RESEARCH REPORT 1250-1

EFFECT OF RECLAIMED ASPHALT PAVEMENT ON BINDER PROPERTIES USING THE SUPERPAVE SYSTEM

Thomas W. Kennedy, Weng O. Tam, and Mansour Solaimanian

CENTER FOR TRANSPORTATION RESEARCH
BUREAU OF ENGINEERING RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

SEPTEMBER 1998

Technical Report Documentation Page

1. Report No. FHWA/TX-98/1250-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EFFECT OF RECLAIMED ASPHALT PAVEMENT ON BINDER PROPERTIES USING THE SUPERPAVE SYSTEM		5. Report Date September 1998
		6. Performing Organization Code
7. Author(s) Thomas W. Kennedy, Weng O. Tam, and Mansour Solaimanian		8. Performing Organization Report No. 1250-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project 0-1250
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Section/Construction Division P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Research Report (9/97 — 8/98)
		14. Sponsoring Agency Code
15. Supplementary Notes Project conducted in cooperation with the Federal Highway Administration.		

16. Abstract

While the use of reclaimed asphalt pavement (RAP) in asphalt mixes is common practice within many state departments of transportation, the evolution of the Superpave system has prompted a need for specific Superpave guidelines for the use of RAP. In this study, rheological properties were measured for different combinations and percentages of aged asphalts and virgin asphalts. The result of this study is a methodology for determining the effect of RAP on rheological properties of PG binders in the Superpave system. It is important to remember that other factors, including mixture properties, aggregate requirements, RAP handling and homogeneity, and project economics, also need to be considered in determining the final amount of RAP to be used in asphalt mixes.

17. Key Words Superpave system, reclaimed asphalt pavement (RAP), binder properties		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 50	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EFFECT OF RECLAIMED ASPHALT PAVEMENT ON BINDER PROPERTIES USING THE SUPERPAVE SYSTEM

Thomas W. Kennedy

Weng O. Tam

Mansour Solaimanian

Research Report 1250-1

Research Project 0-1250

South Central Superpave Center

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

June 1998

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT INTENDED FOR CONSTRUCTION,
BIDDING, OR PERMIT PURPOSES

Thomas W. Kennedy, P.E. (Texas No. 29596)
Research Supervisor

ACKNOWLEDGMENTS

The researchers acknowledge the guidance provided by M. Tahmoressi (MAT), the TxDOT project director for this study. Appreciation is also expressed for the assistance provided by the TxDOT program coordinator, J. Cravens (FHWA).

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

TABLE OF CONTENTS

SUMMARY

While the use of reclaimed asphalt pavement (RAP) in asphalt mixes is common practice within many state departments of transportation, the evolution of the Superpave system has prompted a need for specific Superpave guidelines for the use of RAP. In this study, rheological properties were measured for different combinations and percentages of aged asphalts and virgin asphalts. The result of this study is a methodology for determining the effect of RAP on rheological properties of PG binders in the Superpave system. It is important to remember that other factors, including mixture properties, aggregate requirements, RAP handling and homogeneity, and project economics, also need to be considered in determining the final amount of RAP to be used in asphalt mixes.

CHAPTER 1. INTRODUCTION

1.1 UTILIZATION OF RECYCLED ASPHALT PAVEMENT

While the use of reclaimed asphalt pavement (RAP) in asphalt mixes is common practice within many state departments of transportation, the evolution of the Superpave system has prompted a need for specific Superpave guidelines for the use of RAP. In this study, rheological properties were measured for different combinations and percentages of aged asphalts and virgin asphalts. This study set out to establish guidelines for the use of RAP in asphalt mixes using Superpave binder specifications. It is intended to assist practitioners in their efforts to incorporate RAP in Superpave mixes.

The result of this study is a methodology for determining the effect of RAP on rheological properties of PG binders in the Superpave system. It is important to remember that other factors, including mixture properties, aggregate requirements, RAP handling and homogeneity, and project economics, also need to be considered in determining the final amount of RAP to be used in asphalt mixes.

1.2 BACKGROUND

Agencies are constantly seeking to reap the benefits of utilizing RAP. Experience has indicated that the recycling of asphalt pavements is a very beneficial approach from technical, economical, and environmental perspectives. Some of the advantages of utilizing RAP include the preservation of existing profile, conservation of asphalt and aggregate resources, conservation of energy, and reduction in life-cycle cost. Therefore, it is no surprise that state highway agencies have been moving toward increasing their percentages of RAP in their hot-mix asphalt pavements (1). While up to 80% RAP has been used in some hot-mix asphalt pavements (1), 20-50% RAP is typically used (2, 3). It should be noted that high percentages of RAP are not used in normal practice.

Most highway agencies have noticed a significant reduction in project cost when RAP is used. One Florida Department of Transportation project showed a savings of 15–30% compared with the cost of conventional paving using all virgin materials (4). These savings are due to lower bids by contractors who pass the savings on to state highway agencies and, ultimately, to the taxpayer.

It is clear that the effective rehabilitation of asphalt pavements sometimes requires the removal of old asphalt layers. If agencies and industry had not developed techniques to use RAP, asphalt pavement rehabilitation costs would significantly increase to account for the cost of disposing of nonrecycled materials. Thus, the effective use of RAP solves a larger societal problem in that the material does not occupy landfill space.

In addition to the economic benefits of using RAP, rehabilitation options that create RAP may have substantial engineering benefits. For example, the ability to mill and remove old, distressed pavements allows for more effective rehabilitation techniques. Severely cracked or rutted layers can be removed so that their damage is not reflected through a new surface layer (5).

1.2.1 Utilizing RAP through Superpave

Once a decision has been made to utilize RAP in a hot-mix pavement, it is crucial to characterize the aggregate and asphalt in the RAP. Sampling and testing must be conducted to estimate the material's quality with respect to Superpave mix design guidelines. In addition, it is crucial to ensure that the RAP materials (binder and aggregate) are compatible with the virgin materials, and that the final blend meets all the mix and binder requirements.

One approach for estimating the percent of RAP to be used has been documented by the Asphalt Institute (6). In this approach, a blending chart based on the asphalt viscosity at 60°C is used. This chart shows a linear relationship between the logarithm of viscosity at 60°C and the percent of new asphalt or percent recycling agent in the blend.

The Superpave system, developed as part of the Strategic Highway Research Program (SHRP), is the latest tool for designing hot-mix asphalt concrete. The Superpave mix design manual describes procedures, guidelines, and requirements for designing Superpave mixtures (7). While the manual does not preclude the use of RAP, it offers very little, if any, guidance on the use of RAP in Superpave mixes. Consequently, the RAP expert task force, which is a subcommittee of the FHWA Mixture Expert Task Group, provided specific recommendations for inclusion of RAP in Superpave volumetric design procedures based on percent RAP used in the total mix (8).

In the Superpave system, an appropriate binder is selected based on the climatic conditions for a specific location with a predicted traffic speed and traffic volume. For this reason, it is important to determine how the characteristics of a binder are influenced by the percentage of RAP used. A research study of this nature, using Superpave binder tests at high temperatures, led to the development of a chart indicating the relationship between shear stiffness $(G^*/\sin\delta)$ and percent of virgin asphalt (9). This study indicated a linear relationship between log $(G^*/\sin\delta)$ and percent virgin binder in a blend of virgin binder and extracted RAP binder. The terms G^* and δ refer to the complex shear modulus and phase angle, respectively. In a similar study, the relationship between complex shear modulus and percent virgin asphalt in the blend was investigated based on the results of testing at 58°C, 64°C, and 70°C (10). A decreasing linear trend was evident for $G^*/\sin\delta$ from 0–75% virgin asphalt. From 75–100% virgin asphalt, the $G^*/\sin\delta$ remains fairly unchanged. From this chart, the amount of RAP and the percentage of virgin asphalt required to meet Superpave high-temperature binder specifications could be determined.

1.3 RESEARCH STUDY

This report presents the results of a more extensive research study undertaken to investigate the effect of incorporating different percentages of RAP binder on the mechanical properties of different blends. Not only does it include test results from Superpave binder tests conducted on unaged binders at the high-temperature range; it also includes test results on blends aged using the rolling thin film oven test (RTFOT) and pressure aging vessel (PAV) conducted at the high-, low-, and intermediate-temperature ranges. Based on the results of the study, a new procedure is proposed for determining the percentage of RAP that can be utilized based on Superpave binder specifications. This study will have significant applications in selecting the type and amount of RAP used in constructing new asphalt pavements.

Chapter 2 describes the experimental program used in the study. Four virgin asphalts and two aged asphalts were used to form six blends of virgin asphalt blended with RAP asphalt that contained five different percentages of aged asphalt.

Chapter 3 describes the results of these tests. Some general trends were found to be consistent in all, if not most, of the blend combinations.

Chapter 4 describes a proposed criterion to determine the amount of RAP to use in a mix containing RAP based on Superpave binder specifications.

Chapter 5 then concludes this study and reiterates the important findings. It suggests practical tips as well as necessary precautions to take when using this study’s methodology for determining the amount of RAP to use in a mix containing reclaimed asphalt pavements.

CHAPTER 2. EXPERIMENTAL PROGRAM

2.1 MATERIAL SELECTION

Six asphalts were chosen from the Material Reference Library (MRL) for this experiment. These were part of the core asphalts used in the Strategic Highway Research Program (SHRP). Four of the asphalts, used as virgin asphalts, represent a wide range of temperature susceptibility based on the temperature-viscosity relationship, the penetration at 25°C, and the viscosity at 60°C (PVN). Of these four asphalts, Lloydminster (AAA-2), Redwater (AAC-1), and California Coastal (AAD-1) asphalts were found to have low-temperature susceptibilities, while West Texas Intermediate (AAM-1) asphalt was shown to be highly temperature susceptible. In addition, Lloydminster and West Texas Intermediate asphalts have a low-aging index, while Redwater asphalt has an intermediate-aging index and California Coastal asphalt has a high-aging index (11). (See Table 2.1.)

2.2 PREPARATION OF AGED ASPHALTS AND ASPHALT BLENDS

The West Texas Sour and California Valley binders were chosen arbitrarily to be aged to simulate RAP binder. This was achieved by placing thin films of the binders in pans and heating them in a forced draft oven at 163°C. The aging periods were 21 and 44 hours for West Texas Sour and California Valley asphalts, respectively. A target penetration of between 10 and 20 was to represent RAP asphalt recovered from the field.

After the aged binders were produced, they were combined with four virgin binders at different percentages (see matrix shown in Table 2.1). These blends were coded using two-letter designations. For example, "DG" refers to the blend of unaged California Coastal with aged California Valley and "MF" refers to the blend of unaged West Texas Intermediate with aged West Texas Sour.

Five percentages of RAP binder (0, 15, 25, 55, and 100%) were chosen to study the effects of RAP binder on the stiffness characteristics of the asphalt blends. Table 2.2 shows the testing matrix used in this study. In Table 2.2, "S" refers to creep stiffness and "m" refers to the logarithmic creep rate as measured by the bending beam rheometer.

Table 2.1 Combinations of virgin and simulated RAP asphalts used

Virgin Asphalt	RAP Asphalt	
	West Texas Sour (AAF-1)	California Valley (AAG-1)
Lloydminster (AAA-2)	X	
Redwater (AAC-1)	X	X
California Coastal (AAD-1)		X
West Texas Intermediate (AAM-1)	X	X

Table 2.2 Testing matrix for evaluating effect of RAP binder

Percentage RAP Binder	Unaged Binder (G* and δ)	RTFO-Aged Binder (G* and δ)	RTFO and PAV-aged Binder (G*, δ, S and m)
0	X	X	X
15	X	X	X
25	X	X	X
55	X	X	X
100	X	X	X

2.3 AGING OF ASPHALT BLENDS

Short-term aging, which simulates aging during construction, was achieved using the rolling thin film oven test (RTFOT, AASHTO T240, ASTM D2872). In this test, 35g $\pm$ 0.5g of the binder is poured into a specially designed bottle. Eight bottles are placed in a vertical circular carriage and rotated along a horizontal axis. This rotation is used to continually expose fresh films of the binder to hot air. Once during each rotation, 4,000 ml/min of hot air is blown into the bottle. This test is conducted in the oven at 163°C for 85 minutes (Figure 2.1). To ensure homogeneity in the RTFOT aged binder, the residue from all bottles was combined into a single container and hand stirred. Long-term aging, which simulates field aging in the first 5 to 10 years of pavement service, was achieved using the pressure aging vessel (PAV, AASHTO PP1) shown in Figure 2.2. In this test, 50g $\pm$ 0.5g of RTFO-aged binder is placed in pans. Then, a temperature of 100°C and a pressure of 2.1 MPa are applied to the binder for 20 hours.

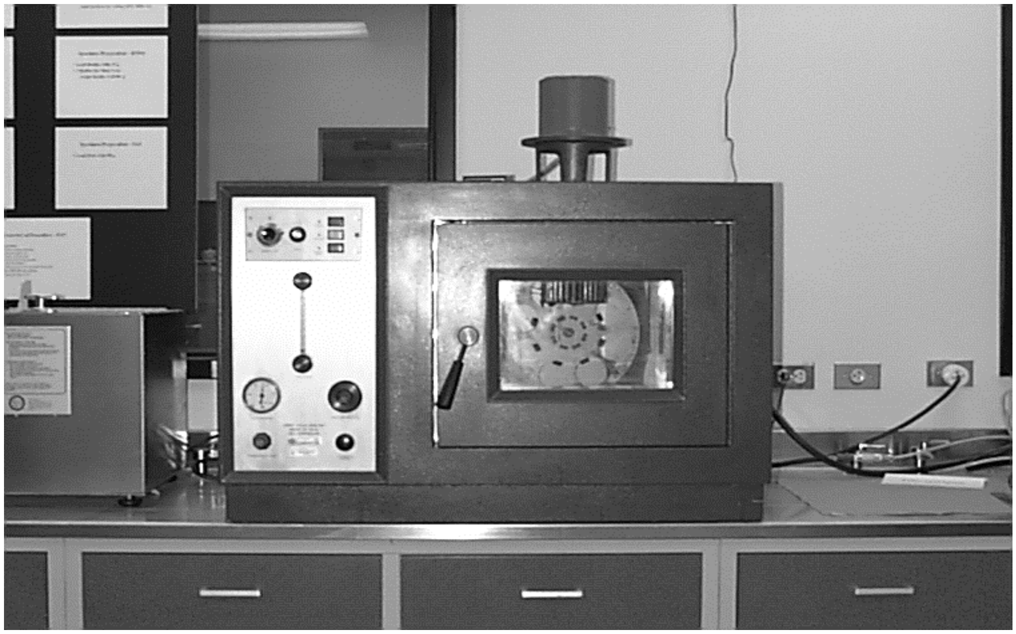

Figure 2.1 Rolling thin film oven

Figure 2.2 Pressure Aging vessel

2.4 TESTING OF ASPHALT BLENDS

Engineering characteristics of the virgin-RAP blends were determined with the aid of a Bohlin dynamic shear rheometer (DSR) and an Applied Test Systems bending beam rheometer (BBR), which are briefly described below.

2.4.1 Dynamic Shear Rheometer

A DSR was used to measure the high- and intermediate-temperature complex shear modulus *(G*)* and phase angle (δ) (Figure 2.3). In this test, a 1–2 mm thick sample of binder is placed between two parallel circular plates. The bottom plate is fixed while the upper place oscillates at a frequency of 10 radians per second to simulate the loading rate of traffic traveling at highway speeds.

Figure 2.3 Dynamic shear rheometer

To determine the high-temperature performance grade, $G^*/\sin\delta$ was determined for the unaged mixture as well as for the RTFO-aged blend. $G^*\sin\delta$ was determined for the PAV-aged asphalt at intermediate temperatures. Figure 2.4 shows the loading geometry of the DSR.

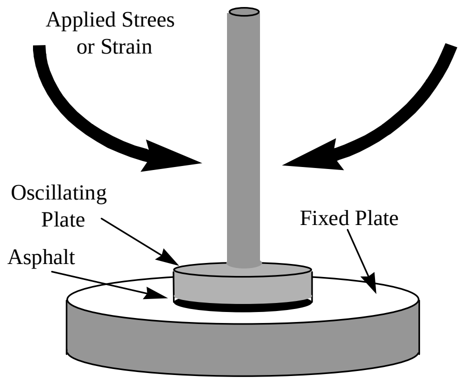

Figure 2.4 Dynamic shear rheometer loading geometry

2.4.2 Bending Beam Rheometer

The bending beam rheometer (BBR) was used to measure the low-temperature creep stiffness and logarithmic creep rate of the asphalt binder (Figure 2.5). In this test, a beam of asphalt binder 125 mm long, 12.5 mm wide, and 6.25 mm thick is formed by pouring binder into a mold and allowing it to cool. This beam is placed in a low-temperature bath to equilibrate its temperature to the desired test temperature. During testing, which must be accomplished within 60 ± 5 minutes of placing the beam in the bath, the beam is placed on two simple supports having a span of 100 mm. A constant load of approximately 1,000 mN, maintained for 240 seconds, was applied to the center of the simply supported beam.

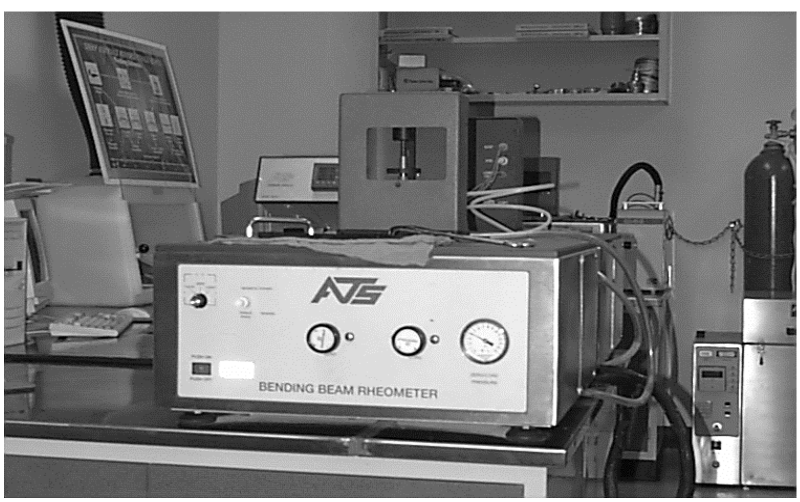

Figure 2.5 Bending beam rheometer

The creep stiffness, *S*, and the creep rate (slope, m) of the relationship between log (stiffness) and log (time) were measured at 60 seconds (loading time). Figure 2.6 shows the loading geometry of the BBR.

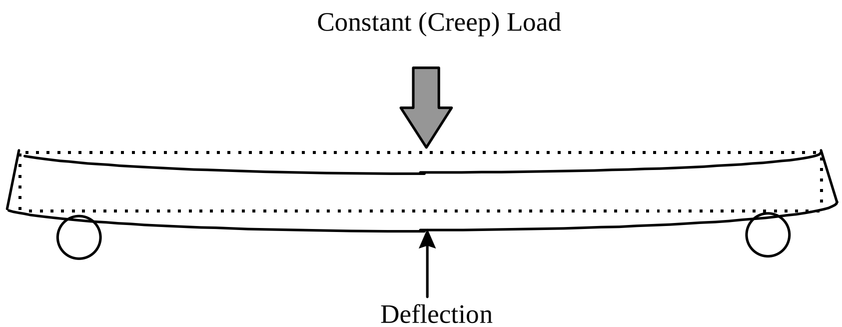

Figure 2.6 Bending beam rheometer loading geometry

CHAPTER 3. RESULTS AND DISCUSSION

3.1 BLEND TRENDS AND CHARACTERISTICS

The change and rate of change of binder properties across the percentages of RAP binder in the blend, 0–100%, for the different combinations of virgin and simulated RAP binders are discussed in this section. Though the different blends showed varying degrees of similarity, two blends that represent the extremes of these trends will be shown and discussed in this section. The trends for the other four blends lie between the two extremes shown. Test data for all blends are shown in Appendix A. Note that the trends were fitted using second- and third-order polynomial curves with equations $y = ax^2 + bx + c$ (second order) and $y = ax^3 + bx^2 + cx + d$ (third order), respectively.

3.1.1 DSR Results on Unaged Blend

As expected, lower temperatures and higher percentages of RAP binder increased $G^*/\sin\delta$. This can be seen in the unaged AF blend (Figure 3.1). Note that there is no significant change in $G^*/\sin\delta$ up to approximately 40% RAP for the unaged AF blend. Lower temperatures and higher percent RAP also increased the rate of increase of $G^*/\sin\delta$ (Table 3.1).

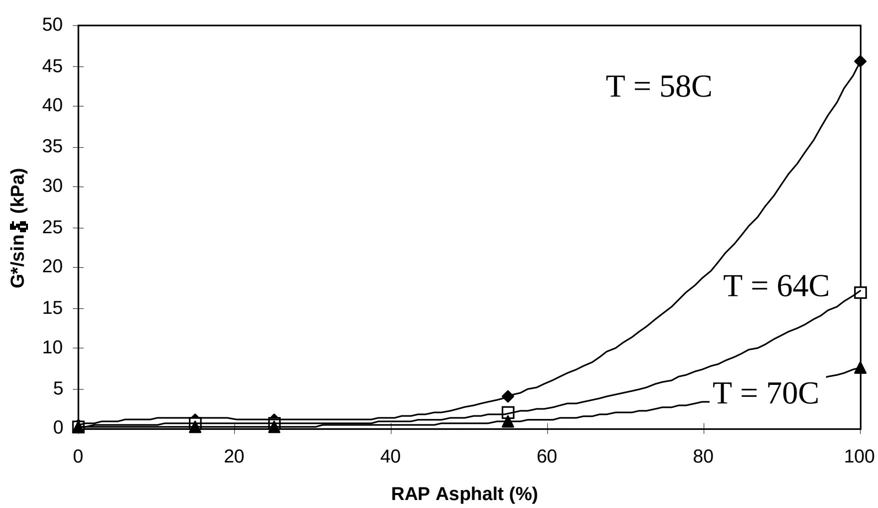

Figure 3.1 G*/sinδ *trend for unaged AF blend*

Table 3.1 Rate of increase in G*/sinδ *for unaged AF blend*

Percent RAP Binder (%)	Increase in *G*/sinδ* (kPa/%RAP)		
	58°C	64°C	70°C
From 0–25%	0.026	0.015	0.007
From 75–100%	1.255*	0.515*	0.286*

*Indicates values calculated from fitted curve

Figure 3.2 shows similar trends for the MF blend. However, the MF blend does not have a range of percent RAP binder where there is no significant change in *G*/sinδ*. When RAP binder is added to the virgin binder, immediately there is a noticeable increase in *G*/sinδ* at 58°C and 64°C. Table 3.2 shows the rate of increase in *G*/sinδ* for the unaged MF blend.

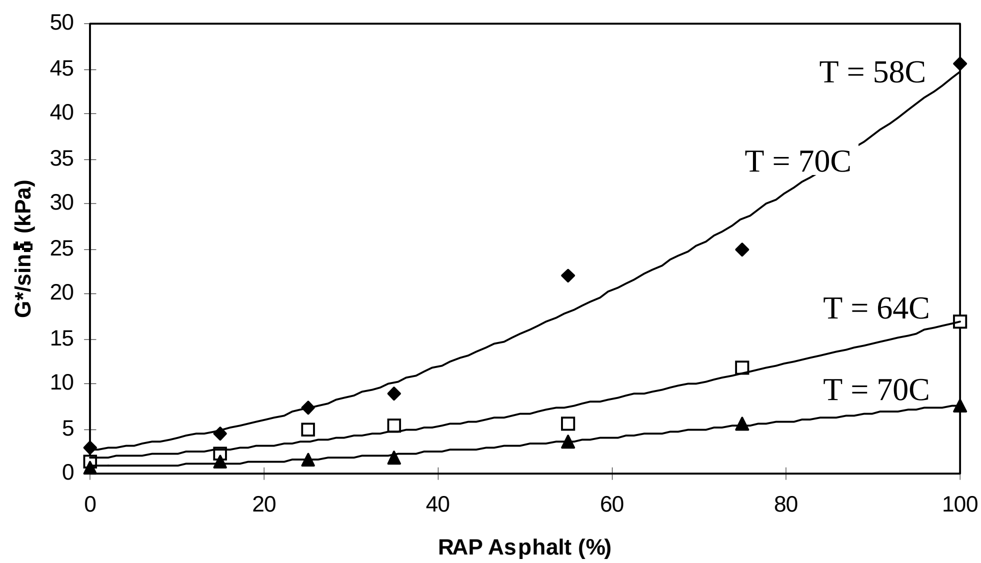

Figure 3.2 G*/sinδ *trend for unaged MF blend*

Table 3.2 Rate of increase in G*/sinδ *for unaged MF blend*

Percent RAP Binder (%)	Increase in *G*/sinδ* (kPa/%RAP)		
	58°C	64°C	70°C
From 0–25%	0.175	0.146	0.037
From 75–100%	0.830	0.207	0.080

The trends of the four other blends lie between the two shown in this section. While they all exhibited similar behavior, it is important to recognize that the properties of the virgin and RAP binders play a large role in determining the effect of adding RAP. This study did not examine the specific properties (e.g., chemical, manufacturing process, etc.) that cause these variations.

3.1.2 DSR Results on RTFOT-Aged Blends

The DSR results for the RTFOT-aged blends showed similar trends to that of the DSR results for the unaged blends. The trend for the RTFOT-aged AF blend is very similar to that for the unaged AF blend (Figure 3.3). Lower temperatures and higher percent of RAP binder increased *G*/sinδ*. Lower temperatures and higher percent of RAP binder also increased the rate of increase of *G*/sinδ* (Table 3.3). However, only in the range of up to approximately 25% RAP binder is there no significant increase in *G*/sinδ.*

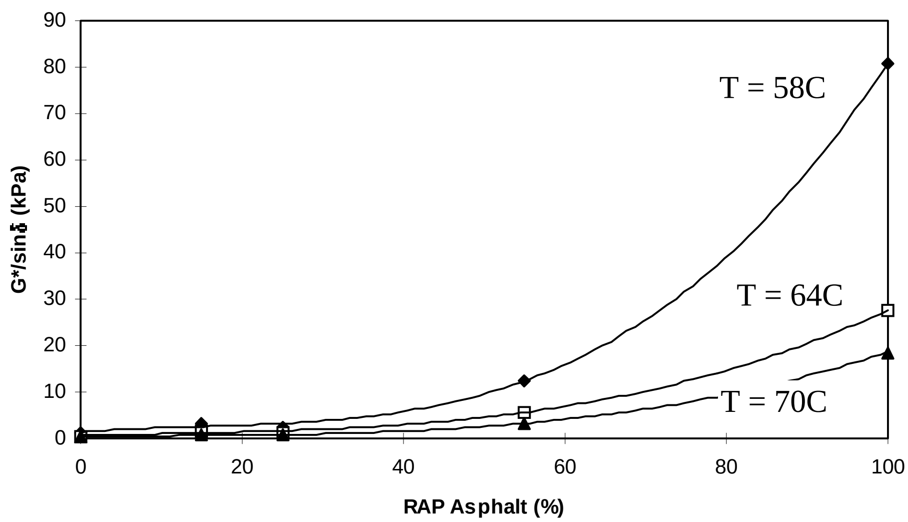

Figure 3.3 G*/sinδ *trend for RTFOT-aged AF blend*

Table 3.3 Rate of increase in G*/sinδ *for RTFOT-aged AF blend*

Percent RAP Binder (%)	Rate of Increase in *G*/sinδ* (kPa/%RAP)		
	58°C	64°C	70°C
From 0–25%	0.055	0.029	0.011
From 75–100%	2.289*	0.617*	0.485*

*Indicates values calculated from fitted curve

The trend for the RTFOT-aged MG blend is similar to that of the unaged MF blend (Figure 3.4). As soon as RAP binder is added to the virgin binder, there is a noticeable increase in *G*/sinδ* at 58°C and 64°C. Once again, lower temperatures and higher percent RAP binder increase *G*/sinδ* along with the actual rate of increase in *G*/sinδ*, as shown in Figure 3.4 and Table 3.4.

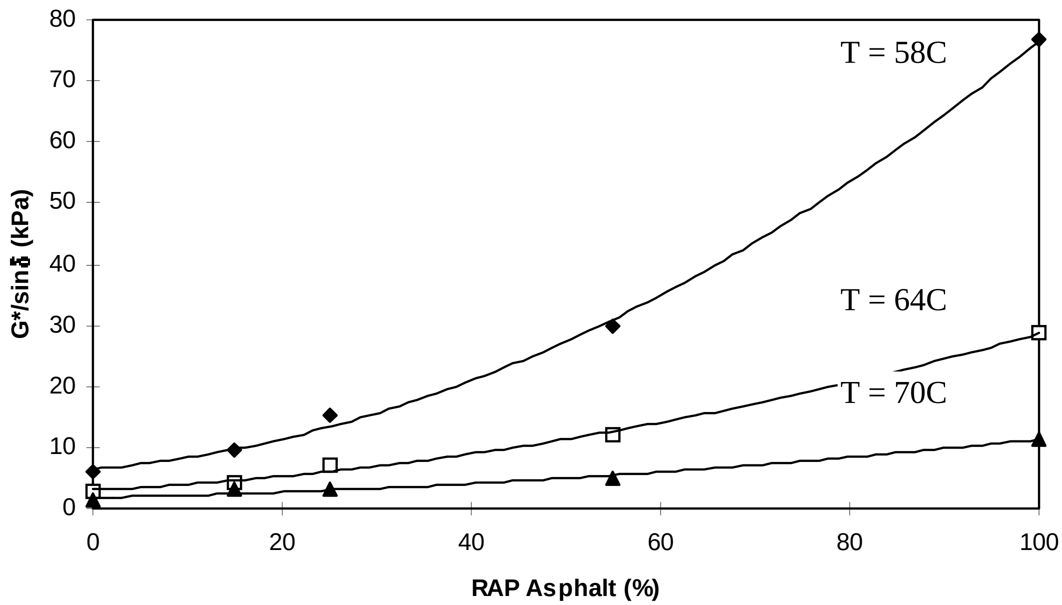

Figure 3.4 G*/sinδ *trend for RTFOT-aged MG blend*

Table 3.4 Rate of increase in G*/sinδ *for RTFOT-aged MG blend*

Percent RAP Binder (%)	Rate of Increase in *G*/sinδ* (kPa/%RAP)		
	58°C	64°C	70°C
From 0–25%	0.371	0.180	0.075
From 75–100%	1.127*	0.393*	0.158*

*Indicates values calculated from fitted curve

3.1.3 DSR Results on RTFOT and PAV-Aged Blends

Unlike the DSR results obtained for the unaged and RTFOT-aged blends, there was little difference among the trends observed for these different blends. Typical examples are shown in Figure 3.5 and Figure 3.6 for the MG and AF blends, respectively.

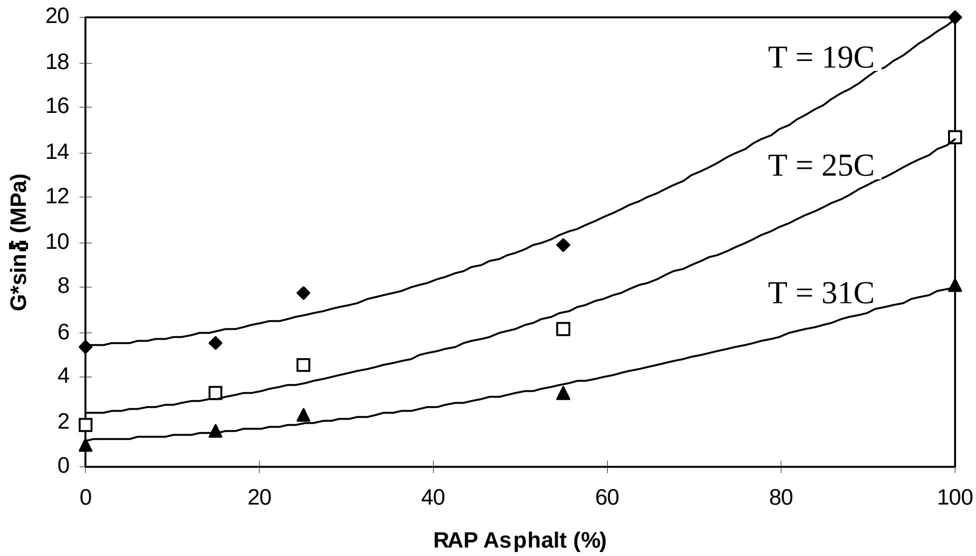

Figure 3.5 G*sinδ *trend for RTFOT and PAV-aged MG blend*

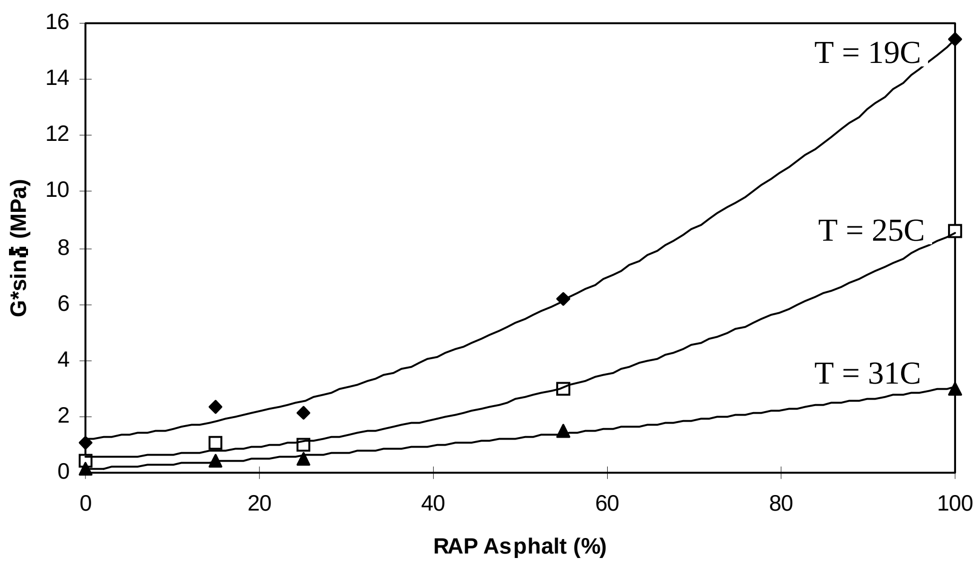

Figure 3.6 G*sinδ *trend for RTFOT and PAV-aged AF blend*

Lower temperatures and higher percent RAP binder increased both *G*sinδ* and the rate increase of *G*sinδ*. The rate of change in *G*sinδ* is strongly affected by test temperature. At the highest test temperature, the effect of test temperature overwhelms the effect of the percent of RAP binder. However, all of the blends showed an increase in *G*sinδ* as soon as RAP was added. This can be seen for the MG and AF blends shown in Table 3.5 and Table 3.6, respectively.

Table 3.5 Rate of increase in G*sinδ *for RTFOT and PAV-aged MG blend*

Percent RAP Binder (%)	Rate of Increase in G*sinδ (kPa/%RAP)		
	19°C	25°C	31°C
From 0–25%	96.952	104.636	55.012
From 75–100%	241.884*	190.968*	116.232*

*Indicates values calculated from fitted curve

Table 3.6 Rate of increase in G*sinδ *for RTFOT and PAV-aged AF blend*

Percent RAP Binder (%)	Rate of Increase in G*sinδ (kPa/%RAP)		
	19°C	25°C	31°C
From 0–25%	45.088	22.226	12.480
From 75–100%	218.664*	130.456*	46.636*

*Indicates values calculated from fitted curve

3.1.4 BBR Creep Stiffness Results on RTFOT and PAV-Aged Blends

For the CG blend, lower temperatures and higher percent RAP binder increased creep stiffness (Figure 3.7). At the same time, the rate of increase of creep stiffness increased with lower temperatures and higher percent RAP (Table 3.7). Creep stiffness increased slowly at lower percentages of RAP binder, but increased much more rapidly at higher percentages of RAP. This is consistent with general trends observed with DSR results at high and intermediate temperatures.

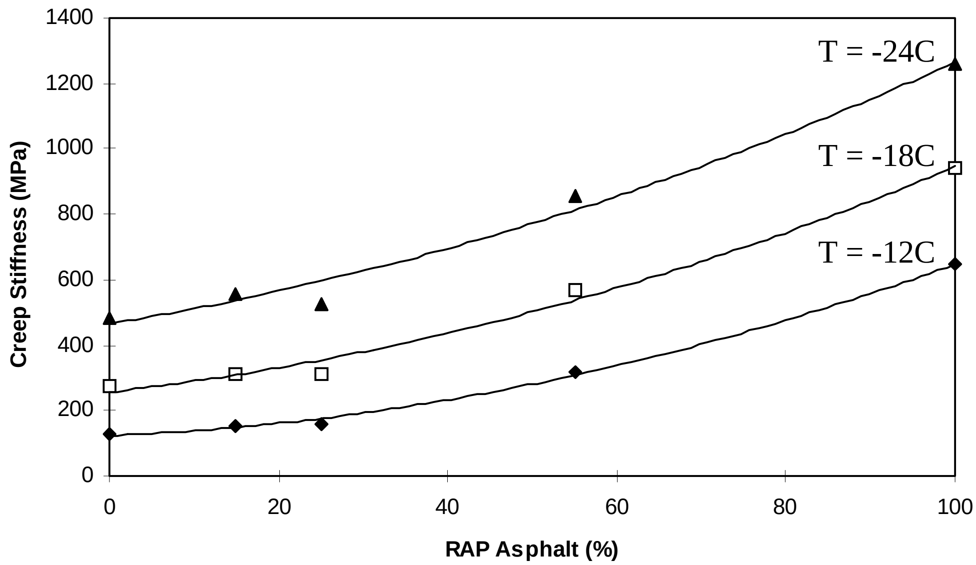

Figure 3.7 Creep stiffness trend for RTFOT and PAV-aged CG blend

Table 3.7 Rate of increase in creep stiffness for RTFOT and PAV-aged CG blend

Percent RAP Binder (%)	Rate of Increase in Creep Stiffness (kPa/%RAP)		
	-24°C	-18°C	-12°C
From 0–25%	1.637	1.677	1.319
From 75–100%	10.461*	9.586*	8.297*

*Indicates values calculated from fitted curve

For the CF blend, lower temperatures and higher percent RAP binder increased creep stiffness. Lower temperatures also showed a higher rate of increase in creep stiffness (Figure 3.8). However, the rate of increase of creep stiffness increases only slightly from 0–100% RAP binder. This indicates that the amount of RAP added in the blend had little effect on how quickly creep stiffness would increase (Table 3.8).

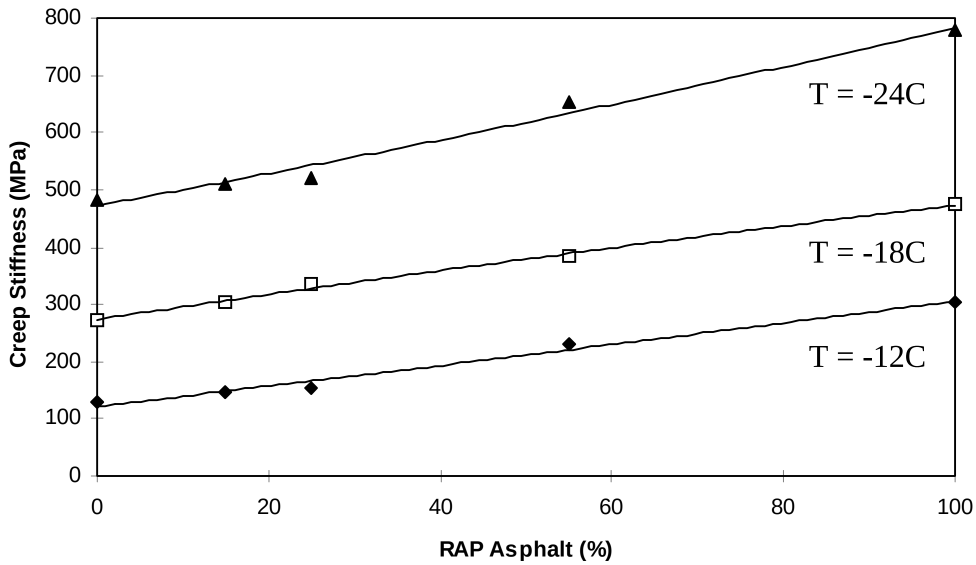

Figure 3.8 Creep stiffness trend for RTFOT and PAV-aged CF blend

Table 3.8 Rate of increase in creep stiffness for RTFOT and PAV-aged CF blend

Percent RAP Binder (%)	Rate of Increase in Creep Stiffness (kPa/%RAP)		
	-12°C	-18°C	-24°C
From 0–25%	0.982	2.555	1.459
From 75–100%	1.807*	1.868*	3.227*

*Indicates values calculated from fitted curve

3.1.5 BBR Creep Rate Results on RTFOT and PAV-Aged Blends

Lower temperature and higher percent RAP binder decrease the creep rate (Figure 3.9). However, the DG blend shows a fairly constant rate of decrease in creep rate regardless of temperature and percent RAP (Table 3.9).

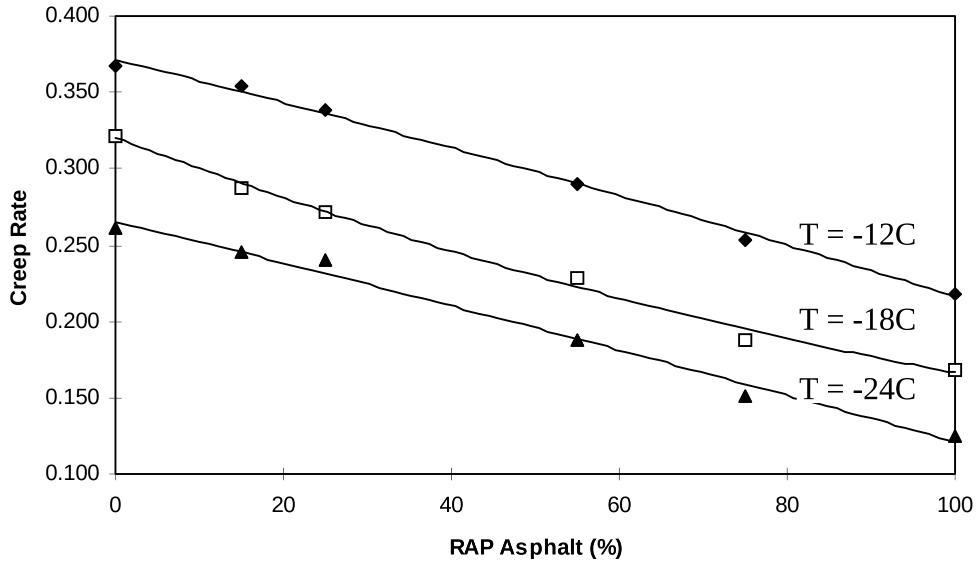

Figure 3.9 Creep rate trend for RTFOT and PAV-aged DG blend

Table 3.9 Rate of decrease in creep rate for RTFOT and PAV-aged DG blend

Percent RAP Binder (%)	Rate of Decrease in Creep Rate (kPa/%RAP)		
	-12°C	-18°C	-24°C
From 0–25%	0.001	0.002	0.001
From 75–100%	0.001	0.001	0.001

As expected, lower temperatures and higher percent RAP also lower the creep rate in the AF blend (Figure 3.10). The rate of decrease of creep rate is observed to be lower at higher percentages of RAP. However, the rate of decrease in creep rate is actually lower at higher percent RAP (Table 3.10). While the magnitude of this decrease is relatively small, it is important to note, as it is contrary to the other test results that show an increase in the rate of change of binder property as more RAP is added.

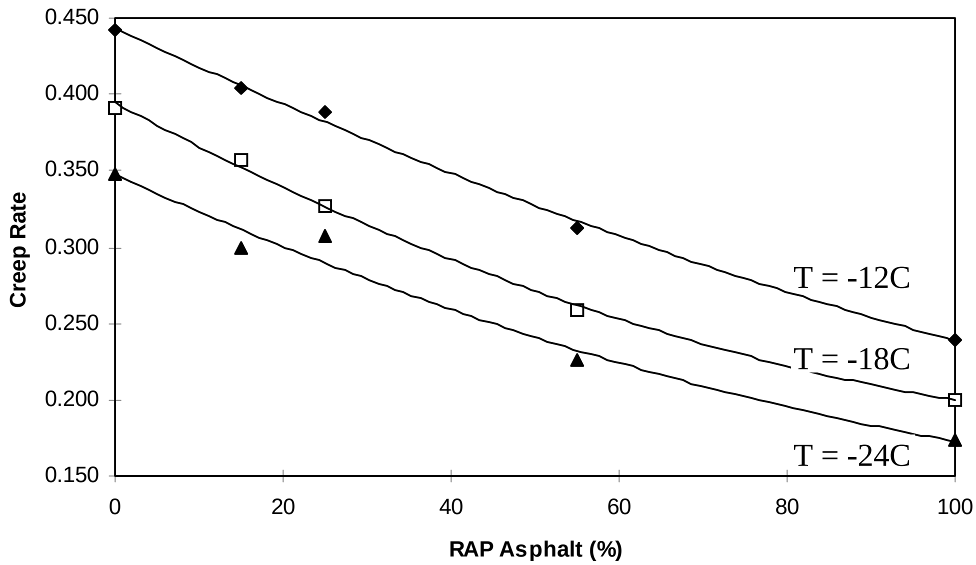

Figure 3.10 Creep rate trend for RTFOT and PAV-aged AF blend

Table 3.1 Rate of decrease in creep rate for RTFOT and PAV-aged AF blend

Percent RAP Binder (%)	Rate of Decrease in Creep Rate (kPa/%RAP)		
	-12°C	-18°C	-24°C
From 0–25%	0.002	0.003	0.002
From 75–100%	0.002*	0.001*	0.001*

*Indicates values calculated from fitted curve

3.2 PERFORMANCE GRADES OF ASPHALT BLENDS

It is important to study the behavior of an asphalt blend as RAP is added. On a more practical note, it is necessary to classify the various blends according to their performance grades. The performance grades of blends containing the aged West Texas Sour (AAF-1) and aged California Valley (AAG-1) are shown in Table 3.11 and Table 3.12, respectively. Note that some of the performance grades were determined by extrapolation from the test data.

Table 3.11 Performance grades of blends with Aged West Sour asphalt

PERCENT RAP BINDER (%)	AF	CF	MF
0	PG 46-34	PG 58-22	PG 64-16
15	PG 58-34	PG 58-22	PG 64-16
25	PG 58-34	PG 58-22	PG 70-16
55	PG 64-22	PG 70-16	PG 70-16
100	PG 76-10	PG 76-16	PG 76-10

Table 3.12 Performance grades of blends with aged California Valley asphalt

PERCENT RAP BINDER (%)	CG	DG	MG
0	PG 58-22	PG 58-28	PG 64-16
15	PG 58-22	PG 64-22	PG 70-16
25	PG 58-22	PG 64-22	PG 70-16
55	PG 70-16	PG 70-16	PG 70-16
100	PG 76-16	PG 76-16	PG 76-16

As expected, the resulting blend cannot have a better high-temperature or low-temperature grade than either one of its constituent binders. The data also indicate that the addition of 15% RAP binder to the virgin binder raises the high-temperature grade by two grades in the AF blend, one grade each in the DG and MG blends, and has no effect on the CF, CG, and MF blends. With the addition of another 10% RAP binder (for a total of 25% RAP binder), only the MF blend is raised by one additional grade over its grade at 15% RAP binder. At the low-temperature range, the addition of 15% RAP binder reduced the low-temperature grade of the DG blend by one grade while having no effect on the other five blends. With an additional 10% RAP binder (for a total of 25% RAP binder) there is no further drop in the low-temperature grade. These effects of adding 15% and 25% RAP binder are shown in Figure 3.11 and Figure 3.12, respectively.

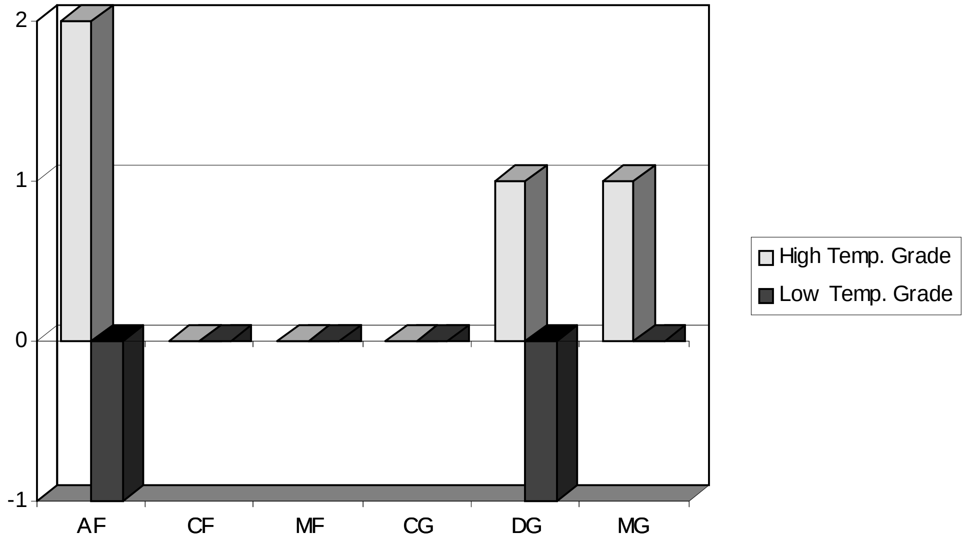

Figure 3.11 Changes in performance grade with 15% RAP added

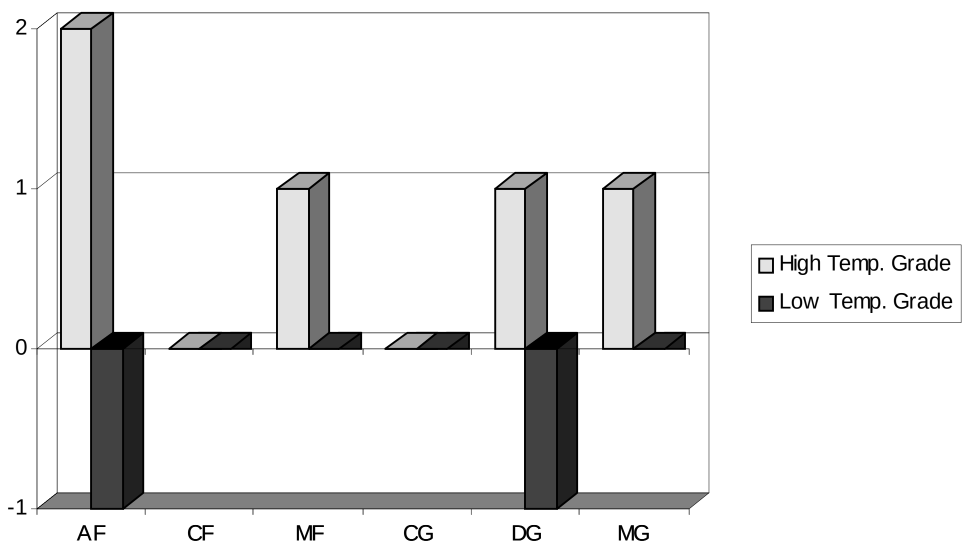

Figure 3.12 Changes in performance grade with 25% RAP added

While these changes in grade may prevent contractors from meeting agency specifications, it is important to examine the actual magnitude of change in the binder properties. For example, an RTFOT and PAV-aged virgin binder with a low-temperature stiffness of 299 MPa needs only a small amount RAP to push it over the maximum allowable limit of 300 MPa and into the next low-temperature grade. On the other hand, another RTFOT and PAV-aged virgin binder having a low-temperature stiffness of 100 MPa can be blended with a fairly large quantity of RAP, as it is 200 MPa below the maximum allowable limit. How near a virgin binder is to the allowable limits should be considered when trying to determine the effect of RAP. It would be too simplistic to look purely at the changes in grade.

CHAPTER 4. PRACTICAL APPLICATIONS

4.1 PROPOSED METHODOLOGY

The results from this research study can be used to determine how the binder grade is affected for different RAP binder contents, as well as the amount of RAP that can be used to satisfy a specific required binder grade.

In most practical cases, the required PG grading will be known. Superpave tests are recommended to be performed on the blend at four different blend percentages to determine the behavior of the blend. From this, the range of allowable RAP content is determined and a suitable percentage is chosen based on mix design criteria and engineering judgment. The following is an example for the proposed approach:

Consider a required binder grade of PG 64-22. It seems reasonable to use a virgin PG 58-28 when trying to achieve a performance grade of PG 64-22 when RAP is included in the mix. In this situation, binder tests would be run the same way as they would normally be run, except that four sets of tests will be conducted — one for each percentage of RAP considered. Figure 4.1 shows a plot of $G^*/sin\delta$ for the unaged blend at 64°C. The minimum allowable value for $G^*/sin\delta$ is 1 kPa. As such, no less than 10% of the blend can be RAP binder in order to meet the criteria. For the RTFOT-aged binder, there are no requirements as the virgin PG 58-28 binder already meets the minimum $G^*/sin\delta$ of 2.2 kPa. It would seem incorrect that this virgin asphalt is not graded at a PG 64-28, since the RTFOT-aged sample meets the required specifications at 64°C. However, it should be noted that this virgin asphalt was not graded as a PG 64-28 because the unaged sample did not meet specifications at 64°C. Thus, for this test, any RAP added to the blend will only increase the level of acceptance (Figure 4.2). From the high-temperature tests, we chose the more stringent of the two high-temperature criteria. The minimum amount of RAP binder that can be added is 10% of the total blend.

Now, we consider the low-temperature range. As shown in Figure 4.3, no more than 55% of the blend can be RAP, so that the maximum creep stiffness of 300 MPa is not exceeded. Similarly, Figure 4.4 shows that no more than 47% RAP can be used in order to meet the minimum creep rate of 0.300. Using the more stringent low-temperature criteria, we conclude that a maximum amount of RAP that can be used is 47% of the total blend.

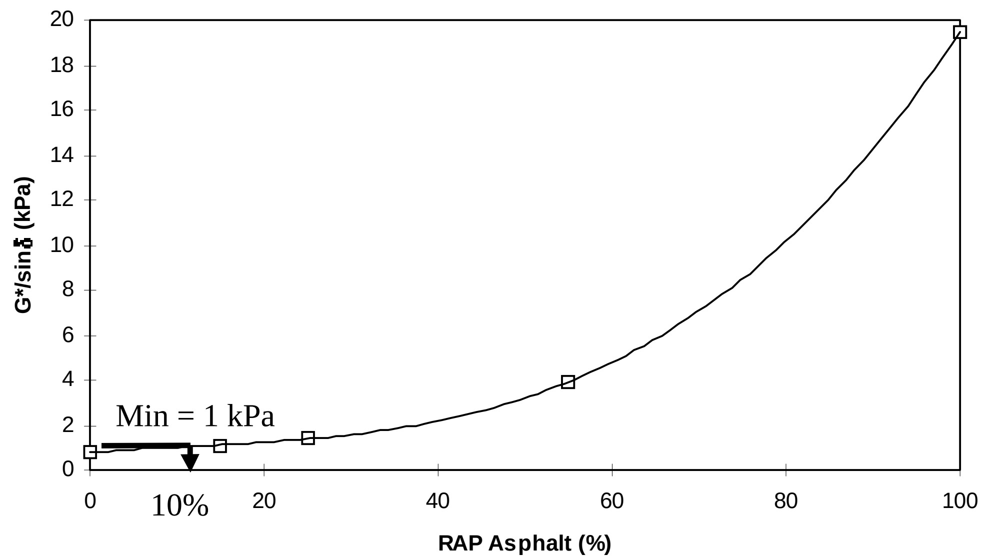

Figure 4.1 G*/sinδ *trend for unaged DG blend at 64°C*

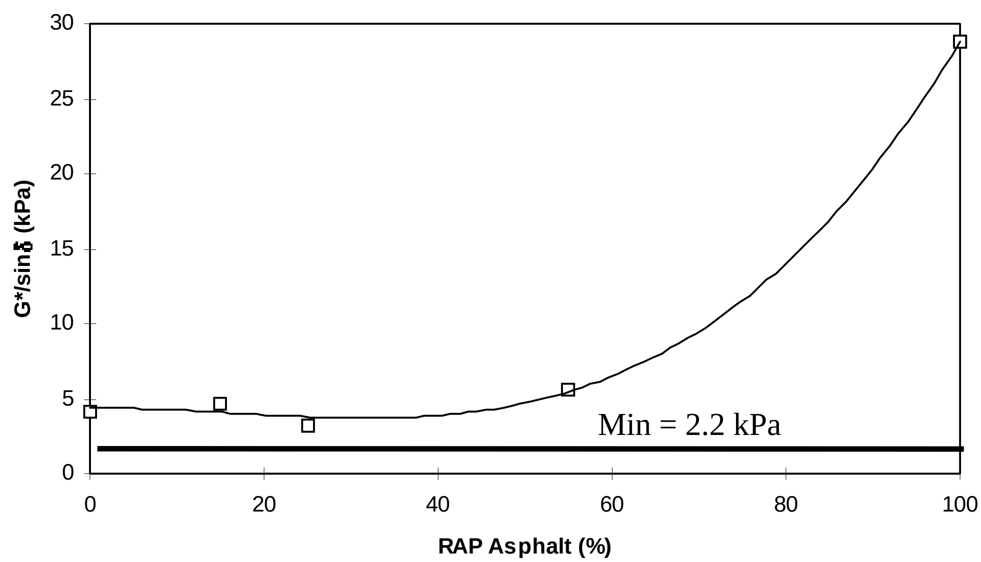

Figure 4.2 G*/sinδ *trend for RTFOT-aged DG blend at 64°C*

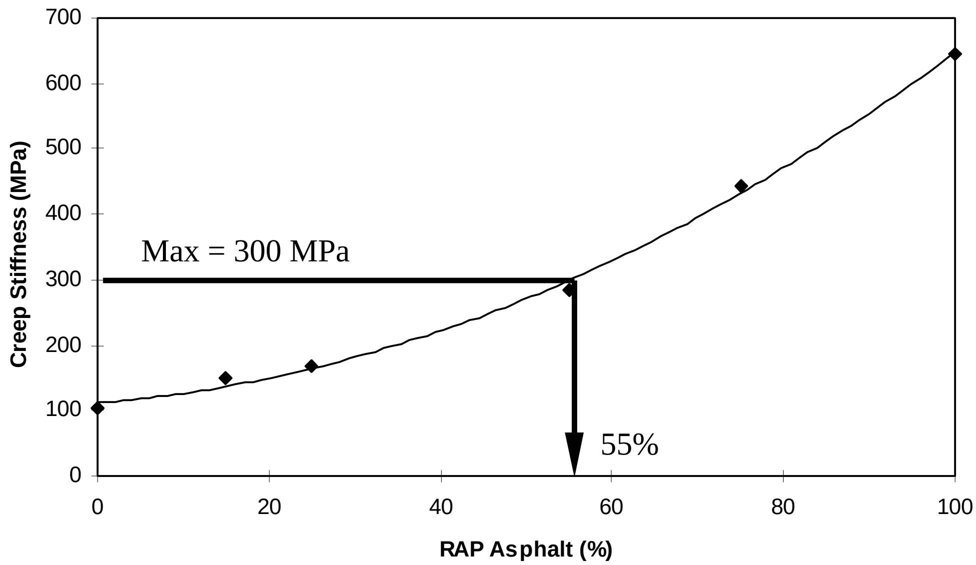

Figure 4.3 Creep stiffness trend for RTFO and PAV-aged DG blend at -12°C

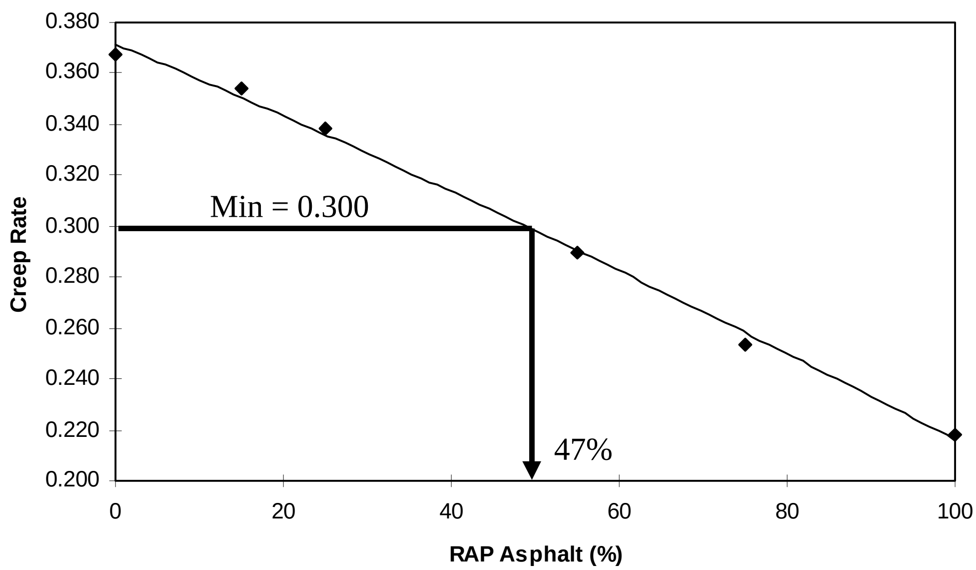

Figure 4.4 Creep rate trend for RTFO and PAV-aged DG blend at -12°C

Finally, the intermediate-temperature range must be considered to prevent fatigue cracking. The intermediate temperature chosen is 25°C, as the grade being considered is PG

64-22. As shown in Figure 4.5, no more than 47% RAP can be used to meet the maximum *G*sinδ* criteria of 5000 kPa.

Based on all these requirements, a blend having between 10–47% RAP would meet the Superpave specifications (Table 4.1).

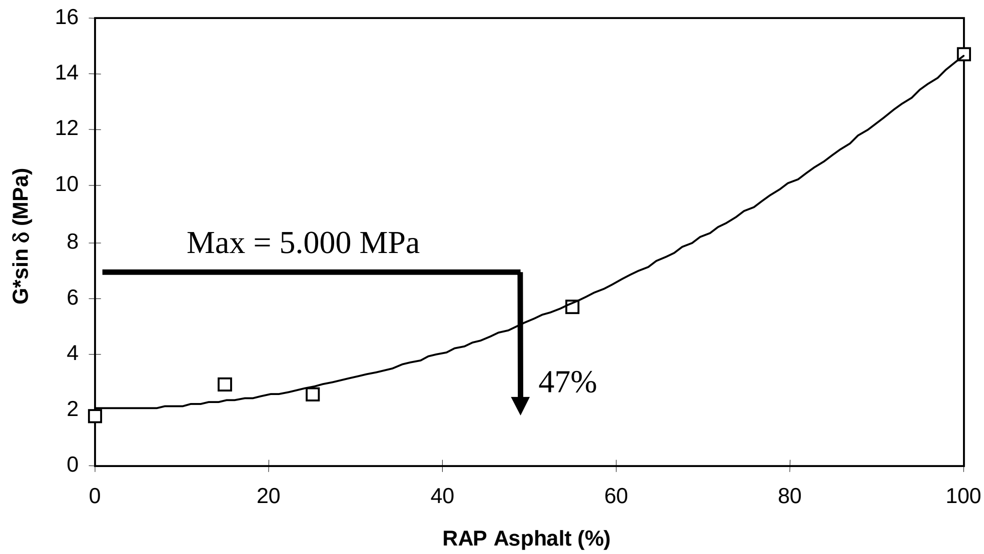

Figure 4.5 G*sinδ *trend for RTFO and PAV-aged DG blend at 25°C*

Table 4.1 Summary of DG blend requirements to meet PG 64-22 specifications

REQUIRED SUPERPAVE BINDER TESTS	LIMITS ON RAP TO MEET SPECIFICATIONS (%)
DSR (original) @ T = 64°C, G*/sinδ	> 10
DSR (RTFO) @ T = 64°C, G*/sinδ	no requirements
BBR (PAV) @ T = -12°C, Stiffness	< 47
BBR (PAV) @ T = -12°C, m	< 55
DSR (PAV) @ T = 25°C, G*sinδ	< 47
Satisfying All Criteria	10 < Required RAP (%) < 47

4.2 PRACTICAL EXAMPLE

In a practical situation, the amount of RAP used in a mix is specified on the basis of an aggregate stockpile blend percentage. In other words, the RAP is treated like an aggregate stockpile. Thus, a check needs to be made to ensure that the final percentage of RAP binder is within the acceptable range. Figure 4.6 shows the materials that would be incorporated in a mix with three aggregate stockpiles and one RAP stockpile.

The following example is used to illustrate this point. Assume that a project mix design requires 5% binder by mass of total mix and that the contractor proposes to use 20% RAP. In addition, the RAP stockpile is analyzed and is known to contain 4.5% aged asphalt. A breakdown of the individual RAP and virgin materials is shown in Figure 4.7.

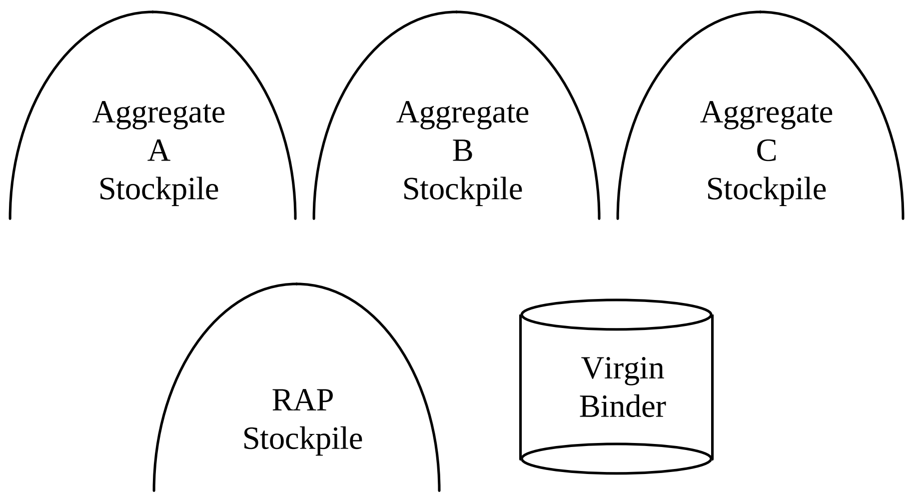

Figure 4.6 Component material in a mix containing RAP

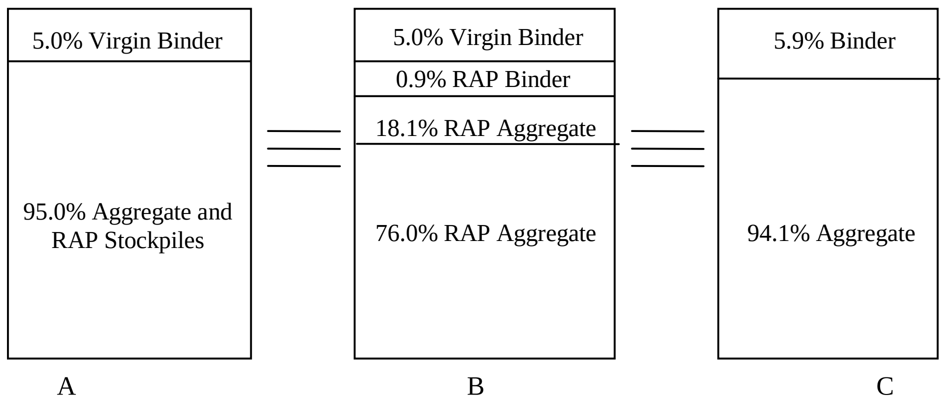

Figure 4.7 Schematic view of material components in the mix

Based on total mix percentages, 5% of the mix comes from the virgin binder and 95% of the mix comes from the aggregates and RAP stockpiles. This is shown in Figure 4.7a. With 20% RAP from the stockpiles, there is 19% RAP material in the total mix (i.e., 0.2 x 95% = 19%). Of this 19% RAP, 0.9% is RAP binder (i.e., 0.045 x 19% = 0.9%) and 18.1% is RAP aggregate (i.e., 0.955 x 19% = 18.1%). The remainder of the stockpile material, 76%, is comprised of virgin aggregates. This is shown in Figure 4.7b. Figure 4.7c shows the actual percentages (virgin and RAP combined) of binder and aggregate in the mix.

Therefore, the RAP binder would represent 14.6% of the total binder in the mix (i.e., 0.9/[5.0 + 0.9] x 100% = 14.6%). Based on the DG blend example presented earlier in this chapter, the 14.6% RAP binder determined in this mix example would fall within the 10% to 47% limits. Consequently, the contractor's goal of using 20% RAP as a stockpile blend percentage is reasonable from the standpoint of the desired PG grade. Obviously, a higher percentage of RAP could be accommodated with respect to the desired PG grade, but it is likely that other considerations would restrict the amount of RAP used.

In determining the amount of RAP to use, it is important to use engineering judgment. That the addition of RAP will increase the stiffness of the mix is an important consideration when incorporating RAP in asphalt mixes.

While this report has attempted to answer some of the binder-related questions regarding how to incorporate RAP, it is important to recognize that other factors are equally (if not more) important in determining how much RAP should be used. These factors include aggregate properties, volumetric properties, and mechanical properties.

CHAPTER 5. CONCLUSIONS

5.1 SUMMARY OF FINDINGS

It is obvious that there must be limits on percent RAP that can be incorporated into virgin material. Previous methods of combining virgin asphalts with RAP were useful in moving the industry forward in its use of RAP. However, a more comprehensive approach is needed to consider the high-, low- and intermediate-temperature conditions as specified by the Superpave system. This study and its analysis demonstrated a rational methodology for accommodating RAP binders in Superpave mixes. Specific conclusions drawn from this study include:

1. The stiffness of the binder is higher at higher percentages of RAP binder.
2. The rate of change of stiffness ($G^*/\sin\delta$, $G^*\sin\delta$, or creep stiffness) is either constant from 0–100% RAP binder or increases with lower temperatures.
3. The rate of change of stiffness is either constant from 0–100% RAP or increases at higher percentages of RAP in the blend.

It is important to recognize that the behavior resulting from blending a virgin binder and a RAP binder is highly dependent on the individual properties of the binders. As such, it is recommended that each blend of virgin and RAP binder must be considered individually in order to obtain an accurate picture of its behavior.

REFERENCES

1. "Recycling of Asphalt Pavements Using at Least 80 Percent Recycled Asphalt Pavement (RAP)," Engineering and Environmental Aspects of Recycled Materials for Highway Construction, Report No. FHWA-RD-93-088, Environmental Protection Agency and Federal Highway Administration, June 1993.
2. Flynn, L., "Three States OK More RAP in Recycling Specs: Asphalt Recycling and Reclaiming," *Roads and Bridges,* October 1992.
3. Solaimanian, M., and M. Tahmoressi, "Variability Analysis of Hot-Mixed Asphalt Concrete Containing High Percent Reclaimed Asphalt Pavements," Presented at the 75th annual meeting of Transportation Research Board, *Transportation Research Record, No. 1543,* National Research Council, Washington, D.C., January 1996, pp. 89-96.
4. Page, G. C., "Florida's Experience in Hot Mix Asphalt Recycling," *Hot Mix Asphalt Technology,* Spring 1988.
5. Page, G. C., and K. H. Murphy, "Hot-Mix Recycling Saves Florida DOT $38 Million," *Asphalt*, Vol. 1, No. 1, Spring 1987.
6. "Hot-Mix Recycling," *The Asphalt Handbook MS-4*, The Asphalt Institute, 1989.
7. Cominsky, R. J., G. A. Huber, T. W. Kennedy, and R. M. Anderson, "The Superpave Mix Design Manual for New Construction and Overlays," Strategic Highway Research Program, SHRP-A-407, 1994.
8. "Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP)," *Draft*, A discussion paper prepared for the FHWA Asphalt Mixture Expert Task Group, October 1996.
9. Kandhal, P. S., and K. Y. Foo, "Designing Recycled Hot-Mix Asphalt Mixtures Using Superpave Technology," Paper prepared for publication in ASTM STP 1322, 1997.
10. Ceccovilli, Renato, *Stiffness of Blended RAP and New Asphalts Experiment*, Research Study, The University of Texas at Austin, Fall 1996.
11. Cominsky, R. J., J. S. Moulthrop, W. E. Elmore, and T. W. Kennedy, "SHRP Materials Reference Library Asphalt Selection Process," Strategic Highway Research Program, SHRP-A/IR-89-002, August 1989.

APPENDIX A

EXPERIMENTAL TEST DATA

Percent RAP (%)	Original, G*/sin δ (Pa)			RTFOT-Aged, G*/sin δ (Pa)			PAV-Aged, G*sin δ (Pa)		
	58°C	64°C	70°C	58°C	64°C	70°C	19°C	25°C	31°C
0	528	258	142	1218	600	366	1037300	419200	167330
15	1206	600	313	3303	1554	878	2369000	1060200	430000
25	1183	624	308	2599	1336	649	2164500	974860	479340
55	3956	1933	888	12579	5722	3308	6176200	3015900	1474100
100	45600	17000	7520	80900	27700	18600	15400000	8580000	3020000

Figure A.1 High- and intermediate-temperature test data for AF blend

Percent RAP (%)	Creep Stiffness (MPa)			Creep Rate		
	-12°C	-18°C	-24°C	-12°C	-18°C	-24°C
0	27.486	76.006	164.206	0.441931	0.391230	0.348061
15	54.380	125.228	276.587	0.403535	0.357357	0.298777
25	58.248	143.547	246.771	0.388821	0.326384	0.307025
55	150.923	292.973	469.115	0.312890	0.259219	0.225457
100	303.225	474.056	779.884	0.239295	0.200328	0.173871

Figure A.2 Low-temperature test data for AF blend

Percent RAP (%)	Original, G*/sin δ (Pa)			RTFOT-Aged, G*/sin δ (Pa)			PAV-Aged, G*sin δ (Pa)		
	58°C	64°C	70°C	58°C	64°C	70°C	19°C	25°C	31°C
0	1052	459	215	2704	1131	506	4992900	2415400	1030700
15	1971	862	393	2550	1098	526	4586500	2355000	1048500
25	2024	906	452	5009	1984	892	5945800	2766600	1215800
55	7654	3133	1443	27687	9222	4022	9766500	5620800	2729000
100	45600	17000	7520	80900	27700	18600	15400000	8580000	3020000

Figure A.3 High- and intermediate-temperature test data for CF blend

Percent	Creep Stiffness (MPa)			Creep Rate		
RAP (%)	-12°C	-18°C	-24°C	-12°C	-18°C	-24°C
0	128.460	272.317	483.304	0.325358	0.279162	0.238222
15	146.480	303.691	511.635	0.332704	0.279609	0.221793
25	153.020	336.181	519.780	0.309721	0.272577	0.225015
55	231.415	383.795	651.750	0.267190	0.223186	0.194152
100	303.225	474.056	779.884	0.239295	0.200328	0.173871

Figure A.4 Low-temperature test data for CF blend

Percent	Original, G*/sin δ (Pa)			RTFOT-Aged, G*/sin δ (Pa)			PAV-Aged, G*sin δ (Pa)		
RAP (%)	58°C	64°C	70°C	58°C	64°C	70°C	19°C	25°C	31°C
0	1052	459	215	2704	1131	506	4992900	2415400	1030700
15	3387	1381	646	4195	1738	783	5380500	2579400	1109500
25	1631	691	325	2861	1221	541	6184700	3008400	1259500
55	8972	3727	1688	27163	11284	4962	11273000	6058900	2783200
100	49597	19490	7706	76831	28784	11480	19978000	14699000	8119900

Figure A.5 High- and intermediate-temperature test data for CG blend

Percent	Creep Stiffness (MPa)			Creep Rate		
RAP (%)	-12°C	-18°C	-24°C	-12°C	-18°C	-24°C
0	128.460	272.317	483.304	0.325358	0.279162	0.238222
15	151.152	311.453	555.096	0.329496	0.287838	0.231061
25	161.433	314.239	524.229	0.331543	0.272968	0.226151
55	318.612	567.427	856.812	0.291152	0.238614	0.176051
100	645.989	938.575	1256.367	0.218445	0.168188	0.125166

Figure A.6 Low-temperature test data for CG blend

Percent RAP (%)	Original, G*/sin δ (Pa)			RTFOT-Aged, G*/sin δ (Pa)			PAV-Aged, G*sin δ (Pa)		
	58°C	64°C	70°C	58°C	64°C	70°C	19°C	25°C	31°C
0	1672	787	413	8517	4200	2133	2428300	1757300	783900
15	2122	1103	560	10580	4705	2345	6381800	2916600	1243000
25	3122	1394	683	6845	3233	1599	5814800	2584500	1005700
55	10359	3923	1701	13600	5573	2458	10813000	5702200	2309800
100	49597	19490	7706	76831	28784	11480	19978000	14699000	8119900

Figure A.7 High- and Intermediate-Temperature Test Data for DG Blend

Percent RAP (%)	Creep Stiffness (MPa)			Creep Rate		
	-12°C	-18°C	-24°C	-12°C	-18°C	-24°C
0	103.818	241.316	453.159	0.367781	0.321256	0.261387
15	149.550	312.706	606.112	0.354250	0.287607	0.245208
25	166.800	339.194	602.208	0.338356	0.272147	0.239626
55	283.416	495.550	782.351	0.289928	0.228767	0.188327
100	645.989	938.575	1256.367	0.218445	0.168188	0.125166

Figure A.8 Low-temperature test data for DG blend

Percent RAP (%)	Original, G*/sin δ (Pa)			RTFOT-Aged, G*/sin δ (Pa)			PAV-Aged, G*sin δ (Pa)		
	58°C	64°C	70°C	58°C	64°C	70°C	19°C	25°C	31°C
0	2887	1360	718	5887	2734	1274	5314800	1897200	975310
15	4356	2203	1443	10132	4168	1889	5300300	2721100	1336000
25	7262	5000	1642	14786	6272	2790	5474500	3637200	1639700
55	21973	5585	3556	58125	23208	10982	10260000	4190100	3415500
100	45575	16984	7520	80943	27668	18591	15368000	8580300	3018900

Figure A.9 High- and intermediate-temperature test data for MF blend

Percent RAP (%)	Creep Stiffness (MPa)			Creep Rate		
	-12◦C	-18◦C	-24◦C	-12◦C	-18◦C	-24◦C
0	141.369	288.783	477.968	0.293683	0.258040	0.213155
15	161.531	297.498	493.568	0.268670	0.244188	0.214648
25	169.818	331.129	510.626	0.265329	0.236398	0.208998
55	228.644	372.731	569.040	0.240265	0.203276	0.186200
100	303.225	449.056	779.883	0.239295	0.200328	0.173871

Figure A.10 Low-temperature test data for MF blend

Percent RAP (%)	Original, G*/sind (Pa)			RTFOT-Aged, G*/sind (Pa)			PAV-Aged, G*sind (Pa)		
	58°C	64°C	70°C	58°C	64°C	70°C	19°C	25°C	31°C
0	2887	1360	718	5887	2734	1274	5314800	1897200	975310
15	10895	4701	2064	9529	4309	3245	5521000	3293200	1604700
25	9524	4063	1976	15172	7224	3153	7738600	4513100	2350600
55	13293	5339	2930	29779	11964	4952	9883600	6165500	3306400
100	49597	19490	7706	76831	28784	11480	19978000	14699000	8119900

Figure A.11 High- and intermediate-temperature test data for MG blend

Percent RAP (%)	Creep Stiffness (MPa)			Creep Rate		
	-12◦C	-18◦C	-24◦C	-12◦C	-18◦C	-24◦C
0	141.369	288.783	477.968	0.293683	0.258040	0.213155
15	178.044	321.015	536.213	0.286739	0.257222	0.215809
25	202.390	368.305	554.699	0.272077	0.228455	0.200361
55	308.255	412.813	710.185	0.260421	0.187148	0.182257
100	645.989	938.575	1256.367	0.218445	0.168188	0.125166

Figure A.12 Low-temperature test data for MG blend