 (bottom)*	2	*7, 8*	*3, 10*	*6, 12*	*4, 11*	*9*	*5*
Performance Grade (PG)	88-xx	70-22	70-22	70-22	70-28	70-28	70-28	70-28	76-28
Continuous PG	90-xx	72-23	72-23	72-23	74-28	74-31	74-28	71-28	79-28
T(°C) when MVR_{ORIG} = 50cc/10min @ 1.225 kg	Data not possible to generate	74.6	73.5	72.6	74.8	81.2	77.2	77.0	80.6
T(°C) when $(\lvert G^*\rvert/\sin\delta)_{ORIG}$ = 1 kPa	94.4	72.8	73.2	72.1	75.5	78.0	75.1	71.7	79.5
T(°C) when $(\lvert G^*\rvert/\sin\delta)_{RTFOT}$ = 2.2 kPa	90.1*	72.9	72.3	73.2	74.1	74.5	74.4	71.8	81.4
T(°C) when $(\lvert G^*\rvert \times \sin\delta)_{PAV}$ = 5 MPa	23.0*	25.4	26.7	26.1	22.6	14.3	17.7	8.6	17.9
T(°C) when $S(60)_{PAV}$ = 300 MPa	Data not possible to generate	-13.8	-13.5	-13.5	-18.9	-21.3	-22.7	-28.5	-22.9
T(°C) when $m(60)_{PAV}$ = 0.3		-13.8	-13.3	-13.0	-18.3	-24.1	-19.3	-29.5	-17.6
Cracking T(°C) using BBR **		-22.2	-21.3	-22.9	-27.1	-31.1	-33.7	-36.0	-32.9

* Estimated value using the method proposed earlier (Shenoy 2002a) for PG specs of aged binders without actually aging them ** Using the method given by Shenoy (Shenoy 2002b) for single-event cracking temperature determination directly from the bending beam rheometer (BBR)

Table 2. *Performance Grades and Rheological Characteristics of the Base Binders Before Modification*

Binder Code	B6269A	B6261	B6224	B6225	B6275	B6286A
Binder Description	Binder used for CR-AZ	Binder used for Air-Blown	Combination of these two binders was used for Terpolymer		Binder used for SBS LG	Binder used for CR-TB
Performance Grade (PG)	58-28	52-28	52-28	64-28	58-22	58-22
Continuous PG	60-29	54-31	54-33	67-28	58-28	68-25
T(°C) when MVR_{ORIG} = 50cc/10min @ 1.225 kg	61.2	59.0	55.8	66.5	58.3	68.9
T(°C) when $(\|G^*\|/\sin\delta)_{ORIG}$ = 1 kPa	61.1	55.3	55.3	67.9	58.3	68.9
T(°C) when $(\|G^*\|/\sin\delta)_{RTFOT}$ = 2.2 kPa	60.8	54.5	54.4	67.2	59.2	70.0
T(°C) when $(\|G^*\|x\sin\delta)_{PAV}$ = 5 MPa	17.8	13.4	8.1	19.9	19.7	21.3
T(°C) when $S(60)_{PAV}$ = 300 MPa	-19.7	-21.8	-23.3	-18.6	-19.8	-17.8
T(°C) when $m(60)_{PAV} = 0.3$	-19.6	-24.0	-26.7	-20.4	-17.9	-15.0
Cracking T(°C) using BBR **	-28.3	-30.6	-35.3	-28.5	-26.7	-26.5

** Using the method given earlier (Shenoy 2002b) for single-event cracking temperature determination directly from the bending beam rheometer (BBR)

CR-AZ mixture ranking is just below them. The lower SPT $E^*\sin\delta$ values for both CRM mixtures compared to control and air-blown mixtures indicate the CRM mixtures may have improved fatigue cracking resistant performance.

Table 3. *French PRT Ranking of ALF Asphalt Mixtures at 74°C*

Mixture/Lane	Rut Depth at 60,000 Passes (mm)	Ranking
CR-TB/Lane 5	6.9	A
Air-Blown/Lanes 3&10	8.1	B
PG 70-22/Lanes 2&8	9.9	C
SBS LG/Lanes 4&11	12.7	D
AZ-CR over PG 70-22/Lane 1	14.3	DE
Fiber/Lane 7	15.1	E
SBS 64-40/Lane 9	20.0	F
Terpolymer/Lanes 6&12	20.0	F

Table 4. *Hamburg WTD Ranking of ALF Asphalt Mixtures at 64°C*

Mixture/Lane	*Wheel Passes to 10-mm Rut Depth*	Ranking
PG 70-22/Lane 1	17,700	A
Air-Blown/Lanes 3&10	14,500	B
PG 70-22/Lanes 2&8	13,100	BC
CR-TB/Lane 5	12,600	C
AZ-CR/Lane 1	9,800	D
SBS LG/Lanes 4&11	9,300	DE
Terpolymer/Lanes 6&12	8,100	E
Fiber/Lane 7	7,000	F
SBS 64-40/Lane 9	5,100	G

Table 5. *SST RSCH Ranking of ALF Asphalt Mixtures at 74°C*

Mixture/Lane	*Cycles to 2% Strain*	Ranking
Terpolymer/Lanes 6&12	2615	A
CR-TB/Lane 5	2121	B
SBS LG/Lanes 4&11	1279	C
PG 70-22/Lanes 2&8	695	D
SBS 64-40/Lane 9	556	DE
Air-Blown/Lanes 3&10	530	DE
Fiber/Lane 7	344	E
AZ-CR/Lane 1	146	F

Table 6. *SST FSCH Ranking of ALF Asphalt Mixtures at 74°C*

Mixture/Lane	*Shear Modulus at 10 Hz (kPa)*	Ranking
CR-TB/Lane 5	49285	A
SBS LG/Lanes 4&11	40430	B
PG 70-22/Lanes 2&8	40874	BC
Air-Blown/Lanes 3&10	40248	BC
Terpolymer/Lanes 6&12	39139	C
SBS 64-40/Lane 9	34707	D
Fiber/Lane 7	30798	E
AZ-CR/Lane 1	28469	F

Table 7. *SPT $E^*/\sin\delta$ Ranking of ALF Asphalt Mixtures at 58°C*

Mixture/Lane	*$E^*/\sin\delta$ at 10 Hz (MPa)*	Ranking
Air-Blown/Lanes 3&10	758	A
PG 70-22/Lanes 2&8	507	AB
CR-TB/Lane 5	505	AB
SBS LG/Lanes 4&11	430	B
Terpolymer/Lanes 6&12	352	C
AZ-CR/Lane 1	307	D
SBS 64-40/Lane 9	272	E

Table 8. *SPT $E^*\sin\delta$ Ranking of ALF Asphalt Mixtures at 19°C*

Mixture/Lane	*$E^*\sin\delta$ at 10 Hz (MPa)*	Ranking
PG 70-22/Lanes 2&8	2450	A
Air-Blown/Lanes 3&10	2281	B
AZ-CR/Lane 1	1953	C
Terpolymer/Lanes 6&12	1844	CD
SBS LG/Lanes 4&11	1842	CD
CR-TB/Lane 5	1759	D
SBS 64-40/Lane 9	1372	E

Table 9. *IDT Tensile Strength Ranking of ALF Asphalt Mixtures at 19°C*

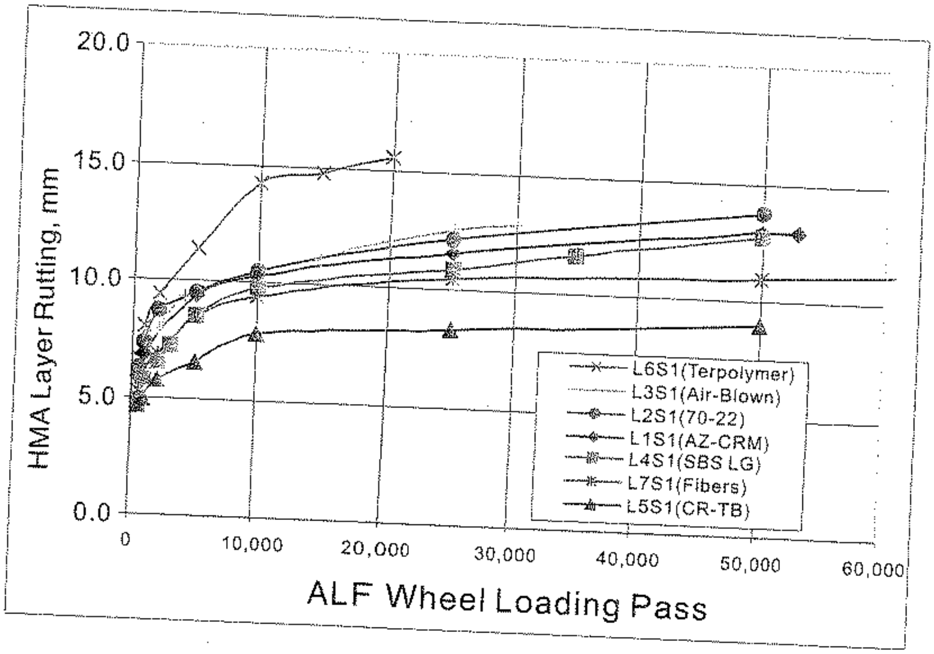
Mixture/Lane	Tensile Strength (kPa)	Ranking
PG 70-22/Lanes 2&8	1261	A
PG 70-22/Lane 1	1241	AB
SBS LG/Lanes 4&11	1032	B
Air-Blown/Lanes 3&10	946	BC
CR-TB/Lane 5	925	BC
Terpolymer/Lanes 6&12	854	C
SBS 64-40/Lane 9	551	D

4.2. *ALF test results*

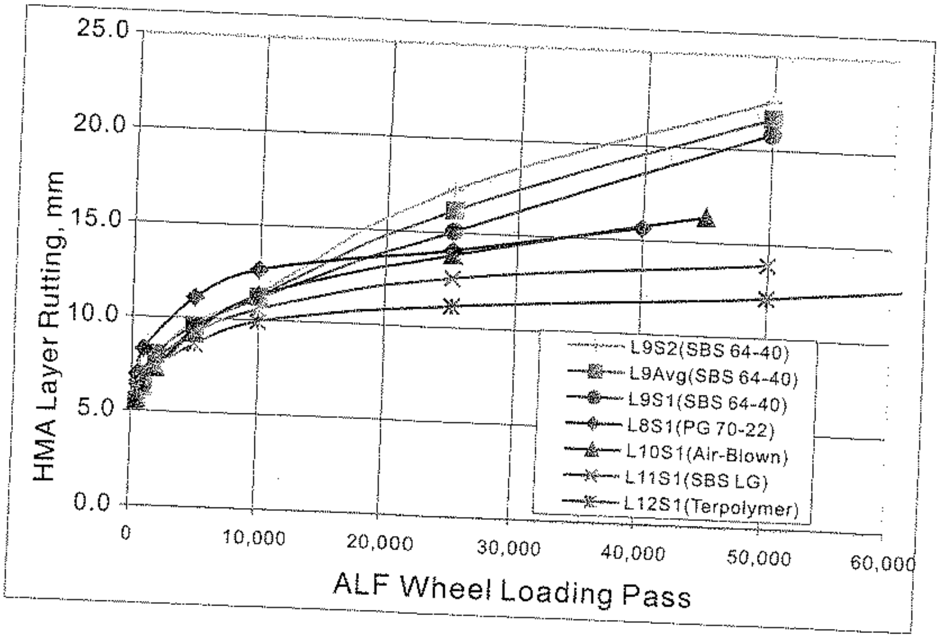
4.2.1. *ALF rutting tests*

The ALF rutting tests conducted at 64 °C and 44 kN load were complete for all 12 lanes. Figure 4 graphically presents the fairly wide range of rutting results in the HMA layer in two groups for the two levels of HMA thickness: 100-mm for Lanes 1 to 7 and 150-mm for Lanes 8 to 12. A statistical analysis was conducted to identify any significant differences among the mean values of rutting at 25,000 ALF passes for each thickness, respectively. This specific number of ALF passes was selected because the rutting measurements at this pass number were available for most of test lanes. The analysis results are showed in Table 10. In the last column of the table, Fisher's least squares difference (LSD) method was used to rank the rutting resistance. As seen from the table, four significant different groups of rutting exist within 100-mm HMA pavements while only two significantly different groups of rutting within 150-mm HMA pavements. Both the graphical figure and statistical analysis show that Lane 5 with CR-TB binder exhibited the highest rutting resistance while Lane 6 with Terpolymer modified binder showed the lowest rutting resistance among the 100-mm HMA pavements. It should be point out that Lane 5's higher rutting resistance is correspondent to its as-built higher PG graded binder compared to the other binders. Lane 1 with CR-AZ binder showed the similar rutting resistance to the control Lane 2 and other modified lanes such as air blown, SBS-LG, and fiber modified binders.

Note that replicate rutting tests were conducted in Lane 9, Site1 and Site 2, with binder SBS 64-40 to see the variation between the replicate tests. Statistical tests on means of rutting from replicate tests showed no significant difference at all ALF load passes. Another interesting finding is that the rutting rankings of Terpolymer binder are just opposite in the two thickness pavements (lanes 6 and 12). These conflicting data are still under investigation. The current hypothesis attributes the poorer performance of Lane 6 to an adverse chemical interaction between the Terpolymer and the hydrated lime added during the mix production to reduce the moisture damage.



(a) Lanes 1 to 7 with 100-mm Pavements



(b) Lanes 9 to 12 with 150-mm Pavements

Figure 4. HMA layer rutting data at 64 °C and 44 kN load

Table 10. *Statistical summary of HMA layer rutting at 25,000 ALF passes at testing conditions: 64 °C & 44.5 kN ALF loading*

HMA Thickness (mm)	Lane/Site Designation	Binder Type	Mean (mm)	Std. Dev. (mm)	CV (%)	LSD Test Ranking
100	L5S1	CR-TB	8.4	0.7	9	A
	L7S1	Fiber	10.5	1.7	16	B
	L4S1	SBS LG	10.9	0.8	7	BC
	L1S1	CR-AZ	11.6	1.5	13	BC
	L2S1	PG 70-22	12.2	1.8	15	BC
	L3S1	Air-Blown	12.6	1.8	14	C
	L6S1	Terpolymer	16.5	3.4	20	D
150	L12S1	Terpolymer	11.1	2.8	25	A
	L11S1	SBS LG	12.6	1.2	10	A
	L10S1	Air-Blown	13.8	2.3	17	AB
	L8S1	PG 70-22	14.1	2.1	15	AB
	L9S1	SBS 64-40	15.1	3.8	25	AB
	L9S2	SBS 64-40	17.3	8.0	46	B

Note: all the rutting data at 25,000 passes are measured values except for Lane 6 Site 1 where predicted values were used.

4.2.2. *ALF fatigue tests*

The ALF fatigue tests at 19 °C and 74 kN have been completed for all 100-mm HMA pavements and are being conducted for 150-mm HMA pavements. Figure 5 shows the pavement cracking conditions for all 100-mm HMA pavements at the end of fatigue testing. In the figure, the labels at the bottom of each pavement lane are lane number, binder type, and the ALF loading pass. The cumulative crack length and the percentage of the area cracked are presented in Figure 6 at various ALF passes. As shown in the figure, the fatigue performance rankings are identical by both crack length and crack area. As expected, a wide range of fatigue performance can be observed from both figures. Based on these original measured cracking data, Lane 5 with CR-TB binder, showed better fatigue cracking resistance than the control Lane 2 and Lane 3 with air-blown binder, but worse than the other types of modified binder pavements. Lane 1 with CR-AZ binder, showed the best fatigue cracking resistance, i.e., no crack was found on the pavement surface after 300,000 ALF passes. It should be pointed out that Lane 1 also has a stiffer aggregate base layer indicated by the FWD testing conducted during construction, which may have a significantly influence on the pavement fatigue performance (Qi *et al.*, 2005). The effect of the variations in the as-built properties, has been recommended to be

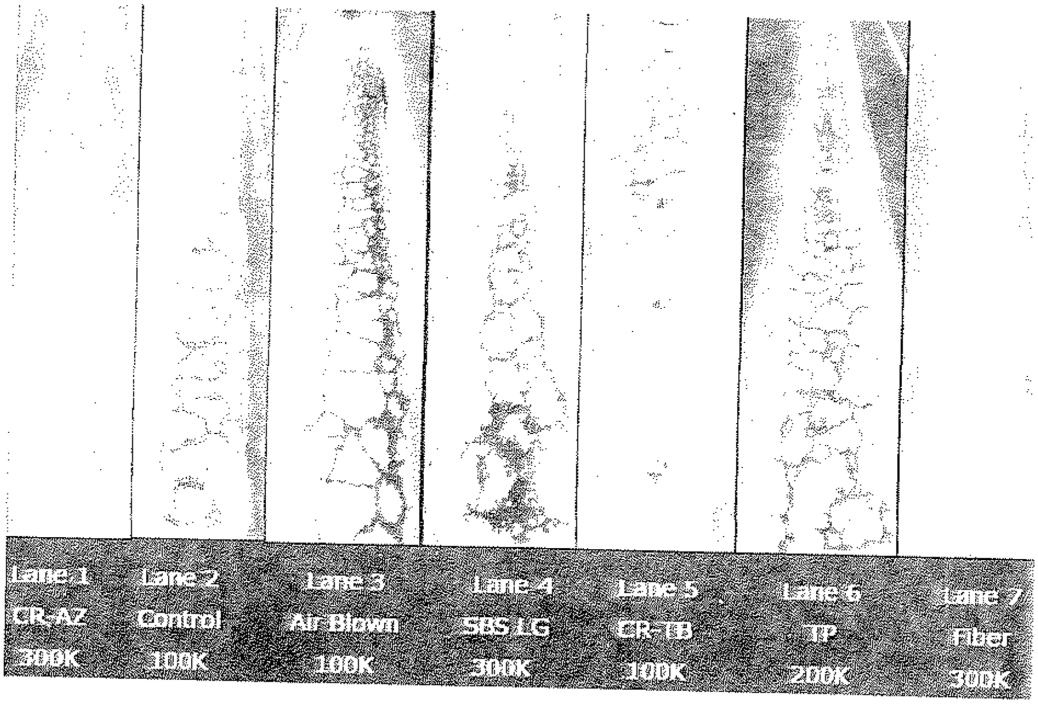


Figure 5. Pavement Cracking conditions at end of fatigue testing at 19 °C and 74 kN

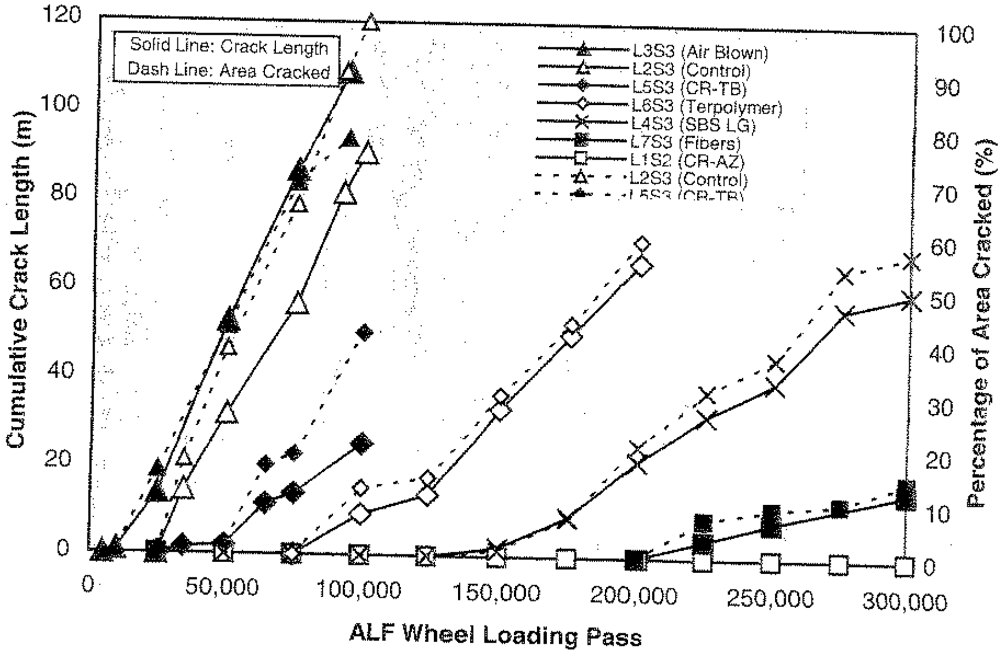
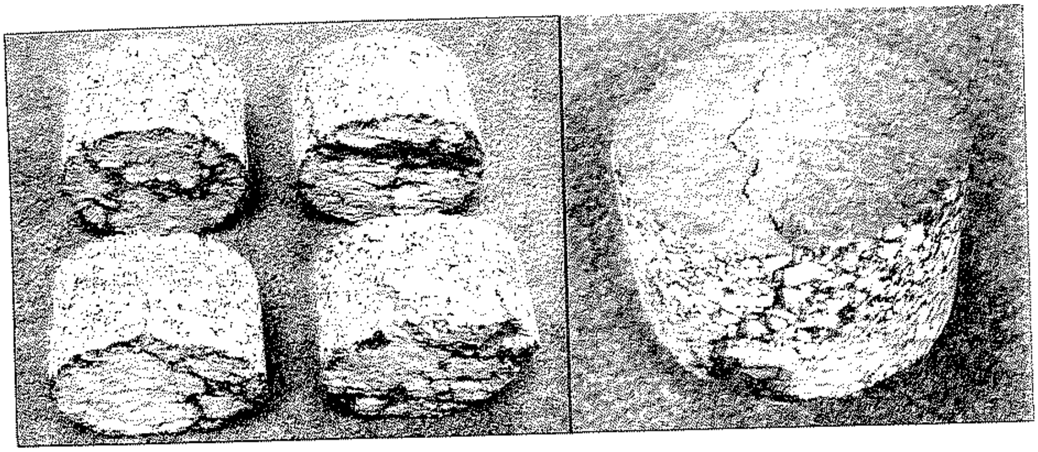


Figure 6. Crack length and percent area cracked vs. ALF passes at 19 °C and 74 kN

quantified through the mechanistic pavement modelling predictions in the future data analysis.

4.2.3. *Lane 1 post-mortem evaluation*

As mentioned early, Lane 1 HMA layer was constructed with a 50-mm Arizona ARM in the top lift and a 50-mm control mix in the bottom lift. It is of interest to know the performance of each lift of pavement. For the fatigue testing site, no crack was found on the pavement surface at the end of ALF loading. However, some cracks showed up on the surface near the ALF wheel landing area approximately 10 moths after the loading. In order to investigate the depth of these cracks and the pavement bottom cracking conditions, 4 cores were cut from the loaded area (one core right at the surface crack and 3 cores from no surface crack area). Figure 7 shows the cracking conditions of these cores. All cores exhibited bottom-up cracks and the cracks are limited in the bottom lift except for the core taken at surface crack, which showed a full-depth crack (Figure 7 (b)). This cracking paten may indicate the higher fatigue cracking resistance in the top lift Arizona ARM.



(a) Cracks shown in bottom lift (b) Crack through the full depth

Figure 7. Pavement cores cut from Lane 1 fatigue test site

For the rutting testing site, 4 pavement cores with 6 in. diameter, were also cut to investigate the rutting distribution between top and bottom lifts. Each core was cut at such location so that half of the core was at the channelized-loading area and the other half was at the unloaded area. The lift thickness was measured at both sides of loaded and unloaded areas. Comparing the top and bottom lift changes after loading should provide indication of the rutting distribution between top and bottom lifts. Table 11 summarizes the information. In average, the percent of change in top lift is almost the same as that in bottom lift. This indicates that the HMA layer rutting in Lane 1 rutting test site is evenly distributed in the top and bottom lifts.

Table 11. *Rutting distribution between top and bottom lifts in Lane 1 rutting site*

Core No.	Top Lift Thickness (mm)		Bottom Lift Thickness (mm)		Top Lift Change after loading (%)	Bottom Lift Change after loading (%)
	Loaded Area	Unloaded Area	Loaded Area	Unloaded Area		
(a)	40	47	50	58	15	14
(b)	50	55	48	53	9	9
(c)	45	49	51	58	8	12
(d)	39	47	45	53	17	15
Avg	44	50	49	56	12	13

5. Comparisons of laboratory and ALF test results

5.1. *Binder to ALF*

Comparisons between laboratory and ALF are performed for two distresses, namely, (a) Rutting and (b) Fatigue Cracking.

5.1.1. *Rutting*

A comparison between the high temperature performance grade of the binder T_{HS} (°C) when $(|G^*|/\sin\delta)_{RTFOT} = 2.2$ kPa at $\omega = 10$ radians/s and the rut depth (mm) for 25,000 ALF passes is done, and shown in Figure 8. Since Lane 1 is a composite

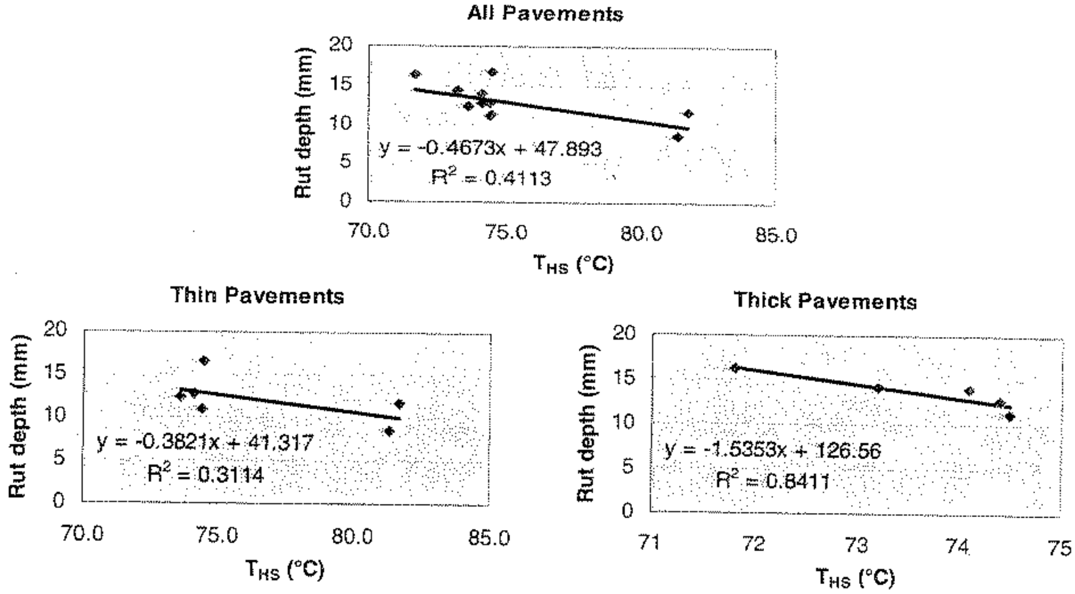


Figure 8: *Comparison between the binder high temperature performance grade and the ALF rut depth (mm) after 25,000 passes.*

pavement of CR-AZ and PG70-22 control, the T_{HS} (°C) for that lane is taken as the weighted average of the two individual binders i.e. 0.5(90.1+73.6) = 81.8. Table 12 shows the results of the coefficient of determination R^2 obtained for a linear fit, including and excluding CR-AZ.

Table 12. *Coefficients of correlation between ALF rutting and binder PG*

	ALF rutting vs.T_{HS} when $(\lvert G^*\rvert/\sin\delta)_{RTFOT}$ = 2.2 kPa at ω=10 radians/s	
	R^2 values	
All Pavements	0.41 (including CR-AZ)	0.53 (excluding CR-AZ)
Thin Pavements (100-mm HMA layer)	0.31 (including CR-AZ)	0.45 (excluding CR-AZ)
Thick Pavements (150-mm HMA layer)	0.84	0.84

5.1.2. *Fatigue Cracking*

A comparison between the intermediate temperature performance grade of the binder T_{IS} (°C) when $(\lvert G^*\rvert\sin\delta)_{PAV}$ = 5 MPa at ω = 10 radians/s and the crack length at 100 K loads shown in Figure 9, ALF passes at 50 m crack length, and ALF passes at 20 m crack length is done. For Lane 1, T_{IS} (°C) is taken as 0.5(23.0+25.4) = 24.2, which is the weighted average of the two individual binders of the composite pavement. Table 13 shows the results of the coefficient of determination R^2 obtained for a linear fit.

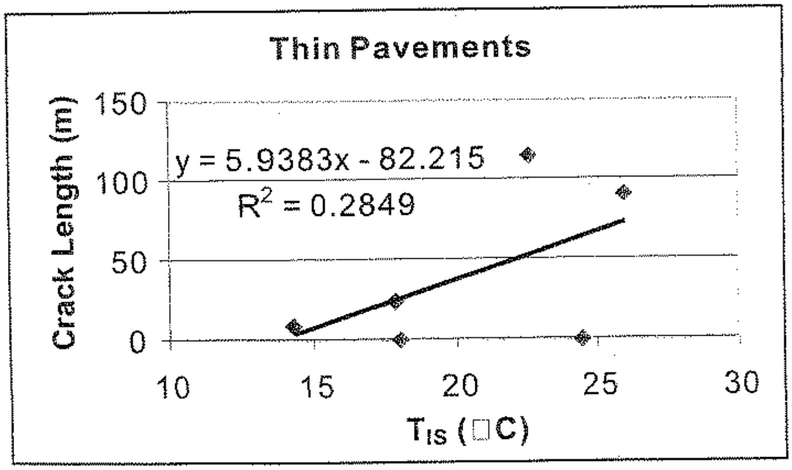


Figure 9. *Comparison between the binder intermediate temperature performance grade and the ALF crack length after 100,000 passes.*

Table 13. *Coefficients of correlation between ALF fatigue cracking and binder PG*

Thin Pavements (100-mm HMA layer)	ALF cracking vs. T_{IS} when $(\lvert G^*\rvert x\sin\delta)_{PAV} = 5$ MPa at ω=10 radians/s	
	R^2 values	
Crack Length (m) at 100 K Loads	0.29 (including CR-AZ)	0.71 (excluding CR-AZ)
ALF Passes at 50 m Crack Length	NA[+]	0.50 (excluding CR-AZ)
ALF Passes at 20 m Crack Length	NA[+]	0.47 (excluding CR-AZ)

[+] (CR-AZ did not show cracks even after 300,000 ALF passes)

5.2. *Mixture to ALF*

The laboratory mixture performance test results were compared with the ALF test results and are shown in Figures 10 and 11. Correlations between the ALF pavement rut depth at 25,000 wheel passes and the different lab rutting parameters were established (Figure 10). The French PRT rutting only showed an R^2 value of 0.40 with the ALF rutting while the Hamburg rutting showed no correlation with the ALF rutting. The parameter $E^*/\sin\delta$ value at 10 Hz provided an R^2 value of 0.57 with the ALF rutting. The best correlation with the ALF rutting was shown by the SST RSCH cycles to 2-percent strain at 74 °C (R^2=0.90). On the other hand, the SST FSCH shear modulus at 74 °C only provided an R^2 value of 0.54 with the ALF rutting. In summary, only SST RSCH provided a high correlation with ALF rutting while other tests provided low to intermediate correlations with ALF rutting.

The laboratory fatigue parameters were also investigated against the ALF fatigue cracking. The correlations between the ALF fatigue cracking data and the laboratory fatigue parameters were established in Figure 11. The SPT parameter $E^*\sin\delta$ value at 10 Hz and 19 °C correlated well with the ALF fatigue crack length at 100,000 ALF passes (R^2=0.75). The IDT strength provided a high correlation with the ALF wheel passes at 20 m crack length (corresponding to approximately 20 percent cracking) with an R^2 value of 0.92. It should be pointed out that this correlation did not include the AZ-CR mixture because the pavement test lane 1 with the AZ-CR showed no cracks after 300,000 ALF loading passes.

6. Summary and conclusions

- In a recent transportation pooled fund study TPF-5(19), twelve lanes of HMA pavement with various modified asphalts were constructed in 2002 at FHWA's Pavement Test Facility in McLean, Virginia. Two of the test lanes use crumb rubber material technology: Lane 1 employs the Arizona wet process and Lane 5 employs a Texas terminal blend process. Lane 2 was constructed with a unmodified asphalt as the control lane. Other lanes include air-blown, polymer, and fiber modified asphalt binders. These pavement lanes are being tested under ALF machine loadings, for both rutting and fatigue cracking performance. The full-scale accelerated performance testing results are being compared with the

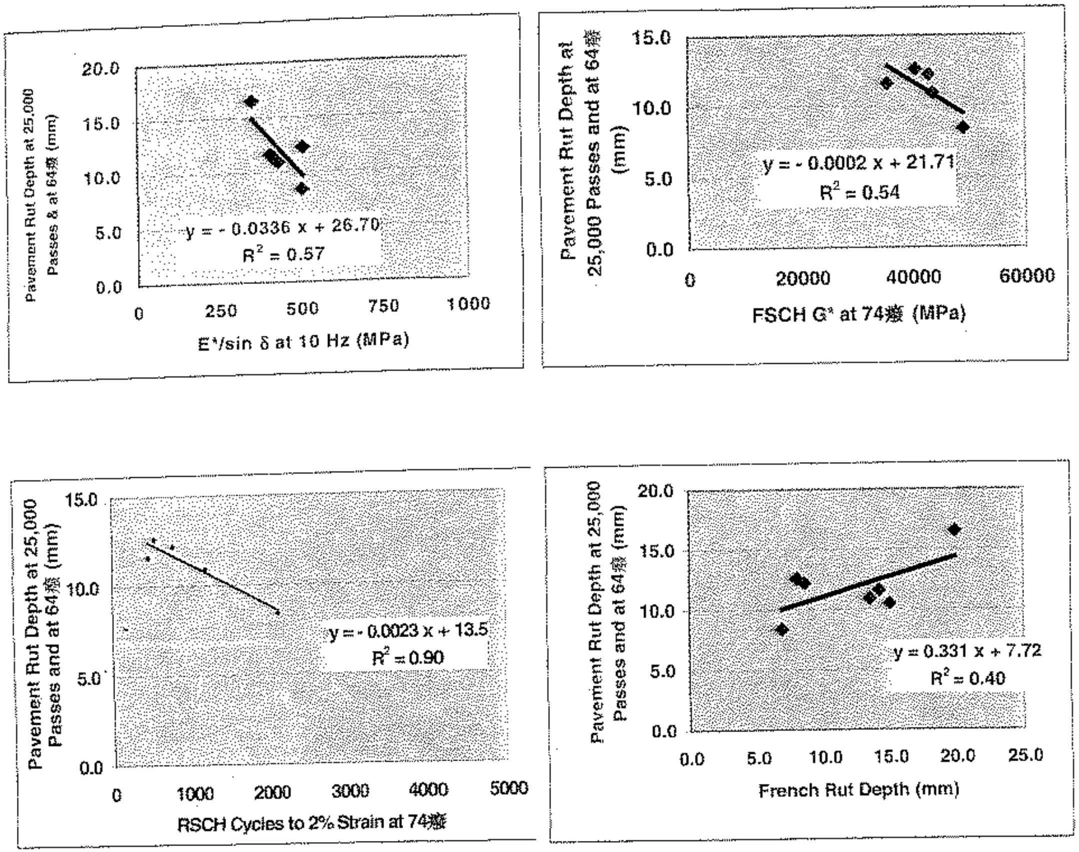


Figure 10. *Comparisons of Laboratory Mixture Rutting Parameters to ALF Rutting*

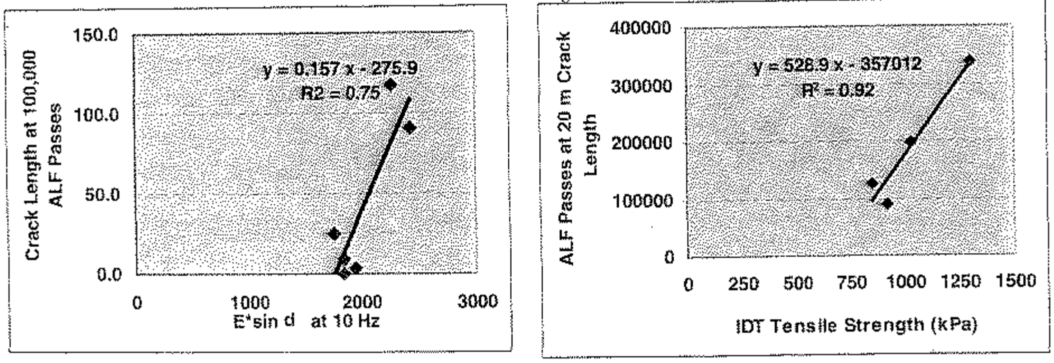


Figure 11. *Comparisons of Laboratory Mixture Fatigue Parameters to ALF Fatigue Cracking*

results of various laboratory mixture performance tests and laboratory binde tests.

– Laboratory binder tests showed that the as-built PG grades at high temperatur are very close to the target PG 74-xx for all binders used in the 100-mm HM pavements except for the CR-TB binder, which is about one grade higher tha other binders. The intermediate temperature performance grades based on $|G^*|$ $\sin\delta = 5$ MPa were found to differ significantly and provided a good opportunit for checking the ability of the current intermediate binder specification to rat asphalt binders according to the fatigue cracking performance. The aged CR-AZ binder, obtained from RTFOT and PAV was not homogeneous and had discrete areas of chunkiness so that the standard DSR tests were not applicable for the aged CR-AZ binder. Alternatively, the original un-aged DSR data were used to estimate the CR-AZ binder performance grade.

– Different laboratory mixture tests did not provide the same rankings of performances. However, three laboratory tests (the French PRT, the SST, and the SPT) did consistently indicate that CR-TB mixture performed the best rutting resistance while the CR-AZ mixture performed poor rutting resistance (SST showed the lowest rutting resistance and French PRT and SPT showed the lower rutting resistance than CR-TB, air-blown, and control PG 70-22 mixtures). Hamburg WTD tests at wet conditions showed the same rankings for the CR-TB and control mixtures while the CR-AZ mixture ranking is just below them. The lower SPT $E^*\sin\delta$ values for both CRM mixtures compared to control and air-blown mixtures indicate the CRM mixtures may have improved fatigue cracking resistance.

– ALF rutting tests at 64 °C and 44 kN revealed that pavement test lane with CR-TB (Lane 5) showed the lowest rut depth in the HMA layer while test lane with CR-AZ (Lane 1) exhibited similar rut depth to the control Lane 2 with conventional mix and other modified lanes within the 100-mm HMA layer pavements. These ALF testing results match the laboratory mixture testing results for CR-TB mixture but do not match for CR-AZ mixture. More laboratory mixture tests have been recommended to investigate the discrepancy.

– Based on the original cracking data measured from the ALF fatigue tests at 19 °C and 74 kN, pavement test lane with CR-AZ (Lane 1) showed the best fatigue cracking resistance while the test lane with CR-TB (Lane 5) showed better fatigue cracking resistance than the control Lane 2 and Lane 3 with air-blown, but worse than other types of modified lanes with the 100-mm HMA layer pavements.

– Pavement cores cut from Lane 1 site 1 (rutting test), indicated that the HMA layer rutting is evenly distributed in the top lift (CR-AZ mix) and the bottom lift (control mix). Cores cut from Lane 1 site 2 (fatigue test) showed that bottom control mix lift has cracked after 300,000 ALF loading applications.

– A correlation analysis was conducted between the ALF testing results and the binder performance grades. Since the performance grade for the CR-AZ was not determined on RTFOT and PAV material but estimated from the original binder, the correlations including and excluding CR-AZ were made. The correlation coefficients were better when CR-AZ was excluded. The correlations for the high temperature performance grade were strongly dependent on the pavement HMA thickness. Moderate correlations were found between ALF fatigue cracking and the intermediate temperature performance grades.

– Correlation analyses between laboratory mixture and ALF test results were also performed. Only SST RSCH provided a high correlation with ALF rutting (R^2=0.90) while other laboratory rutting performance tests provided low to intermediate correlations with ALF rutting. The SPT parameter $E^* \sin\delta$ values at 10 Hz and 19°C correlated well with the ALF fatigue crack length at 100,000 ALF passes (R^2=0.75). The IDT strength provided a high correlation with the ALF wheel passes at 20 m crack length (R^2=0.92).

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