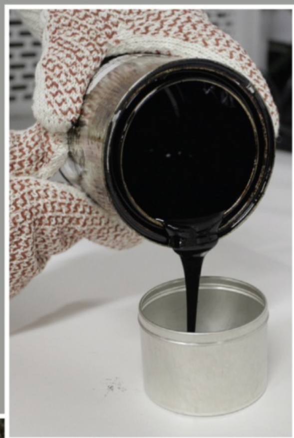
NCAT Report 15-03



LABORATORY EVALUATION OF SYLVAROAD™ RP 1000 REJUVENATOR

Phase I

By
Pamela Turner
Adam Taylor, P.E.
Nam Tran, Ph.D., P.E., LEED GA

June 2015

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

LABORATORY EVALUATION OF SYLVAROAD^{TM} RP 1000 REJUVENATOR

Final Report

By

Pamela Turner
Adam Taylor, P.E.
Nam Tran, Ph.D., P.E., LEED GA

National Center for Asphalt Technology
Auburn University, Auburn, Alabama

June 2015

ACKNOWLEDGEMENTS

This project was funded by Arizona Chemical Company, LLC. The authors would like to thank the many personnel who contributed to the coordination and accomplishment of the work presented herein. Special thanks are extended to Laurent Porot for serving as the technical representative and reviewing this report.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the sponsored agency, the National Center for Asphalt Technology or Auburn University. This report does not constitute a standard, specification, or regulation. Comments contained in this paper related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

TABLE OF CONTENTS

PURPOSE AND SCOPE

This study was conducted to determine the benefits of using SYLVAROAD™ RP 1000 rejuvenator for improving the performance characteristics of recycled binders and mixtures. In Phase I, a laboratory testing program, including binder performance grading and Superpave mix design, was conducted at the National Center for Asphalt Technology (NCAT) to compare the performance of rejuvenated reclaimed asphalt pavement (RAP) mixtures and binders with that of mixtures and binders produced (1) without the rejuvenator and (2) without both RAP and the rejuvenator (virgin materials). Results of Phase I study will be used in Phase II, which focuses on laboratory performance testing of asphalt mixtures.

TESTING PLAN

Materials

Table 1 shows the materials used in Phase I. The RAP and virgin binder materials were sampled in Alabama. The Granite M10 and Shorter Sand aggregate stockpiles were produced in Alabama, while the Granite 89 material was produced in Columbus, GA. The virgin aggregate and binder materials have been used in previous studies at NCAT. The RAP source was chosen so that its binder had a performance grade (PG) at least two but not more than six grades higher than the virgin binder, which was a PG 64-22.

Table 1 Materials Used in Phase I Laboratory Testing Program

Material	Source	Location
Granite 89	Vulcan Materials	Columbus, GA
Granite M10	Vulcan Materials Notasulga Quarry	Loachapoka, AL
Shorter Sand	Lambert Materials	Shorter, AL
RAP (-1/2”)	Midsouth Paving	Dothan, AL
Virgin PG 64-22	Ergon	Vicksburg, MS
SYLVAROAD™ RP 1000	Arizona Chemical	

Plan for Binder Testing

Testing of asphalt binders was conducted in the following steps:

- Step 1: Extraction and recovery of binder from RAP according to AASHTO T164, Method A with Trichloroethylene as the solvent and ASTM D5404.
- Step 2: Continuous grading of RAP binder according to AASHTO M 320 and R 29
- Step 3: Continuous grading of RAP binder treated with 5% of rejuvenator
- Step 4: Continuous grading of RAP binder treated with 10% of rejuvenator

In Step 1, the RAP binder was extracted and recovered in a sufficient quantity to run the full PG grading as required in AASHTO M 320 and R 29.

Steps 2, 3, and 4 were conducted as follows:

- The extracted RAP binder with and without rejuvenator is identified as "virgin" binder and was RTFO- and PAV-aged to simulate mixing and construction in the field. Each extracted binder sample with/without rejuvenator was tested in its unaged, RTFO-aged, and RTFO+PAV-aged conditions for continuous grading according to AASHTO M 320 and R 29.
- Mass change was measured and reported for both RTFO- and PAV-aged samples.
- In addition to continuous grading, a DSR frequency sweep was conducted on the extracted RAP binder (without RTFO/PAV conditioning) with and without rejuvenator. The results were used to develop a master curve (at 20 °C) and black space plots for comparing with those of the PG 64-22 virgin binder.

Plan for Mixture Testing

Testing of asphalt mixtures was performed in three steps, as follows:

- Step 1: Characterization of RAP (AC Content by Centrifuge Extraction, Washed Gradation)
- Step 2: Superpave mix design for a control mix with 50% RAP without rejuvenator
- Step 3: Superpave mix design for the 50% RAP mix with rejuvenator

The 50% RAP mix was designed based on a virgin mix that had been tested in a previous study at NCAT. The virgin mix was not tested in this study, but the test results of this mix were used for analysis later in this report.

In Step 1, the RAP characterization, in addition to the PG grading as previously described, included:

- Determining asphalt content according to AASHTO T164 method A (Trichloroethylene)
- Determining gradation of RAP before extraction
- Determining gradation of RAP aggregate after extraction

The gradation of the RAP aggregate after extraction was used for the mix design. In steps 2 and 3, testing was conducted as follows:

- The 50% RAP mix used in Steps 2 and 3 was designed so that its gradation and volumetric properties would be as close as possible to those of the virgin mix.
- The rejuvenator used in the mix design in Step 3 was included as part of the final asphalt content. The proper dosage for the rejuvenator was determined based on the results of previous binder testing and consultation with Arizona Chemical.
- In addition to the volumetric mix design, the following tests were conducted for the 50% RAP mix with and without rejuvenator:
    - Mix samples were compacted in a Superpave gyratory compactor up to 120 gyrations and the shear force was recorded. Densification and shear force measurements were plotted against the number of gyrations.
    - Moisture susceptibility was tested according to AASHTO T 283 without freeze/thaw cycles.

Laboratory Mixing Protocol

The purpose of the rejuvenator is to allow high RAP contents to be used in hot mix or warm mix asphalt. The following laboratory mixing protocol is based on EN 12697-35, in which RAP is introduced through a RAP collar to mix with the superheated virgin aggregate.

1. Dry and heat the virgin aggregates at a higher mix temperature for 8 hours to compensate for the lower RAP temperature.
2. Dry the RAP and keep it in an oven for 2.5 hours (temperature not exceeding 130 °C).
3. Heat the virgin binder at the normal mixing temperature for 3 hours and stir it until the material is homogeneous.
4. Put the RAP in the planetary mixer, add the rejuvenator (kept at ambient temperature), and mix for 30 seconds.
5. Add the virgin aggregates to the mixer and mix for 60 seconds.
6. Add the hot virgin binder to the mixer and mix for another 90 seconds.

For future studies, mixing time may be varied depending on the type of mixer and mixing speed to make sure all of the aggregate particles are fully coated. If filler is used, it should be added after the mixing of all aggregates is completed but before virgin binder is added into the mix.

RESULTS AND ANALYSIS

Results of Binder Testing

The recovered RAP binder was graded with and without rejuvenator according to AASHTO M 320, *Performance Graded Asphalt Binder*, and AASHTO R 29, *Grading or Verifying the Performance Grade (PG) of an Asphalt Binder* to determine its PG grade. Specific binder tests in this methodology include:

- Short-term aging using the Rolling Thin Film Oven (RTFO) procedure, as described in AASHTO T 240.
- Long-term aging using the Pressure Aging Vessel (PAV) procedure, as described in AASHTO R 28.
- Binder complex shear modulus (G^*_{binder}) and phase angle (δ_{binder}) using a Dynamic Shear Rheometer (DSR) at high and intermediate-temperatures, as described in AASHTO T 315.
- Low-temperature stiffness and relaxation properties from the Bending Beam Rheometer (BBR), as described in AASHTO T 313.

The results of a virgin binder (PG 64-22) tested in a previous project are included in this report for reference purposes. This virgin binder is not from the same source as the virgin binder used in the production of the RAP. Therefore, direct comparisons of the RAP results to the virgin PG 64-22 results are not possible. The virgin binder results are included only to provide a comparison between the recovered RAP binder with and without rejuvenator and a similar virgin binder. Table 2, Figure 1, and Figure 2 show the grading results of the recovered RAP alone and blended with 5 and 10% of the rejuvenator. Both long- and short-term aged results are presented. According to AASHTO M 323, Appendix X1, the recovered RAP binder is not typically long-term aged, and intermediate temperature DSR and low temperature BBR testing is usually only performed on recovered RAP binder that has been short-term aged. For this study, the materials were long-term aged at the sponsor's request.

Table 2 Performance Grading

Aging	Sample Type	T_{crit} High	T_{crit} Int	T_{crit} Low S	T_{crit} Low m	True-Grade	PG
RTFO	0%	100.7	36.0	-15.8	-13.2	100.7 - 13.2	100 - 10
RTFO	5%	92.0	25.8	-24.7	-26.0	92.0 - 24.7	88 - 22
RTFO	10%	83.3	16.9	-33.4	-34.2	83.3 - 33.4	82 - 28
PAV	0%	100.7	39.7	-14.4	-9.5	100.7 - 9.5	100 - 4
PAV	5%	92.0	30.6	-22.4	-20.5	92.0 - 20.5	88 - 16
PAV	10%	83.3	22.7	-30.6	-28.3	83.3 - 28.3	82 - 28
PAV	Virgin 64-22	68.1	24.0	-26.6	-24.3	68.1 - 24.3	64 - 22

Figures 1 and 2 show that the effect of adding rejuvenator to the recovered RAP binder was fairly consistent, with each 5% rejuvenator resulting in a temperature improvement of 8-13°C on the low, intermediate, and high critical temperatures. The short-term aged recovered RAP binder without rejuvenator graded to be a PG 100–10 with high, intermediate, and low critical temperatures of 100.7, 36.0, and -13.2°C respectively. Long-term aging of the recovered RAP binder resulted in an increase in intermediate critical temperature of approximately 4°C to 39.7°C and increased the low critical temperature to -9.5°C. The PG grade of the long-term aged RAP binder was PG 100–4 (high critical temperature is not affected by long-term aging).

Adding 5% rejuvenator to the recovered RAP binder decreased the high temperature stiffness from a grade of 100 to a grade of 88, two PG grades lower than the recovered RAP binder without rejuvenator. The short-term aged 5% blend had an intermediate critical temperature of 25.8°C, which increased to 30.6°C after PAV aging. Adding 10% rejuvenator to the recovered RAP binder further decreased binder stiffness. The high critical temperature decreased approximately 17°C from the 0% results, with the 10% blend meeting the requirements for a PG grade of 82. The low and intermediate critical temperatures for both the short- and long-term aged samples decreased by approximately 19-20°C from that of the recovered RAP binder.

Looking at the effect of the rejuvenator on the low critical temperatures shows a decrease (improvement) of approximately 9°C for stiffness and 13°C for m-value (relaxation) at the RTFO-aged condition after adding 5% rejuvenator to the recovered RAP binder. Adding another 5% rejuvenator further improves the stiffness critical temperature another 9°C and the m-value critical temperature 8°C. Overall, for the RTFO-aged blends, the rejuvenator appears to have a slightly larger effect on the relaxation criteria than on the stiffness criteria at low temperatures. The same is true for the PAV-aged blends, with the first 5% rejuvenator decreasing the m-value critical temperature by 11°C and the stiffness critical temperature by 8°C. An additional 5% rejuvenator results in a further 8°C drop in critical temperature.

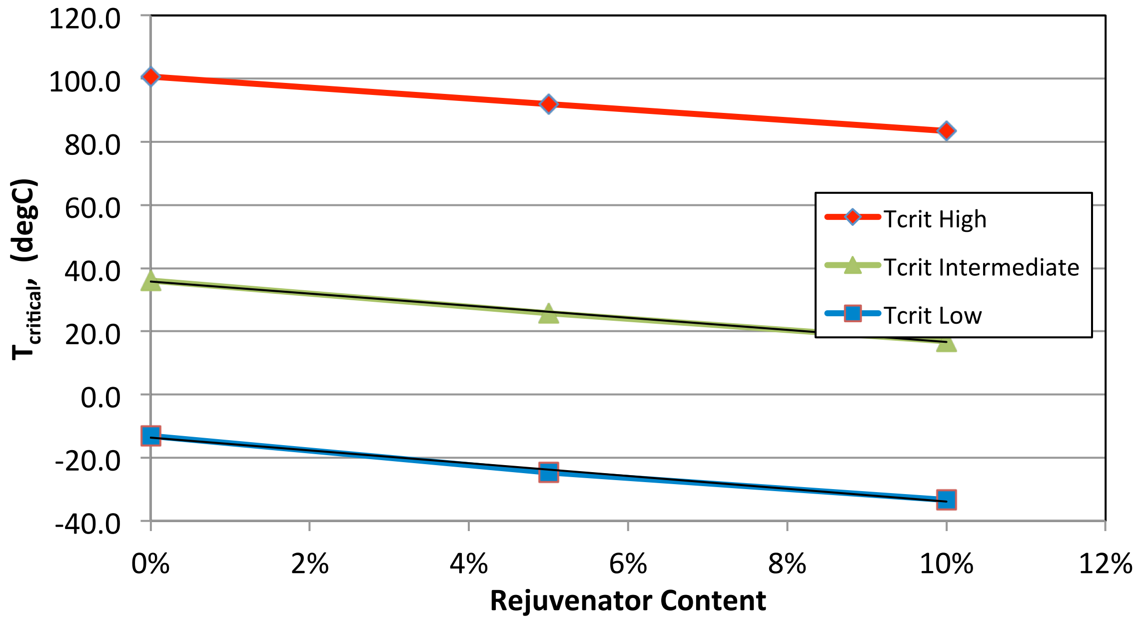


Figure 1 Effect of Rejuvenator Content on RTFO-Aged RAP Binder

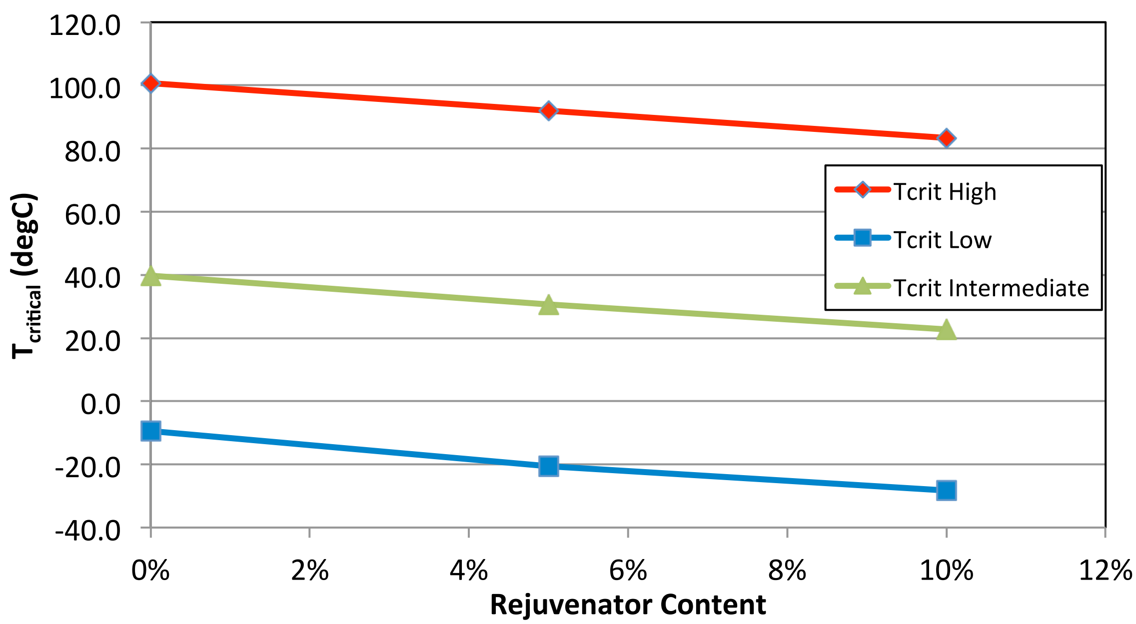


Figure 2 Effect of Rejuvenator Content on PAV-Aged RAP Binder

Overall, the short-term aged recovered RAP binder with 5% rejuvenator graded to be a PG 88–22 and the long-term aged sample graded to be a PG 88–16. The 10% rejuvenator sample was graded to be a PG 82–28 after both short- and long-term aging. Based on these PG results, a dosage rate of 6.8% of SYLVAROAD™ RP 1000 by the weight of the RAP binder was selected to restore the continuous grade of RAP binder from 100.7-9.5 to 88.8-22.8.

The change in mass that occurs during aging is an important characteristic of an asphalt binder. It is used as an indicator of the amount of volatiles that are being burned off during heating and can also measure the amount of mass increase due to oxidation. Table 3 shows the mass change results after both RTFO and PAV aging.

Table 3 Mass Changes

Material	**% Change after RTFO (≤ 1%)**	**% Change after PAV**
RAP Binder	-0.879	+0.407
RAP Binder + 5% RJV	-0.837	+0.460
RAP Binder + 10% RJV	-0.872	+0.545

The mass change values were almost the same for all three samples and met the AASHTO M 320 requirement of less than 1.00% change in mass after the RTFO aging procedure, indicating that the rejuvenator did not have a detrimental effect on the mass loss results. After the PAV aging procedure, all of the recovered RAP and rejuvenator samples experienced a mass gain. The recovered RAP binder without rejuvenator had the lowest mass gain (0.407%), the 5% rejuvenator blend had a mass gain of 0.460%, and the 10% rejuvenator blend had a mass gain of 0.545%.

In addition to PG grading of the recovered RAP and rejuvenator blends, frequency sweep testing was performed at four temperatures (20, 40, 60, and 80°C) and multiple frequencies (0.06 – 60 rad/sec). The resulting isotherms were shifted using the Microsoft Excel Solver function to create master curves for the recovered RAP and rejuvenator blends. At the request of the sponsor, this testing was conducted using samples that had not been aged. A virgin PG 64-22 master curve was included for comparison. All master curves shown were created using the Christensen – Anderson (CA) model with modified Kaeble shift factors. The model equations are shown in Equations 1 and 2.

$$G^*(\omega) = G_g \left[1 + \left(\frac{\omega_c}{\omega_r}\right)^{\frac{\log 2}{R}}\right]^{\frac{-R}{\log 2}} \qquad (1)$$

where

$G^*(\omega)$ = complex shear modulus, Pa;
G_g = glass modulus;
ω_r = reduced frequency at the reference temperature, rad/sec;
ω_c = crossover frequency at the reference temperature, rad/sec; and
R = rheological index.

$$\log(a_T) = -C_1 \left[\frac{T - T_d}{C_2 + |T - T_d|} - \frac{T_r - T_d}{C_2 + |T_r - T_d|} \right] \quad (2)$$

where

$Log(a_T)$ = shift factor;
T = temperature, °K;
T_r = reference temperature, °K;
T_d = defining temperature, °K; and
C_1, C_2 = constants.

Master curves help define both time dependency (the location and shape of the master curve) and temperature dependency (shift factors) of a material and allow for the determination of stiffness properties at temperatures and frequencies that are not easily tested in a laboratory setting (*1*). Figure 3 shows the master curves for the recovered RAP binder without rejuvenator and with the addition of 5% rejuvenator. The master curve for the virgin PG 64-22 is also shown.

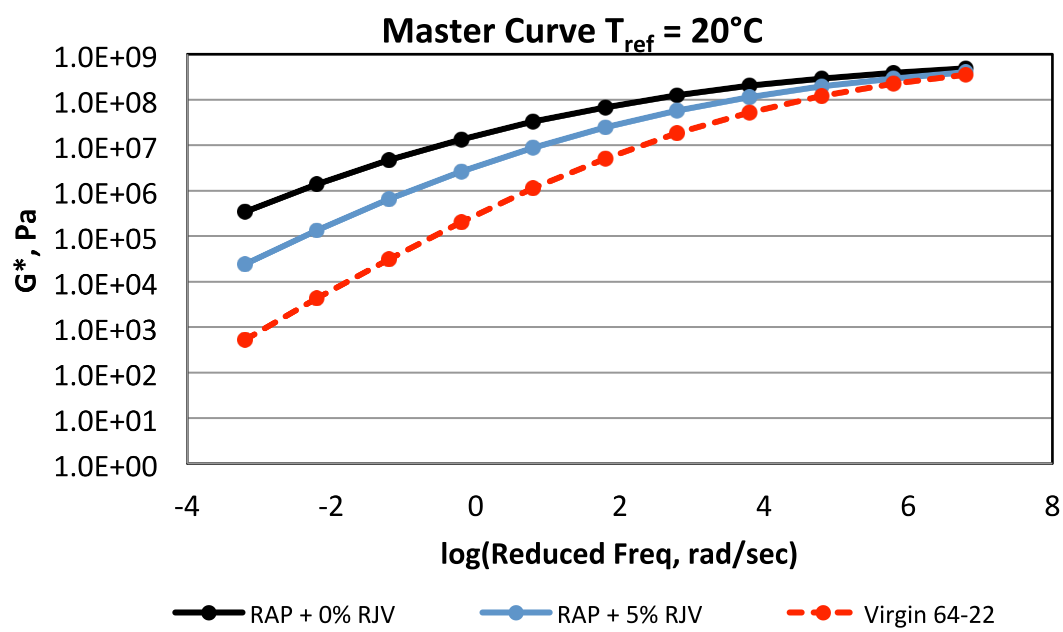


Figure 3 G* Master Curves of Unaged Binders

The virgin PG 64-22 master curve shown in Figure 3 has the lowest stiffness and highest slope over the range of frequencies, while the recovered RAP binder without rejuvenator has the highest stiffness and a flatter slope. The addition of 5% rejuvenator to the RAP binder decreased stiffness and shifted the master curve of the blended materials closer to the PG 64-22 master curve. This behavior matches expectations based on the PG grading of the binder. A master curve for the RAP with 10% rejuvenator is not shown in the figure but was also in line with expectations based on the reduction in stiffness seen in the PG grading for that blend.

The parameters used to create the master curves can also be used to compare the rheological behavior of different asphalt binders. Table 4 shows the values determined for rheological index (R) and crossover frequency (ω_c) for the blended binders.

Table 4 Master Curve Parameters

Blend	Rheological Index, R, $\log_{10}$ Pa	$\log_{10}$ Crossover Frequency, ω_c, rad/sec	Crossover Temperature @ 10 rad/sec, °C
0% Rejuvenator	2.4	-1.27	39.7
5% Rejuvenator	2.14	0.63	23.1
PG 64-22	1.69	2.88	5.91

The crossover frequency, ω_c, is defined as the frequency at which the phase angle is 45° at the reference temperature, and the crossover temperature, T_{vet}, is the temperature at which the phase angle is 45^o at the reference frequency (10 rad/sec). ω_c and T_{vet} are indicators of the hardness of the asphalt binder. Lower values of ω_c or higher values of T_{vet} indicate a harder binder, while increasing ω_c or decreasing T_{vet} values indicate a softer binder. The values reported in Table 4 for ω_c and T_{vet} show that the hardness of the recovered RAP binder decreases with addition of the rejuvenator.

The rheological index, R, is an indicator of rheological type and is calculated as shown in Equation 3.

$$R = \left(G_g\right) - \left(G_c\right) \quad (3)$$

where

G_g = glassy modulus, Pa; and
G_c = modulus at the ω_c, Pa.

R typically increases with binder aging, indicating a flattening of the master curve. As shown in Table 4, all of the R values for the recovered RAP blends are higher than the R value of PG 64-22, with the 0% rejuvenator sample having the highest value. The addition of the rejuvenator has a decreasing effect on the R value of the blended binders.

Figure 4 shows the Black Space diagrams for the recovered RAP with and without rejuvenator, and the virgin PG 64-22 binder. A Black Space diagram is a convenient way to quantify the changes in the rheological behavior of an asphalt binder due to aging, additives, etc. Typically, as an asphalt binder ages, the Black Space curve shifts downward, indicating a decrease in phase angle at any given modulus value. This behavior is indicative of a binder that is becoming less viscous or more brittle (*2*). For example, Figure 4 shows the difference in phase angle at 5,000 kPa (represented by the dashed vertical line) for the recovered RAP binder as compared to the unaged PG 64-22 virgin binder. The recovered RAP binder is significantly aged compared to the virgin binder and, as would be expected, has a lower phase angle at the same stiffness level. The 5% rejuvenator blend, while less stiff than the recovered RAP binder, still shows phase angles at all stiffness levels that are closer to the recovered RAP binder than to the PG 64-22 binder. The 10% rejuvenator blend, while not shown, demonstrated similar behavior to the 5% blend, with the phase angles at all stiffness levels being closer to those of the RAP binder that to the PG 64-22 binder.

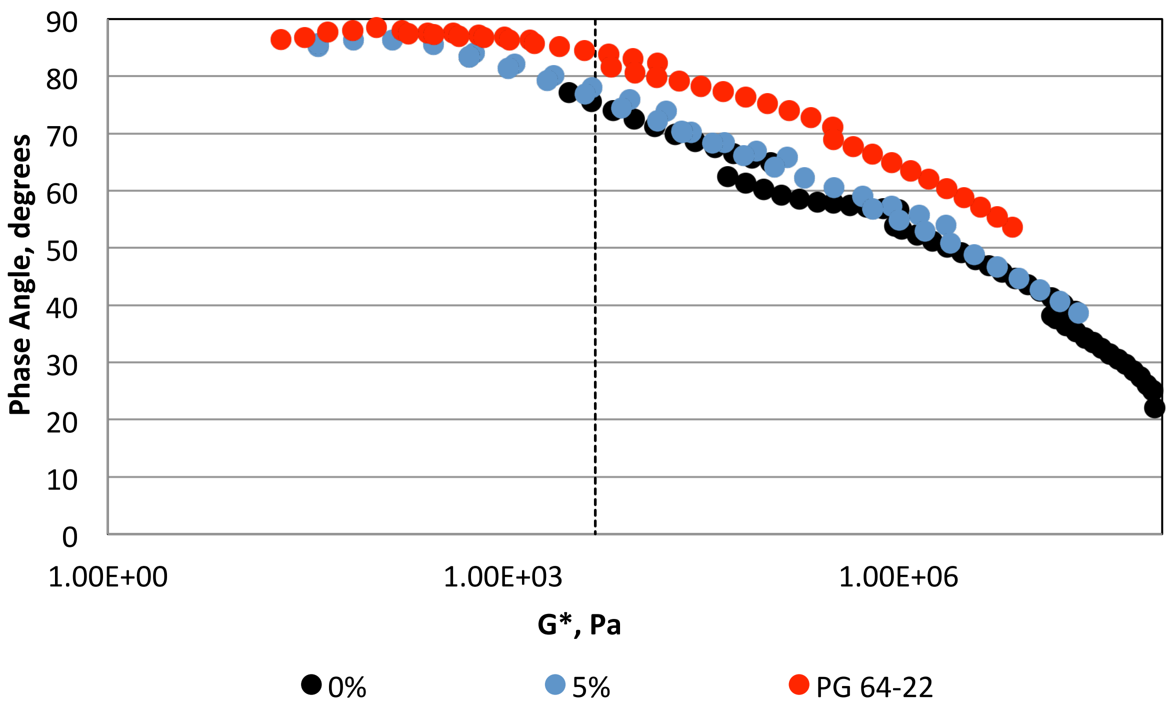


Figure 4. Black Space Diagrams of Unaged Binders

Results of Mixture Testing

Two mix designs were utilized for the laboratory testing program. The first mix design was a 9.5-mm NMAS virgin (0% recycled binder) control mixture with a PG 64-22 binder. The mix was designed to 60 gyrations. This mix design was selected due to it having been used in previous NCAT research studies (NCAT Reports 12-03 and 12-05). Table 4 summarizes the gradations of the individual aggregate stockpiles (identified in Table 1) as well as the gradation of the total blend. The second mix design was conducted using 50% of the Dothan RAP material. For the mix design, the blend gradation of the 50% RAP mix was matched to that of the virgin control mix as closely as possible. Both mixtures were 9.5 mm NMAS mixtures using PG 64-22 virgin asphalt binder designed to 60 gyrations, which is a typical Alabama Department of Transportation (ALDOT) compaction level for Superpave mixes. Table 5 summarizes the gradations of the individual aggregate stockpiles as well as the gradation of the total blend. The minor differences in aggregate stockpile gradations are due to those gradations being updated between the time the virgin control mix and when the 50% RAP mixes were tested in the NCAT lab.

Table 4 Design Aggregate Gradations – Virgin Control Mix

Sieve (in.)	Sieve (mm)	Granite 89	Limestone 8910	Granite M10	Shorter Sand	Virgin Mix JMF
1/2"	12.5	100	100	100	100	100
3/8"	9.5	100	100	100	100	100
#4	4.75	32	99	99	100	75
#8	2.36	5	90	89	89	59
#16	1.18	3	65	70	70	45
#30	0.6	2	48	54	39	30
#50	0.3	2	36	37	14	17
#100	0.15	1	27	23	4	10
#200	0.075	0.8	20.2	13.2	0.8	5.9
Cold Feed		**36.0%**	**15.0%**	**18.0%**	**31.0%**	

Table 5 Design Aggregate Gradations – 50% RAP Mix

Sieve (in.)	Sieve (mm)	Granite 89	Granite M10	Shorter Sand	Dothan RAP	50% RAP Blend
1/2"	12.5	100	100	100	100	100
3/8"	9.5	100	100	100	93	97
#4	4.75	32	100	100	73	76
#8	2.36	5	85	92	54	58
#16	1.18	3	64	66	44	44
#30	0.6	2	48	34	34	31
#50	0.3	2	34	9	19	17
#100	0.15	1	21	2	10	9
#200	0.075	0.8	13.5	1.0	6.6	5.7
Cold Feed		**15.6%**	**15.2%**	**19.2%**	**50.0%**	

The 50% RAP mixture was designed both with and without rejuvenator. The mixing procedure for the rejuvenator was documented earlier in this report. The target mixing temperature for these samples was 310-320°F with a compaction temperature between 290-300°F after a two hour oven age in accordance with AASHTO R 30, *Mixture Conditioning of Hot Mix Asphalt (HMA)*. To achieve the desired mixing temperature, the aggregate was superheated in excess of 400°F. Mixing times were generally shorter than previously mentioned in order to prevent excessive heat loss from the mixing bowl due to the use of a planetary mixer and individual mixing of the gyratory samples. For the mix design with rejuvenator, SYLVAROAD™ RP 1000 was added to the RAP in the mixing bowl at a dosage rate of 6.8% of the RAP binder (by weight). Samples were compacted in accordance with AASHTO T 312, *Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor,* using a PINE® Model AFG2AS Gyratory Compactor. Bulk Specific Gravity (Gmb) of the gyratory samples was determined in accordance with AASHTO T 166, *Bulk Specific Gravity of Compacted (Gmb) Hot Mix Asphalt (HMA) using Saturated Surface-Dry Specimens.* Maximum Specific Gravity (Gmm) of the mixture was determined in accordance with AASHTO T 209, *Theoretical Maximum Specific Gravity (Gmm) and Density of Hot Mix Asphalt (HMA)*.

A comparison of the volumetric properties of the three mix designs at the optimum binder content is provided in Table 6. The design criteria from AASHTO M 323, *Superpave Volumetric Mix Design,* are provided as well. All of the mixtures were designed to an optimum of 4.0% air voids (96% Gmm) at a design gyration level of 60 gyrations. The optimum asphalt content of the virgin mixture was 6.1% and the optimum asphalt content of the 50% RAP mixture was 6.0%. The other volumetric criteria of the virgin control and 50% RAP mixes were almost an identical match. The addition of the rejuvenator lowered the optimum asphalt content of the 50% RAP mix by 0.2% to 5.8% total asphalt. The volumetric properties of the 50% RAP with rejuvenator mix are very consistent with those of the 50% RAP mix (within 0.2 percent for all main properties). Each mixture met the target volumetric requirements of a 9.5 mm NMAS mix specified in AASHTO M 323.

Table 6 Mix Volumetric Properties

Properties	Virgin	50% RAP w/o RJV	50% RAP with RJV	Criteria
RAP AC Content, %	N/A	4.4	4.4	
Binder from RAP, %Pb (RAP)	N/A	2.2	2.2	
Virgin Binder, %Pb (Virgin)	6.1	3.8	3.45	
Rejuvenator, %RJV	N/A	0	0.15	
Total Binder Content, %Pb (Total)	6.1	6.0	5.8	
Air Voids, %Va	4	4	4	4
Voids in Mineral Aggregate, %VMA	16.5	16.3	16.1	>=15%
Voids Filled with Asphalt, %VFA	75.4	75.4	75.2	73 - 76%
Effective Binder, %Pbe	5.4	5.4	5.3	
Dust Proportion, DP	1.1	1.1	1.1	0.6 - 1.2

Tensile Strength Ratio (TSR) testing was performed in accordance with AASHTO T 283, *Resistance of Compacted Hot Mix Asphalt to Moisture-Induced Damage*. TSR testing is required by AASHTO M323, *Superpave Volumetric Mix Design,* to ensure the design is resistant to moisture damage. The virgin control mix with liquid anti-stripping agent (0.5% of AdHere LOF® by total binder weight) was tested for TSR. The result was a passing TSR value of 0.92 with an average conditioned tensile strength of 120.6 psi and an average unconditioned tensile strength of 130.5 psi. For this study, the 50% RAP and 50% RAP with rejuvenator mixes were tested with no liquid anti-strip. Six specimens of each mixture were fabricated with a target air void content of 7.0±0.5%. A summary of those test results is presented in Table 7. Both the 50% RAP and 50% RAP + RA mixture had a TSR value of 0.80, which is the minimum value required to pass the AASHTO standard. However, both the conditioned and unconditioned indirect tensile strength (ITS) values were statistically lower for the 50% RAP + RA mixture versus the

50% RAP mixture. This was confirmed by a two-sample t-test (α = 0.05) on both the conditioned (p-value = 0.010) and unconditioned (p-value = 0.002) ITS values. Hence, the data shows the addition of the rejuvenating additive to the mixture softens the overall mixture and lowers the mixture's ITS.

Table 7 TSR Results

Mix ID	Conditioned ITS (psi (MPa))		Unconditioned ITS (psi (MPa))		TSR
	Average	St. Dev.	Average	St. Dev.	
Virgin	120.6 (0.83)	5.0 (0.03)	130.5 (0.90)	1.7 (0.01)	0.92
50% RAP	161.1 (1.11)	8.2 (0.06)	201.1 (1.39)	4.3 (0.03)	0.80
50% RAP + RA	115.1 (0.79)	6.9 (0.05)	144.7 (1.00)	8.8 (0.06)	0.80

In addition to the mix design samples, samples were compacted using the PINE® Model AFG2AS Gyratory Compactor to quantify the gyratory shear resistance of both the 50% RAP and 50% RAP + RA mixture. This testing was performed to see if there were differences between the compactability of the mixtures with and without the rejuvenating additive. A total of eight gyratory specimens were compacted for this evaluation. Two replicate specimens were compacted for each of the two mixtures at a target compaction temperature of 290°F (143°C) and 250°F (121°C), respectively. The samples were compacted to a total of 120 gyrations, as per the recommendation of PINE®. The individual data files for each specimen recorded by the gyratory compactor included specimen height, internal angle, ram pressure, and moment for each gyration. The bulk specific gravity of the samples was determined in accordance with AASHTO T 166. An analysis spreadsheet was provided by PINE® to determine the %Gmm, resistive effort, and gyratory shear for each combination of mixture and temperature as a function of the number of gyrations. These plots are shown as Figures 5, 6, and 7, respectively, for %Gmm versus number of gyrations, resistive effort versus number of gyrations, and gyratory shear versus number of gyrations.

All three comparisons showed minimal differences between the four tested data points. The relative rankings of the mixtures remained consistent in each plot. At a given gyration, the values from highest to lowest would be as follows: 50% RAP + RA at 250°F, 50% RAP at 250°F, 50% RAP + RA at 290°F, and 50% RAP at 290°F. This ranking suggests that temperature had a greater effect on the overall relative rankings than the presence of the rejuvenator. However, as previously mentioned, the differences between the four tested mixtures were not graphically significant. The minimum effect of temperature on %Gmm, resistive effort, and gyratory shear in Figures 5, 6, and 7 may be due to the fact that the gradation of this mix design is well graded.

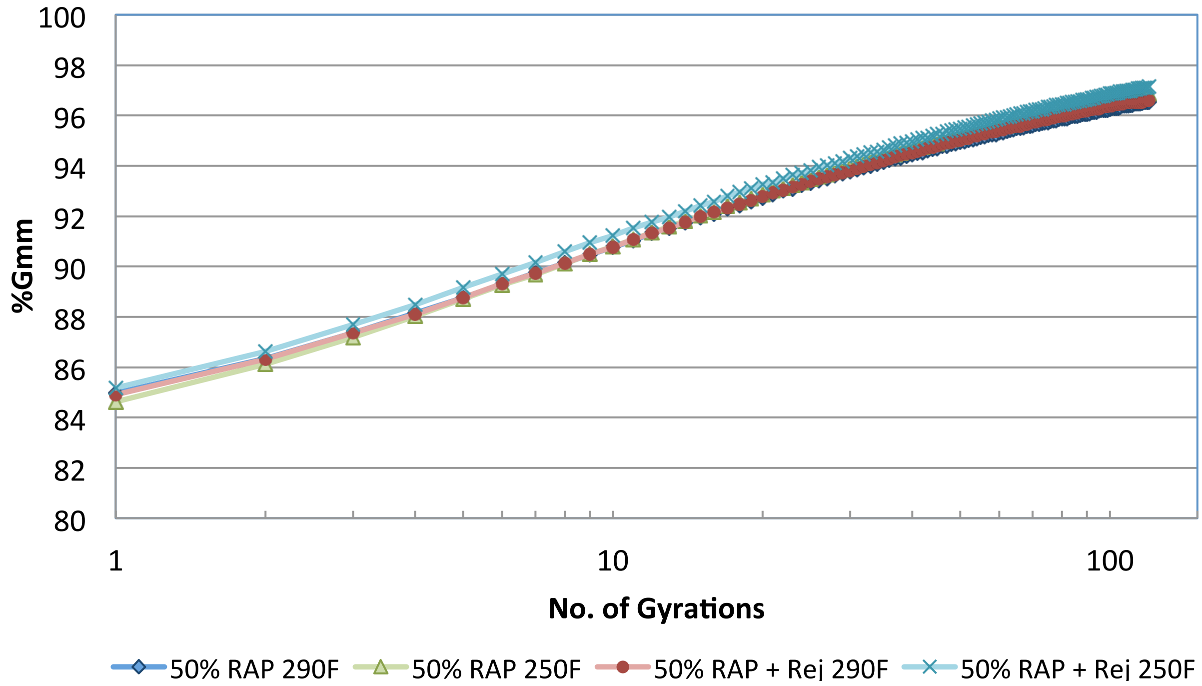


Figure 5 %Gmm versus No. of Gyrations

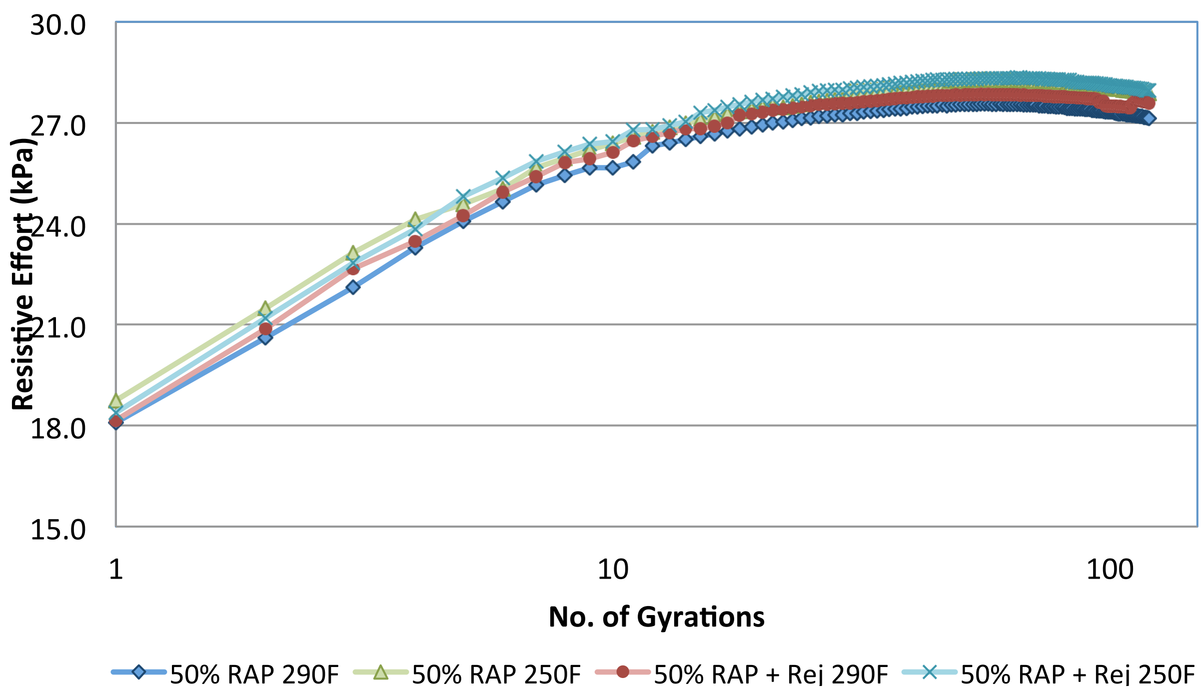


Figure 6 Resistive Effort versus No. of Gyrations

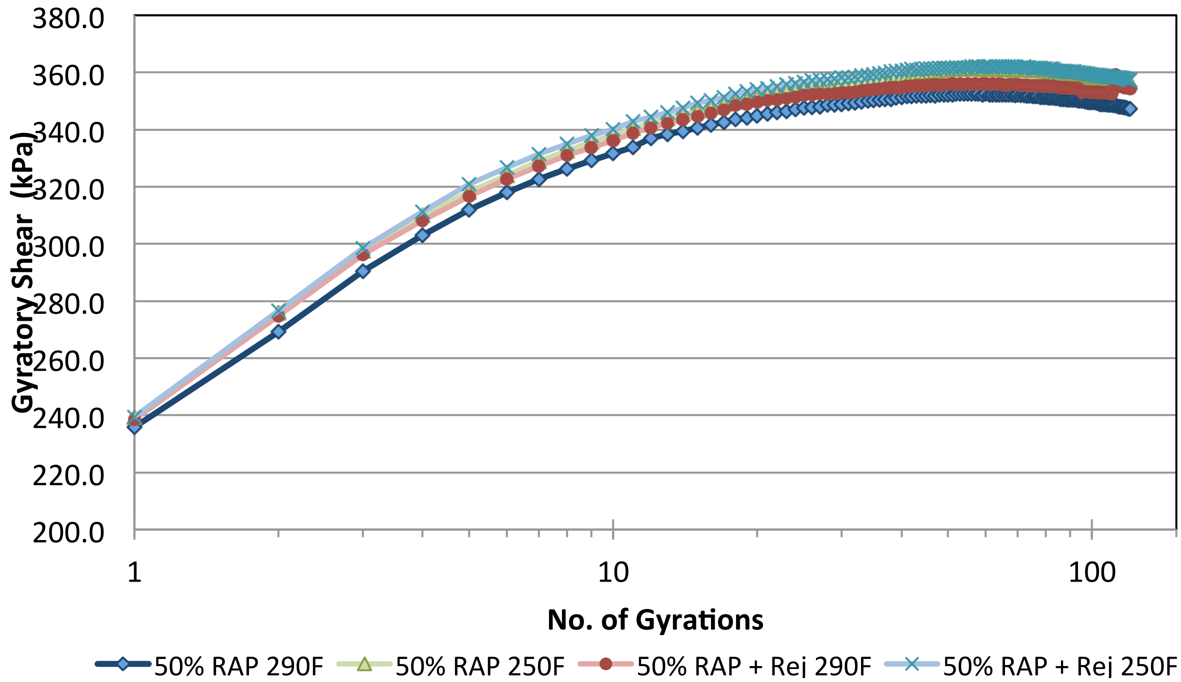


Figure 7 Gyratory Shear versus No. of Gyrations

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of Phase I study, the following conclusions and recommendations can be offered:

- The addition of 5 and 10% rejuvenator to the recovered RAP binder decreased the high temperature stiffness. This reduction led to a decrease in high PG grade from a PG 100 for the recovered RAP sample without rejuvenator to a PG 88 for the sample with 5% rejuvenator. The addition of 10% rejuvenator to the binder resulted in a PG 82 grade.
- The addition of 5 and 10% rejuvenator decreased the low temperature stiffness of the recovered RAP binder. Short-term aged samples resulted in an improved grade of -22 for the 5% rejuvenator sample and -28 for the 10% rejuvenator sample compared to -10 for the recovered RAP binder without rejuvenator. Long-term aging the samples resulted in an improved PG grade of -16 for the 5% rejuvenator sample compared to -4 for the 0% rejuvenator sample. The 10% rejuvenator sample remained a -28 grade after long-term aging. The rejuvenator appears to have a slightly larger effect on the relaxation (m-value) than on the stiffness (S) at low temperatures.
- The addition of 5 and 10% rejuvenator to the recovered RAP binder also decreased the intermediate temperature stiffness for both blends and aging conditions (approximately 10^{o}C) compared to the recovered RAP binder without rejuvenator.

- Based on the performance grading results, a dosage rate of 6.8% of SYLVAROAD™ RP 1000 by the weight of the RAP binder was selected to restore the continuous grade of the RAP binder from 100.7-9.5 to 88.8-22.8. One percent of SYLVAROAD™ RP 1000 can improve approximately 2 degrees of the critical temperatures.
- The addition of rejuvenator did not significantly affect the mass change properties of the recovered RAP binder after short- or long-term aging compared to the recovered RAP sample without rejuvenator.
- While both of the rejuvenator samples showed decreased stiffness compared to the recovered RAP sample without rejuvenator, the Black Space plots indicate that there may not be an improvement in the elasticity/relaxation properties of the blended binders.
- The 50% RAP mix design closely matched the volumetric properties of a virgin control mixture was performed with and without rejuvenator. The optimum asphalt content of the virgin mixture was 6.1% and the optimum asphalt content of the 50% RAP mixture was 6.0%. The other volumetric properties of the virgin control and 50% RAP mixes were almost an identical match. The addition of the rejuvenator lowered the optimum asphalt content of the 50% RAP mix by 0.2% to 5.8% total asphalt. The volumetric properties of the 50% RAP with rejuvenator mix were very consistent with that of the 50% RAP mix.
- TSR testing was performed for the 50% RAP mix with and without the rejuvenator in accordance with AASHTO T 283. The TSR values for the mixtures were identical at 0.80, the minimum amount allowed by AASHTO for a moisture-resistant mix. However, the addition of the rejuvenator did significantly reduce both the conditioned and unconditioned indirect tensile strengths relative to the 50% RAP mix without rejuvenator.
- Samples were compacted using the PINE® Model AFG2AS Gyratory Compactor to quantify the gyratory shear resistance of both the 50% RAP and 50% RAP + RA mixture. Samples of the 50% RAP mix both with and without rejuvenator were compacted at two different temperatures (290°F and 250°F) for this evaluation. Minimal effect of the rejuvenator or temperature was seen on the mixtures in terms of effects of compaction, resistive effort, and gyratory shear, possibly because the gradation of this mix design is well graded.

REFERENCES

1. Anderson, D. A., and R. Bonaquist. *NCHRP Report 709: Investigation of Short-term Laboratory Aging of Neat and Modified Asphalt Binders*. Transportation Research Board of the National Academies, Washington, D.C., 2012.
2. Hanson, D. L., G. King, M. Buncher, J. Duval, P. Blankenship, and M. Anderson. *Techniques for Prevention and Remediation of Non-Load Related Distress on Hot Mix Asphalt*. AAPTP Project 05-07, Final Report. April, 2009
3. Tran, N., A. Taylor, and J. R. Willis. *Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents*. NCAT Report 12-05. National Center for Asphalt Technology, Auburn, Ala., 2012.
4. Willis, J. R., P. Turner, G. Julian, A. J. Taylor, N. Tran, and F. G. Padula. *Effects of Changing Virgin Binder Grade and Content on RAP Mixture Properties*. NCAT Report 12-03. National Center for Asphalt Technology, Auburn, Ala., 2012.