Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement

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Abstract: Rejuvenator is not a commonly used softening agent to be used in recycling of reclaimed asphalt pavement (RAP). In this study, Superpave mixtures containing RAP were designed using rejuvenating agents, including a rejuvenator and a softer binder, and subsequently evaluated in terms of the volumetric results, obtained the indirect tensile strength (ITS) of samples as well as evaluating the mixtures for rutting using the asphalt pavement analyzer (APA). The content of the rejuvenator used for those mixtures containing the rejuvenator was determined from the blending charts of RAP binders containing the rejuvenator. A total of 12 Superpave mixtures including 10 containing RAP and two virgin were designed. The results indicated, for the mixtures tested for this project, that: (1) properties of the recycled mixtures using the rejuvenator, such as ITS and APA, were better than those containing the softer binder; (2) 10% more RAP could be incorporated in the Superpave mixtures by using the rejuvenator than using the softer binder; and (3) the blending charts established under the Superpave binder specifications can be used to determine the content of the rejuvenator for the recycling.

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CE Database subject headings: Recycling; Asphalt pavements; Asphalt mixes; Flexible pavements; Aging; Shear deformation.

Introduction

The use of reclaimed asphalt pavement (RAP) helps to conserve natural resources and land needed for disposal of these materials. Currently, according to the Federal Highway Administration (FHwA 1997) 80% of the RAP removed each year during resurface projects, approximately 73 million tons, is reused in the United States. Increasing the percentage of the RAP and improving the quality of recycled mixtures will facilitate the further utilization of the RAP.

For many years, research on the use of a high percentage of RAP in hot-mix asphalt (HMA) was reported using the recycling technologies developed decades ago (Noureldin and Wood 1988; AI 1981). With Superpave specifications being gradually adopted in the United States and RAP being used under this method, both binder grade and aggregate structure of recycled mixtures are to meet the proper specifications. For example, blending charts of RAP binders containing a rejuvenating agent have to be established within the specifications instead of the conventional penetration/viscosity system. RAPs are blended with virgin aggregates to obtain required aggregate structure and volumetric properties of the mixtures.

A procedure for determining the optimum RAP percentage for a Superpave mixture was proposed by considering the blend charts of RAP binders containing a softer binder (Kennedy et al. 1998). A similar study was reported on determining the content of a rejuvenator for recycling a RAP binder with Superpave binder specifications (Shen and Ohne 2002). Interim guidelines for selecting a grade of a neat binder for recycling RAP were prepared (Bukowski 1997). It was suggested that up to 15% RAP could be used in Superpave mixtures without changing the grade of the added virgin binder. For mixtures containing 25% RAP, blending charts of RAP binders containing a rejuvenating agent should be used for selecting the type and determining the content of softer binders/rejuvenators. The properties of coarser 12.5 mm Superpave mixtures containing RAP fractions, screened coarse, and fine materials, were investigated (Stroup-Gardiner and Wagner 1999). Little change was observed in tensile strength because of the addition of as much as 40 and 15% of the coarser and finer RAP fractions. However, substantial increase in mixture stiffness was observed when 15% of RAP was used, suggesting the need for a softer binder. Superpave mixtures containing RAP can perform well provided the mixtures are properly designed and constructed (McDaniel et al. 2002). Many of these researchers indicated the need for additional research on the utilization of rejuvenating agents for Superpave recycled mixtures.

In general, a rejuvenator is used to recover the properties of aged binders by reconstituting the chemical compositions of the aged binders. An asphalt binder that experiences aging of oxidization has a lower concentration of more reactive components [Nitrogen base (N)+first acidaffins (A1)] and higher concentration of less reactive components [Paraffines (P)+second acidaffins (A2)]. A rejuvenator used for restoring the aged asphalt binders usually has a minimum N/P ratio of 0.5 to insure the compatibility of the rejuvenator and the aged binder and to prevent syneresis. Rejuve-

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nators have to satisfy several the requirements for viscosity (60°C), flash point, volatility, compatibility, chemical composition, and specify gravity (ASTM 1980).

Research on the effectiveness of the rejuvenators on blended RAP binders and recycled mixtures has been conducted. The influence of the rejuvenators with different ranges of viscosity on the properties of reconstituted RAP binder was confirmed (Escobar and Davidson 1979). The effect of the rejuvenators on the structural performance of recycled asphalt mixtures was also investigated (Little et al. 1981). The structural layer coefficients used for pavement thickness design were found to be higher for the recycled mixtures than the control mixture, depending on the RAP content and source and the rejuvenator. Difference in performance, especially in cracking potential, was obtained for recycled mixtures using different RAP and rejuvenator. More recently, rejuvenator has been introduced in mixtures using a large percent of RAP and hot in-place recycling (Crawley 1999; Kazmierowski et al. 1999). The recycled mixtures containing 80% RAP were designed using a rejuvenator, 19% by weight of the binders in the RAP (Crawley 1999). Acceptable properties of the recycled mixtures were attainable. The effectiveness of the rejuvenators on rejuvenating the penetration was confirmed for the past 10 years in Canada (Kazmierowski et al. 1999). In Japan, a research on the properties of recycled mixtures using recycling agents with different components was conducted. The results indicated that the aged binders could be recovered to a target penetration by using different rejuvenating agents if adequate amount is added (Takahashi and Hachiya 2000). However, some states around the United States do not allow using any kind of rejuvenator for the mixtures to be recycled for many reasons including the negative effect on the rutting resistance of the mixtures and additional equipment needed to introduce the rejuvenator into the mix.

Objectives

1. To evaluate the properties of Superpave mixtures containing various RAP sources using a rejuvenator and compare to those of the recycled Superpave mixtures using a softer binder;
2. To investigate the possibility of using blending charts of aged binders and a rejuvenator for determining the rejuvenator contents for the design of Superpave mixtures containing RAP; and
3. To investigate the possibility of incorporating RAP in Superpave mixtures by evaluating the properties of virgin Superpave mixtures and Superpave mixtures containing RAP.

Scope

In this study, two typical South Carolina RAPs were incorporated in 9.5 mm Superpave mixtures with either a rejuvenator or a softer binder (for control samples) as a rejuvenating agent. The volumetric design, mechanical properties, moisture sensitivity and a selected performance properties of the HMA were obtained or calculated. Blending charts of extracted RAP binders containing the rejuvenator were established by dynamic shear rheometer (DSR) and bending beam rheometer (BBR) and implemented to determine the content of the rejuvenator by Superpave binder requirements. A total of 12 Superpave mixtures including ten recycled and two virgin mixtures were designed.

Materials and Test Program

Materials Used

Aggregates

Two types of aggregate (referred to as C and L) were selected to make virgin mixtures as control samples and mixtures containing RAP. Aggregate Source C is granite, while Source L is gneiss. The gradations and other properties of the two virgin aggregates are shown in Table 1.

RAPs containing identical Aggregate Sources C and L were selected. The RAP was sieved into two fractions as a normal practice, namely coarse fraction retained on Sieve No. 4 (4.75 mm, labeled as +#4) and fine fraction Passing Sieve No. 4 (labeled as −#4) (Table 2). The gradation and binder content of each fraction were obtained (Table 2). When RAP containing Source C was incorporated, recycled mixtures using a high percentage of the two fractions could not meet the Superpave volumetric requirements, therefore, fraction particles retained on No. 8 (2.36 mm labeled as +#8) were incorporated.

Asphalt Binders

The grade of all binders in various mixtures was expected to have a final grade of PG64-22. A neat PG64-22 binder was selected for the control virgin mixtures, whereas neat PG52-28 binder was

Table 1. Gradation and Properties of Virgin Aggregates

	Virgin Aggregate C			Virgin Aggregate L		
Measurement	#789	MS	RS	#789	MS[a]	RS[b]
12.5 mm	100	100	100	100	100	100
9.5 mm	81.5	90	100	90	100	100
4.75 mm	22.9	35	99.8	35	99.8	99.4
2.36 mm	4.3	6.3	96	6.3	96	82.5
0.6 mm	1.5	1.4	60.5	1.4	60.6	47.2
0.15 mm	0.9	0.7	22.3	0.7	22.3	7.6
0.075 mm	0.6	0.44	12	0.44	12	2.3
LA abrasion loss (%)		31			51	
Absorption (%)		0.3			0.5	
Bulk specific gravity (SSD)		2.62			2.67	
Sand equivalent		96			65	

[a]MS=manufactured screenings.

[b]RS=regular screenings.

Table 2. Gradation (% Passing) and Binder Contents (%) of Two RAP Sources

	RAP with Aggregate C			RAP with Aggregate L	
Measurement	+#4	−#4	+#8	+#4	−#4
12.5 mm	100	100	100	100	100
9.5 mm	100	84	88	97	100
4.75 mm	100	43	57	59	100
2.36 mm	90	33	38	45	88
0.6 mm	56	21	24	30	57
0.15 mm	16	9	10	14	24
0.075 mm	8	5.4	6	8	14
Binder content (%)	4.46	5.66	4.66	4.66	6.94

Table 3. Critical Temperatures of RAP Binders and Possible Percentage of the RAP Using a Softer Binder

	RAP containing Aggregate C		RAP containing Aggregate L	
Temperature	T_c (°C)	Percentage	T_c (°C)	Percentage
High	98.3	>16.8	93.5	>16.9
Intermediate	29.6	<66.1	30.6	<61.6
Low	−3.9	<42.9	−3.9	<42.9

used as the softer binder as recommended by the South Carolina Department of Transportation (SCDOT 2004). Both the virgin binders were obtained from the same source.

RAP binders used for obtaining the critical temperatures and for blending charts were extracted from the two RAPs. The critical temperatures (T_c) of the RAP binders obtained from DSR and BBR tests are shown in Table 3.

Rejuvenator

One oil type of rejuvenator available commercially in the United States was selected for this study. The properties of the rejuvenator are listed in Table 4. The content of the rejuvenator (%) needed for rejuvenating the RAP binder to PG 64-22 was determined on the blending charts established by DSR and BBR.

When using RAP, there has long been a question regarding to what extent the RAP binder blends with the virgin binder/rejuvenator to achieve a target PG grade. To answer this question, three situations of the RAP, i.e., black rock, total blending and real world were proposed. Black rock is the idea that there is absolutely no mixing between the RAP binder and virgin binder/rejuvenator, whereas total blending is assumed that the two binders completely and uniformly mix. The research indicated that the real-world results more closely match the total-blending, depending upon the amount of RAP. Based on this finding, the total amount of the rejuvenator needed in the mixtures was obtained by multiplying the amount of the RAP binder contained in RAP with the %rejuvenator.

Percentage of RAP

The possible percentage of RAP incorporated was carefully determined so that both Superpave binder and mixture specifications could be met. The percentage of RAPs, 17–43%, was initially calculated using Eq. (1) below (McDaniel and Anderson 2001) (Table 3):

$$\%\text{RAP} = (T_{\text{blend}} - T_{\text{virgin}})/(T_{\text{RAP}} - T_{\text{virgin}}) \qquad (1)$$

where T_{virgin}=critical temperature of virgin binder (PG58-22, in this study); T_{blend}=critical temperature of blend binder (PG64-22, in this study); T_{RAP}=critical temperature of extracted RAP binder (Table 3); and %RAP=percentage of RAP expressed as a decimal (i.e., 0.30 for 30%).

When the softer binder was used as a rejuvenating agent, the maximum percentages of 38 and 30% were determined to be satisfying the volumetric requirements and the combined gradation requirements for the two RAP sources containing Aggregate Sources C and L, respectively. This process of determining the RAP percentage was completed by adjusting the percentages of the two fractions of the RAPs into designated aggregate structure and satisfying the volumetric parameters. When the rejuvenator was used, 10% more (48 and 40%) of RAPs with Aggregate Sources C and L were incorporated, respectively (Table 5).

Table 4. Properties of the Rejuvenator Used

Properties	Ranges
Specific gravity (15.6/15.6C)	0.98–1.02
Viscosity, 60C CST	200–500
Flash Point, COC (°C)	204 minimum
RTFO-C 163°C [weight loss (%)]	4.0 maximum
RTF-C (viscosity ratio)	2.5 maximum
Compatibility (PC/S ratio)	0.5 minimum
Saturates (w%)	28 maximum
Chemical compatibility	0.2–1.2

Table 5. Various Superpave Mixtures Used in the Study

Code[a]	Aggregate	Binder	RAP (%)
CV0	C	PG 64-22	0
CV15	C	PG 52-28	15
CR15	C	Rejuvenator, PG 64-22	15
CV38	C	PG 52-28	38
CR38	C	Rejuvenator, PG 64-22	38
CR48	C	Rejuvenator, PG 64-22	48
LV0	L	PG 64-22	0
LV15	L	PG 52-28	15
LR15	L	Rejuvenator, PG 64-22	15
LV30	L	PG 52-28	30
LR30	L	Rejuvenator, PG 64-22	30

[a]First letter=aggregate source; second letter=type of rejuvenating agents; V=virgin binder; R=rejuvenator; and numbers=percentage of RAP incorporated in each mixture.

Test Program

Fig. 1 shows the experimental design used in this study. Table 5 shows the combination of all Superpave mixture designs.

Critical Temperatures and Blending Charts–DSR and BBR Tests

Extraction and recovery tests of the RAP binders were performed according to ASTM D 2172-81 (centrifuge extraction with rotavapor recovery) and ASTM D 1856-95a [recovery of asphalt cement (Abson method)] procedures. Samples were prepared in accordance with ASTM Method D 979 (sampling bituminous paving mixtrure). The properties of the RAP binders were obtained by DSR and BBR on samples of the extracted RAP binders in three stages: aged binder (no further aging), RTFO residual, and RTFO+PAV residual.

Conventional blending chart is established with the viscosity/penetration as ordinate and the percentage of a rejuvenator as abscissa for selecting the type and the content of the rejuvenating agent. This chart uses only two percentages of the rejuvenating agent: 0 and 100% of the rejuvenating agent with the relationship showing the viscosity/penetration and the percentage being assumed to be linear (Kandhal and Foo 1997). In the research project presented in this paper, blending charts were established with performance properties at high temperature (64°C), intermediate temperature (25°C) and low temperature (−12°C) as ordinates and the percentage of the rejuvenator as abscises. Three

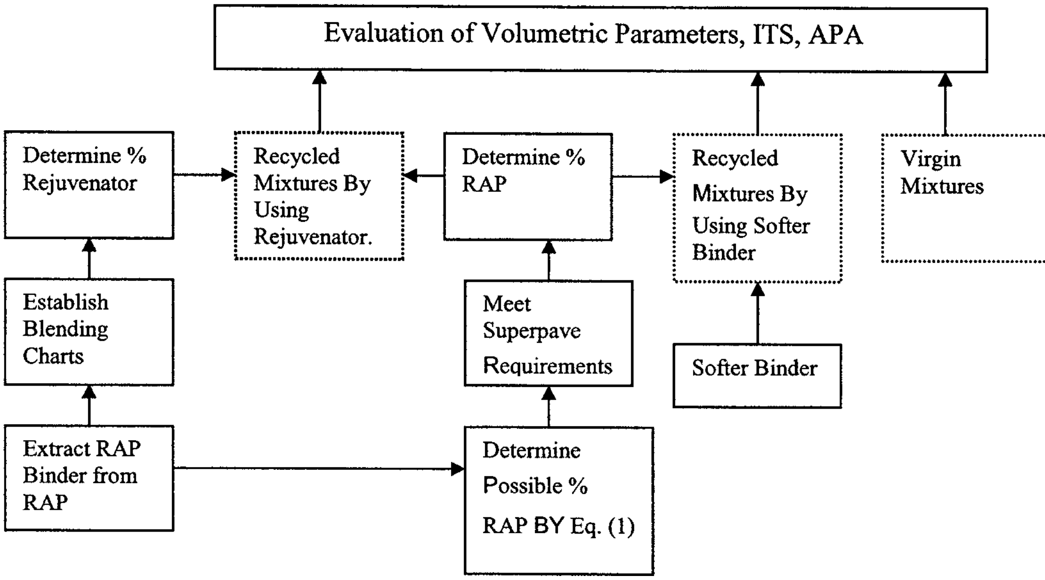


Fig. 1. Experimental design

percentages of the rejuvenator were added into the RAP binders so that linear regression equations could be obtained (Shen and Ohne 2002; Kennedy et al. 1998).

Volumetric Parameters—Superpave Mixture Design
Volumetric parameters of all mixtures were obtained using Superpave mixture design. A gyration of 75 was used by assuming a traffic volume of 3 million ESALs for these mixtures. One aggregate structure was finally adopted among three trials for 9.5 mm Superpave mixtures. This aggregate structure was obtained for virgin aggregates, but used for all mixtures. The use of an identical aggregate structure for all mixtures was to eliminate the influence of the aggregate structure on the properties of the mixtures. It is important to note that the final percentage of the RAP incorporated was adjusted in this stage so that all Superpave specifications were satisfied.

Performance Properties—Rutting Resistance (APA Test)
It is well known that pavement rutting is caused mostly by the shear flow of HMA mixtures under high temperatures by repeated traffic loading. This shear flow largely depends on the properties of the aggregate and the asphalt binder. This issue is one of the main concerns when utilizing RAP in mixtures containing a rejuvenator.

The asphalt pavement analyzer (APA), one of the methods to identify the rutting resistance of an asphalt mixture, has been adopted in some agencies for evaluating the rutting resistance properties of Superpave mixtures (Kandhal and Cooley 2002; Kandhal and Cooley 2003; Zhang et al. 2002; Martin and Parks 2003). The APA test was used in this study and carried out on cylinder samples with air void contents of 4.0±0.5%, height of 75 mm, a test temperature of 64°C, and a hose pressure of 690 kPa. The rut depth was recorded automatically after 8,000 cycles.

Mechanical Properties—Indirect Tensile Strength
The mixtures susceptibility of all mixtures were evaluated by obtaining the indirect tensile strength (ITS) of samples and calculating the tensile strength ratio (TSR) of various mixtures. For this test, two sets of three samples each after being cured under different specified conditions were tested by following the SC-T-70 testing procedures.

Results and Discussions

Rejuvenator Content

The content of the rejuvenator needed for RAP Binder Source C to reach a target grade of PG64-22 was calculated with the blending charts established in the following steps (Shen and Ohne 2002). First, a maximum allowable content was determined by satisfying the rutting parameter, $G^*/\sin(\delta)$, of the blends in the original state (no aging) and after RTFO. Figs. 2 and 3 show the $G^*/\sin(\delta)$ obtained from the blends of RAP binders containing the rejuvenator in original state and after RTFO aging at 64°C; respectively. Overall, good linear correlations between the rejuvenator content and $G^*/\sin(\delta)$ were obtained for the three blends as reported before (Shen and Ohne 2002). These linear regression equations/lines were then used for the determination of the con-

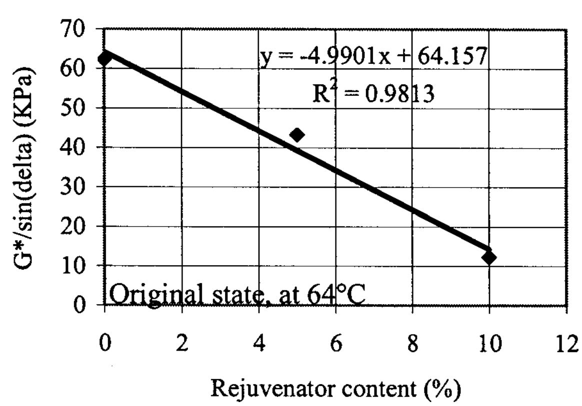


Fig. 2. $G^*/\sin(\delta)$ versus rejuvenator content at 64°C (original state)

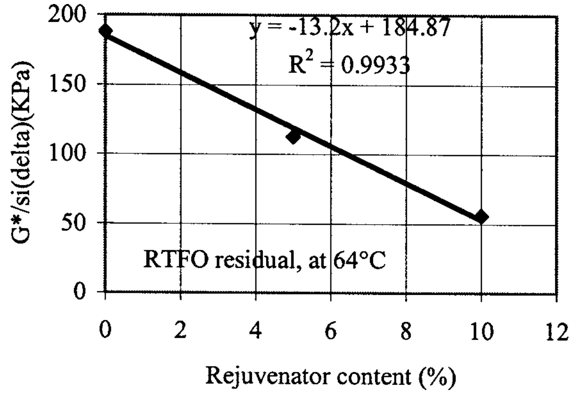


Fig. 3. $G^*/\sin(\delta)$ versus rejuvenator content at 64°C (RTFO residual)

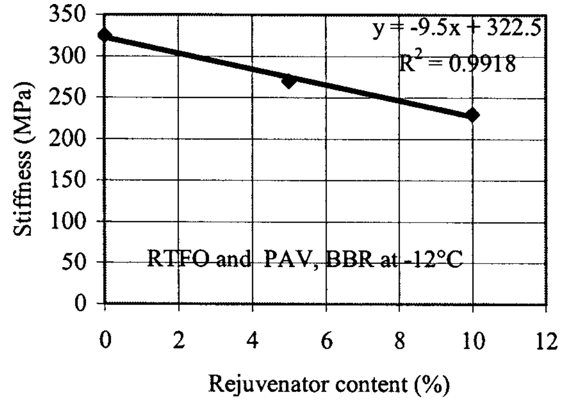


Fig. 5. Stiffness versus rejuvenator content at −12°C (RTFO +PAV residual)

tents with which the $G^*/\sin(\delta)$ reaches 1.0 and 2.2 kPa for the blends in the original state (no aging) and after RTFO, respectively. These contents of 12.7 and 13.5% were obtained by extrapolating the lines or algebraically using the equations for no aging and RTFO aging cases; respectively.

Second, a minimum allowable content was determined by satisfying the fatigue and the shrinkage parameters, i.e., $G^*\sin(\delta)$, stiffness and m-value, of the blends after RTFO+PAV aging. $G^*\sin(\delta)$ that was obtained at the intermediate temperature of 25°C was also linearly correlated with the content of the rejuvenator (Shen and Ohne 2002). A minimum rejuvenator content of 12.3% was obtained by extrapolating the regression line with the $G^*\sin(\delta)$ value being less than 5.0 MPa (Fig. 4). Similarly, the m-value and stiffness obtained at low temperature of −12°C were correlated linearly with the contents (Figs. 5 and 6). A minimum rejuvenator content of 10.8 and 2.9% were obtained by extrapolating the regression lines with the stiffness value being less than 300 MPa and the m value being larger than 0.3, respectively. As a result, the minimum rejuvenator content satisfying the fatigue and the shrinkage parameters was found to be 12.3%.

Finally, a mean value of the common contents, 12.5%, with which all requirements were satisfied (AI 2001), was used as a design value in this study (Table 6). This content is approximately 2-3% of the weight of the mixtures containing 30–50% of RAP. This is a reasonable and practical value for this rejuvenator according to the manufacturer.

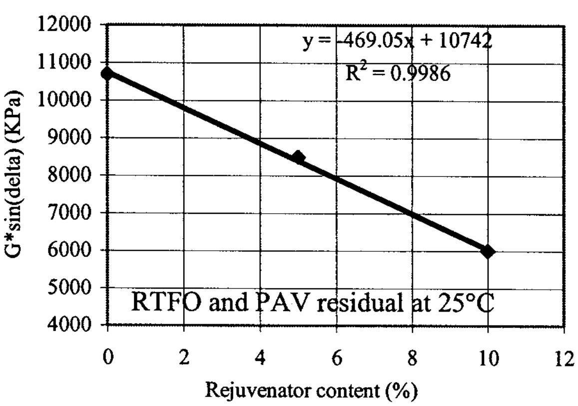


Fig. 4. $G^*/\sin(\delta)$ versus rejuvenator content at 25°C (RTFO+PAV residual)

Volumetric Results

Results of the 12 Superpave mix designs are shown in Table 7. The average optimum binder content of Superpave mixtures containing RAPs using the rejuvenator was lower than that of those using the softer binder regardless of the sources of the RAP sources (i.e., C or L). Generally, the optimum binder content of the Superpave mixtures containing RAPs decreased slightly with the increased content of the RAP, but no clear relationship between the optimum binder content and the content of the RAP was found, Fig. 7. In addition, optimum binder content of virgin mixtures was higher than that of all recycled mixtures.

The change in the optimum binder content may be caused by the difference in the viscosity of the binders in the mixtures. The amount of the rejuvenating agents (rejuvenator or softer binder) was obtained based on the estimated weight of the RAP binders

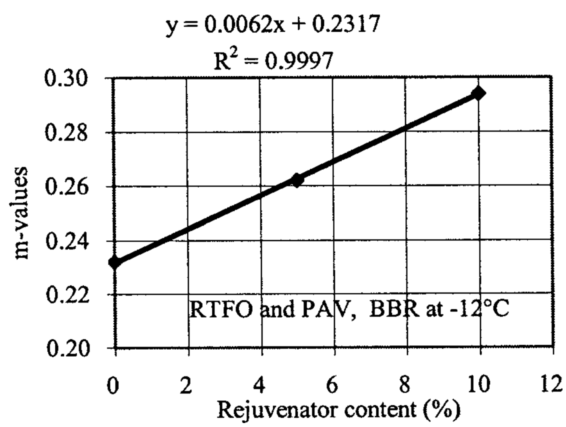


Fig. 6. m values versus rejuvenator content at −12°C (RTFO +PAV residual)

Table 6. Rejuvenator Content (%) from Blending Charts for PG64-22

SHRP binders requirements	Rejuvenator
$G^*/\sin(\delta) > 1.00$ kPa, T=64°C, DSR (original)	<12.7
$G^*/\sin(\delta) > 2.20$ kPa, T=64°C, DSR (RTFO)	<13.5
$G^*\sin(\delta) < 5.00$ MPa, T=25°C, DSR (RTFO PAV)	>12.3
Stiffness < 300 MPa, T=−12°C, BBR (RTFO PAV)	>10.8
$m > 0.30$, T=−12°C, BBR (RTFO PAV)	>2.9
Common contents (%)	12.3–12.7

Table 7. Results of 9.5 mm Superpave Mixtures

Specification		Type of Superpave mixture											
		RAP source containing Aggregate C						RAP source containing Aggregate L					
Sieve	Limit	CV0	CV15	CR15	CV38	CR38	CR48	LV0	LV15	LR15	LV30	LR30	LR40
12.5 mm	98–100	100	100	100	100	100	98	100	100	100	100	100	100
9.5 mm	90–100	91	90	90	90	90	88	95	94.2	94.2	94	94	95
4.75 mm	54–70	61	58	58	59	59	58	53	62.7	62.7	57	57	61
2.36 mm	32–48	42	41	41	40	40	39	32	42	42	35	35	40
0.6 mm	14–26	21	21	21	21	21	21	18	24.7	24.7	21	21	25
0.15 mm	13–5	8.4	7.8	7.8	8.1	8.1	8.7	5.7	8.3	8.3	9.3	9.3	10.6
0.075 mm	9–3	4.95	4.4	4.4	4.62	4.62	5.11	5.02	4.5	4.5	5.5	5.5	5.9
Aggregate blend		% Passing						% Passing					
Stone 789		50	49.2	49.15	31.4	31.4	25	69	52.9	52.85	59.3	59.3	50
Regular screenings		18	10	10	5	5	4	25	12	12	10	10	4
Manufactured screenings		31	25	25	25	25	20	5	19	19	0	0	5
Lime		1	0.85	0.85	0.6	0.6	1	1	0.85	0.85	0.7	0.7	1
−4RAP		0	9	9	0	0	0	0	9	9	18	18	24
+4RAP		0	6	6	0	0	0	0	6	6	12	12	16
+8RAP		0	0	0	38	38	48	69	52.9	52.85	59.3	59.3	50
Test results													
%Max density at N_{des}	96	95.5	95.9	96	95.8	96	96	94.9	95.9	96	95.8	96	96
%VMA	15.5–17.5	16.2	15.8	15.62	15.52	15.55	15.52	16.6	15.8	15.85	15.52	15.58	15.65
%VFA	70–80	72.5	76.1	75	71.9	72	74.5	76.2	76.1	74.5	71.9	70	72
%Max density at N_{ini}	⇐89	88	88.4	88	88.5	88.3	88.2	87	88.4	89	88.5	88.3	87.8
%Max density at N_{max}	⇐98	96.5	97.1	96.5	96.9	97.2	97.3	96.1	97.1	97	96.9	97.4	97
Dust-to-asphalt ratio	0.6–1.2	0.95	0.83	0.89	0.94	0.92	1.05	0.91	0.83	0.9	0.94	1.13	1.18
Optimum binder content (%)		5.02	5.3	4.93	5.05	5.01	4.87	5.5	5.4	5.09	4.9	4.8	4.85

Note: C=Aggregate Source C; V=virgin binder; R=rejuvenator; L=Aggregate Source L; and 0, 15, 38, and 48=percent of RAP incorporated in each mixture.

using the binder content in each RAP source. Considering the Black Stone effect of some RAPs in the mixtures, the amount of the rejuvenating agents added may overdose, leading to a smaller viscosity than expected. The volumetric properties of HMA is closely related with the content and viscosity of the binder for a given compaction condition. In general, a lower viscosity and higher binder content will make the compaction easier to accomplish. Therefore, to get the same air void content (i.e., 4%), less asphalt content is needed for a lower viscosity binder.

Percent voids in the mineral aggregate (%VMA) of the mixtures, as shown in Fig. 8, were greater than 15.5%, a value required by the Superpave specifications. The values of %VMA of the Superpave mixtures containing RAPs with the rejuvenator were less than those using the softer binder regardless of the sources of the RAP. The virgin mixtures had a higher %VMA than the recycled mixtures using either rejuvenator or the softer binder. In general, the %VMA decreased with the increase of the rejuvenator content in mixes made with aggregate C and containing RAP Source C. The percent voids filled with asphalt (%VFA) and dust asphalt ratio of all the mixtures satisfy the requirements of Superpave mix specifications (Table 7).

ITS and TSR Results

Fig. 9 shows the ITS average values of three samples of the mixtures incorporating Aggregate Sources C and L in wet and dry states. Generally, it is shown that all of the Superpave mixtures have higher wet ITS values than the standard of 0.46 MPa (65 psi) required by the SCDOT, regardless of the aggregate source, the rejuvenating agent, and the curing state. The mixtures containing the rejuvenator agent produced higher strengths than those containing the softer binder. Furthermore, the mixtures containing RAP, in general, had higher ITS values than the corresponding virgin mixture of the same aggregate source. The mixture made with 10% more RAP Source L and containing the rejuvenator still had higher strength than required by SCDOT's specifications. This trend was also true for mixtures containing Aggregate Source C. This indicated that the mixtures containing the rejuvenator produced ITS results as good as or even better than the mixes made with the softer binder. There was no apparent relationship between the percentage of the RAP incorporated in the mixtures and the ITS values. In addition, some mixtures produced higher ITS values in wet state than in dry state, especially for Aggregate Source C. This phenomenon was occasionally observed in experiments for the mixtures using hydrophobic aggregates. However, the curing of the recycled mixtures under hot water may improve the interaction of the RAP aggregate with the binders.

The percent tensile strength ratio (%TSR), defined by the ITS strength in the wet state divided by that in the dry state, are higher than the standard of 85% required by the SCDOT (Fig. 10) for all mixtures. For Aggregate Source C, the ratios ranged from 95.7%, the lowest for the virgin mixture and as high as 141% for the mixture containing 15% RAP. For Aggregate Source L, the range of TSR ratio was from 83.3%, for the mixture containing 30%

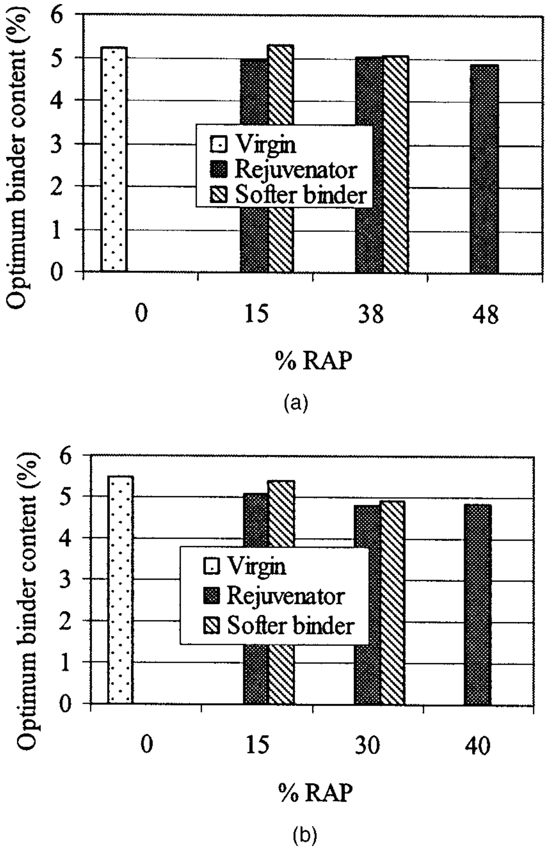


Fig. 7. Optimum binder content of the Superpave mixtures containing RAPs for aggregate sources: (a) C; (b) L

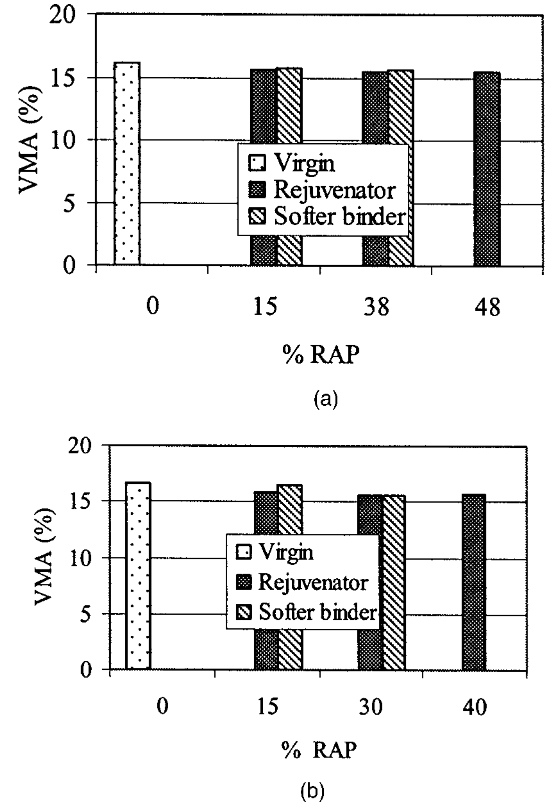


Fig. 8. %VMA of the Superpave mixtures containing RAP sources: (a) C; (b) L

RAP, to 118%, for the control mixture. The data indicated that the mixtures containing RAP, in general, have better antistripping properties than the virgin mixtures regardless of the aggregate type.

Based on the results, it was concluded that the mixtures containing RAP have the same potential as the control virgin mixtures to provide a bearing strength and having the same type of moisture susceptibility as the virgin mixtures. Test samples containing RAP did not exhibit visual signs of stripping even for the mixtures containing the highest percent of RAP (40 and 48%) for Aggregates L and C; respectively.

Rut Depth Results

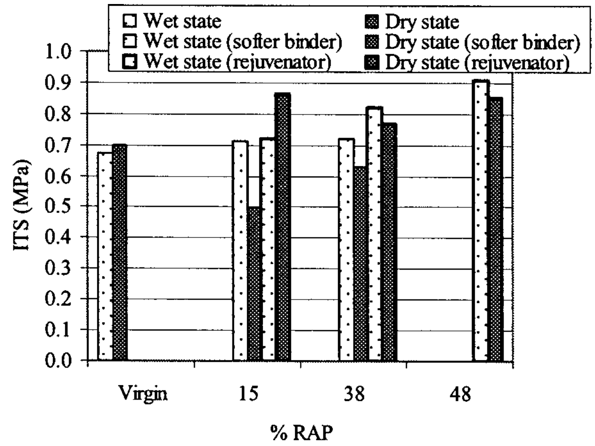
Fig. 11 shows the rut average depths from six replicate samples of various mixtures containing different %RAP contents. Kandhal and Cooley (2003) suggested tentative acceptance criteria for mixtures after 8,000 cycles using either automatic or manual measurements. For a 4% air void sample designed for the traffic level of 3 million EASLs, the acceptable rut depth is 8.0 mm for automatic measurements. In general, the rut depths of all the mixtures were less than this value. In addition, most of the rut depths of the mixtures containing Source C RAP are less than that of the virgin mixture. Even for the mixture containing 38% of the RAP with softer binder, the maximum rut depth observed was still much less than the virgin mixture. The rut depths of the mixtures containing the rejuvenator are much less than those mixtures made with softer binder. It was also found that when a lower RAP percentage (i.e., 15%) was used, the difference between the rut depths of the mixtures containing RAP with a rejuvenator and with a softer binder was less than the mixtures made with a higher RAP percentage (e.g., 38%).

The control mixtures containing Aggregate Source L showed a very small rut depth value. For mixtures containing 15% RAP, less difference was observed in rut depth of specimens made with a rejuvenator compared to that of a softer binder. Whereas, when a high percent of 30% RAP was used, the rut depth of the recycled mixtures using the softer binder was higher than those using the rejuvenator. However, all of the rut depths were smaller than the tentative criteria value. When 40% RAP was used, the rut depth values of the recycled mixtures with rejuvenator were still acceptable.

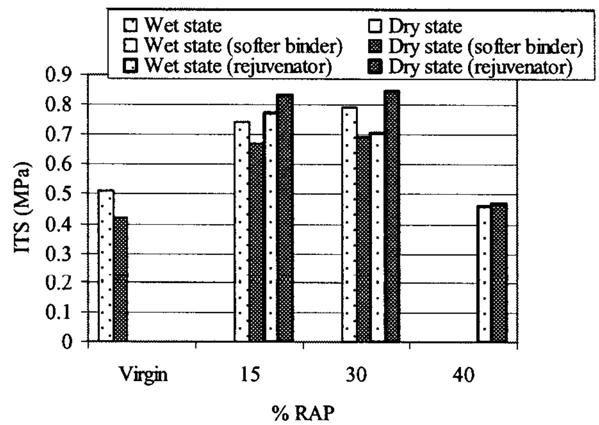
The rut depths of the mixtures using rejuvenator were, in most cases, smaller than those using softer virgin binder, specifically when a higher amount of RAP is incorporated. A higher percent of RAP can be incorporated by using a rejuvenator than a softer binder considering the APA results. Aggregate type still has an obvious influence on the rut depth, which can be seen by comparing mixtures containing Aggregate Sources C and L (Fig. 10).

Summary and Conclusions

Blending charts of extracted RAP binders containing a rejuvenator were established through DSR and BBR testing in order to investigate the possibility of determining the rejuvenator content when RAP is incorporated in Superpave mixtures. Superpave mixtures incorporating two sources of RAPs were designed with the rejuvenator content determined by the blend charts. Virgin control mixtures and mixtures containing RAPs using a softer

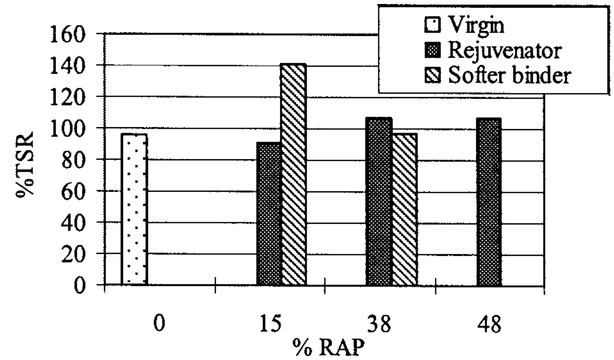


(a)

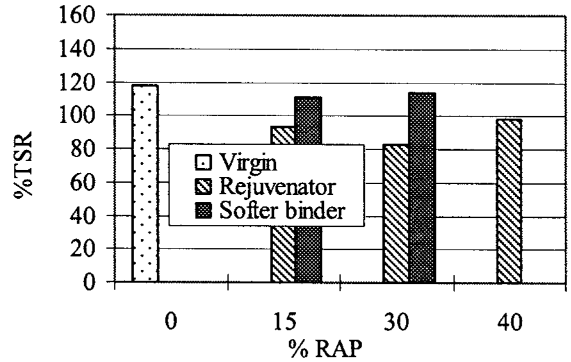


(b)

Fig. 9. Indirect tensile strength for aggregate sources: (a) C; (b) L

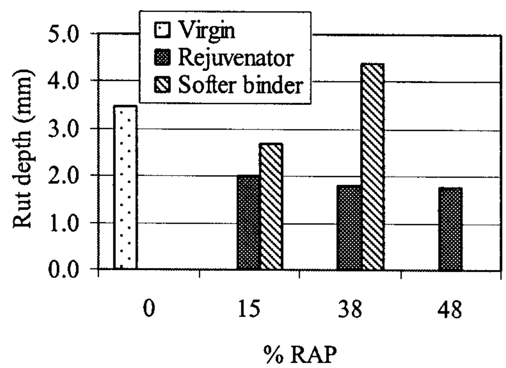


(a)

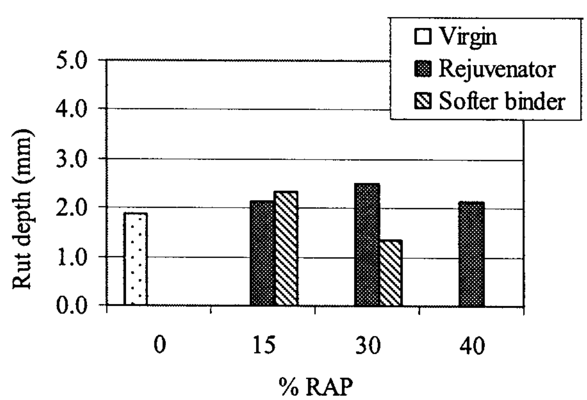


(b)

Fig. 10. %tensile strength ratio for aggregate sources: (a) C; (b) L



(a)



(b)

Fig. 11. Rutting depths of the Superpave mixtures containing various RAP contents for aggregate sources: (a) C; (b) L

binder were designed for comparison purposes. Moisture susceptibility of the mixtures was investigated by the indirect tensile strength test. The rutting properties were evaluated using the asphalt pavement analyzer. The main conclusions are drawn, for the materials tested, as follows:

1. The Superpave mixtures containing RAPs and a rejuvenator content determined with the blend charts produced mechanical and rutting performance properties that were as good as or even better than those using a softer binder.
2. The recycled mixtures containing as much as 40 and 48% of the RAP Sources L and C, respectively, can be incorporated in the 9.5 mm Superpave mixtures when a rejuvenator is used. However, only 30 and 38% of the two RAPs can be incorporated in the same Superpave mixtures with softer binder.
3. All Superpave mixtures incorporating RAPs show as good properties as the two control virgin mixtures. Volumetric requirements of recycled mixtures were satisfied and ITS results of the recycled mixtures were within the requirements. A visual observation of the ITS samples indicated the lack of stripping in all mixtures.
4. The rut depth of all mixtures containing RAPs from APA testing after 8,000 load cycles, was much less than the tentative criteria of 8.0 mm.
5. Blending charts of extracted aged binders with a rejuvenator show that there are good relationships between the performance parameters and the rejuvenator contents. It is possible

to determine a design content of the rejuvenator for recycling RAP under Superpave specifications by using these charts.

6. RAP percentage incorporated in Superpave mixtures is dependent not only on properties of the RAP binder, the RAP aggregate (e.g., critical temperature, the blend charts of the aged binder and rejuvenator added, the RAP gradation, etc.), but also the requirements for Superpave mixtures (e.g., volumetric properties, mechanical and performance properties, etc.). Changes in the fractions (e.g. from mesh -#4 to -#8 in the study) of the RAP incorporated can effectively affect the possible percentage of RAPs.

Acknowledgments

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