Performance Characteristics of Plant Produced High RAP Mixtures

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Abstract

Reclaimed Asphalt Pavement (RAP) has been used in asphalt pavements at percentages ranging from 10 to 20 percent in the top lift. The resulting pavements have generally performed as well as pavements made with exclusively new materials. Still, many transportation agencies have been reluctant to allow producers to use more than 10 to 20 percent RAP because of concerns that mixtures with higher RAP contents will be too stiff, less workable, difficult to compact and may lead to mixtures more prone to field failures (cracking, rutting, etc.). Furthermore, it is unknown if the RAP binder is mobilized allowing for adequate blending to occur between the RAP and virgin binder. Inadequate blending may result in reduced film thickness on the virgin aggregates and reduced effective asphalt content of the mixture. Nevertheless, the recent increases in the cost of asphalt binder and diminishing supplies of quality aggregates has made using higher RAP contents in Hot Mix Asphalt mixtures a priority for the industry.

The degree of blending between the RAP and virgin asphalt binders and the performance of high RAP content HMA are not only dependent on the RAP and HMA mixture properties, but also a function of the mixture production parameters, such as: plant type, production temperature, mixing time, discharge temperature, and storage time and temperature. The main focus of this study was to obtain plant produced RAP mixtures, document the mixture production parameters, and evaluate the degree of blending between the virgin and RAP binders. Furthermore, the effect of mixture production parameters on the performance and workability of the mixtures was also evaluated. Performance was measured in terms of stiffness, cracking, rutting, and moisture susceptibility.

Eighteen plant produced mixtures were obtained from three locations in the Northeast. Mixtures were obtained from New York, New Hampshire

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The oral presentation will be made by Dr. Mogawer.

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and Vermont. The mixtures were produced using different RAP contents that ranged from no RAP to 40 percent RAP. For the New York and Vermont mixtures, softer binders were used also with high RAP contents. The production parameters of the mixtures were documented.

The data and analysis illustrated that the degree of blending between RAP and virgin binders is function of production parameters in particular, the discharge temperature and silo storage time. Also, softer binders were found to reduce the stiffness of the resultant binder but did not always improve the cracking resistance in the Overlay Tester. Overall, the stiffness of the mixtures increased as the percent of RAP increased. However, this does not hold true when the discharge temperature of the mixtures were inconsistent. The cracking resistance was reduced as the percent of RAP increased. Meanwhile, the rutting and moisture damage resistance improved as the percent of RAP in the mixtures increased. Finally, reheating the mixtures in the laboratory prior to specimen fabrication caused a significant increase in the stiffness of the mixtures and stiffness change insensitivity to the increased RAP contents.

Keywords: Reclaimed Asphalt Pavement, Production Parameters, Plant Produced Mixture, Blending, Stiffness

Background

Reclaimed Asphalt Pavement (RAP) has been used since the 1970's in asphalt pavements at percentages ranging from 10 to 20 percent in the top lift. The resulting pavements have generally performed as well as pavements made solely with virgin materials. Still, many transportation agencies have been reluctant to allow producers to use more than 10 to 20 percent RAP. A survey conducted as part of a Federal Highway Administration (FHWA) sponsored State of the Practice report for RAP in Hot Mix Asphalt (HMA) mixtures showed that many state transportation agencies specifications allow up to 30% RAP in the surface layers even though a majority of these states are still only using RAP percentages of 10 to 20%. (1). One reason for state transportation agencies reluctance to use more RAP is due to concerns that the resultant mixtures will be too stiff and consequently less workable, difficult to compact and may lead to mixtures more prone to field failures (cracking, rutting, etc.). Another reason for reluctance to using more RAP is because it is unknown if adequate blending occurs between the RAP and new materials. Furthermore, it is unclear if adequate blending provides a benefit or detriment to the overall performance of mixtures incorporating high RAP contents. However, even with the reluctance to use more RAP and questions surrounding mixture stiffness and blending, the recent increases in the cost of asphalt binder as well as diminishing supplies of quality aggregates has made using higher RAP contents in HMA mixtures a priority for the industry as a method to optimize the use of available resources (1).

RAP contains asphalt binder that has been aged. Because of this fact there has been a concern that incorporating higher RAP contents into HMA may lead to mixtures that are high in stiffness and accordingly may be prone to failures in the field (2, 3, 4). In an attempt to mitigate this stiffness increase, state transportation agency specifications have suggested/recommended the use of a softer binder when RAP (typically 15-20%) is utilized. If good blending occurs between the softer and RAP binder, the resultant binder in the mixture should have compatible properties to the typical specified asphalt binder used at low or zero percent RAP contents. However, the use of larger RAP contents (>20%) and a softer binder that experiences good blending may still result in a mixture that is very stiff. Mixtures that are very stiff may experience low-temperature cracking and may crack prematurely for pavements experiencing higher deflections (1). On the other hand, if poor blending occurs between the soft binder and the RAP binder, the resultant mixture will also be susceptible to distresses in the field. These distresses could be an increase in rutting due to the soft binder dominating the performance of the mixture, moisture damage due to reduced film thicknesses resulting from limited RAP binder contributing to the mixture, and cracking due to the incorporation of aged RAP binder (even though the RAP binder contribution may be a small percentage of the total binder due to the poor blending).

Several laboratory research studies have been conducted to measure the degree of blending between the RAP and virgin binder (2, 3). These studies illustrated that there is a degree of blending between RAP binder and virgin binder by comparing the dynamic modulus of the mixtures to a dynamic modulus predicted using the complex modulus of the recovered binder and the Hirsch model (2, 3). Recently, McDaniel (3) conducted a research study that focused on evaluating the properties of plant produced mixtures with up to 40% RAP and two virgin binders. This study illustrated that the dynamic modulus (stiffness) of the RAP mixtures tested were not significantly different than the control mixture with no RAP. However, little information is provided as to how these mixtures were produced or handled prior to test specimen fabrication.

One factor that is commonly ignored when comparing mixture performance is the influence of the various mixture production factors. The production factors that might affect the degree of blending between the RAP and virgin asphalt binders and consequently impact the performance of high RAP content HMA are: plant type, production temperature, mixing time, discharge temperature, storage time, RAP source, RAP properties, and virgin

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binder grade. However, limited work to date has been attempted to relate mixture production parameters to changes in asphalt material characteristics.

Further testing of plant-produced mixtures with different RAP contents (and different PG grade binders) presented herein will address the concerns of state transportation agencies by evaluating the degree of blending and its impact on the performance of high RAP content mixtures. Finally, the effect of reheating plant produced RAP mixtures on the stiffness of the mixtures was evaluated. The RAP mixtures will generally have higher stiffness than the same mixtures with no RAP. A significant increase in the stiffness of the RAP mixtures could have a detrimental effect on the cracking susceptibility of the mixtures.

Objectives

The focus of this research was to obtain plant produced surface mixtures, specifically 9.5 mm and 12.5 mm Superpave mixtures that were produced by incorporating different percentages of RAP and with different asphalt binder grades. Utilizing the available plant produced mixtures; subsequent testing and performance evaluations of each mixture and extracted/recovered binder were completed. These tests and evaluations were undertaken to meet the objectives of the study which were:

1. Obtain plant produced mixtures that incorporated different percentages of RAP.
2. Document construction parameters such as mixing and discharge temperatures, storage time, and plant type.
3. Using Christensen-Anderson model, develop a master curve for the extracted and recovered binders from each mixture produced. The master curves will be used to determine the effect of the construction parameters on the rheological properties of the recovered binders.
4. Measure the dynamic modulus |E*| of the mixtures.
5. Evaluate any effects on the mixture stiffness due to reheating the mixture in the laboratory.
6. Use binder master curve of the recovered binders to predict |E*| of the mixtures.
7. Compare the predicted |E*| to the measured |E*| to determine whether a good or poor degree of blending occurred between the RAP binder and the virgin binder.
8. Measure the performance of the mixtures in terms of cracking, rutting, and moisture damage.
9. Evaluate the effect of high RAP contents on the workability of the mixtures.

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10. Assess the impact of production parameters on the degree of blending and the performance of the mixtures.
11. Evaluate any benefits/detriments to the mixture performance resulting from the use of a softer binder at the higher RAP contents.

Experimental Plan

Plant produced mixtures were obtained from plants in three states: New York, New Hampshire, and Vermont. For these mixtures, the percentages of RAP in the mixtures typically ranged from 0 to 40 percent. The PG binders utilized were a PG52-34, PG58-28, PG64-22 and PG64-28. The exact RAP percentage and PG binder combinations are shown in the experimental plan in Figures 1 and 2.

Production data such as plant type, mixing and discharge temperatures, and storage time were collected to determine their effect on the performance, workability and degree of blending of the mixtures.

The methodology to evaluate the degree of blending between the RAP and virgin binders utilized the Hirsch model relationship between the complex shear modulus of the binder (G*) and the dynamic modulus (E*) of the corresponding mixture (2). The degree of blending was then used to evaluate its impact on the workability and mixture performance in terms of stiffness, cracking and moisture damage of the mixtures was evaluated.

The need to use a softer binder was examined by evaluating the performance and blending of the RAP mixtures that were produced using a softer binder as recommended in AASHTO M320 (5).

Finally, the effect of reheating the mixtures in the laboratory was evaluated by measuring the stiffness of plant produced specimens and specimens produced after reheating the loose plant produced mixture in the laboratory.

Plant Produced Mixtures & Production Data

Plant produced mixtures incorporating varying percentages of RAP were obtained from Callanan Industries in New York (NY), Pike Industries in Portsmouth, New Hampshire (NH), and Pike Industries in Williston, Vermont (VT). The New York facility consisted of a Cedar Rapids Counter Flow drum plant. Production rates on the project were approximately 250 tons per hour (tph) for the 30 and 40% RAP mixtures and 300 tph for the virgin and 20% RAP mixes. The Portsmouth, NH Pike facility consisted of a 2008 Gencor Ultra drum plant with 400 tons per hour capacity. Mixing times of the asphalt mixture were determined to be approximately 40 seconds. At the Williston,

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VT facility, the asphalt mixtures were produced in a 1966 H&B 5-ton drop batch plant. The batch plant mixing times and burner set temperature varied depending on the RAP content, as noted below:

- Virgin Mix: 6 sec Dry Mix Time; 36 sec Wet Mix Time
- 20% RAP: 10 sec Dry Mix Time; 36 sec Wet Mix Time
- 30% RAP: 13 sec Dry Mix Time; 36 sec Wet Mix Time
- 40% RAP: 13 sec Dry Mix Time; 36 sec Wet Mix Time

The mixture gradations, properties and production information are shown in Tables 1 and 2. Each location provided two sets of mixtures for evaluation; 1) Samples compacted at the plant's Quality Control (QC) laboratory that were sampled from the trucks prior to leaving the facility, and 2) Loose mix sampled from the trucks prior to leaving the facility and placed into 5-gallon metal cans for future sample fabrication.

Loose Plant Produced Mixture Reheating Procedure

All of the loose plant produced mixtures were reheated in the same manner in order to fabricate specimens in the laboratory. This reheating procedure was compiled into a formal document which was utilized by all parties involved with the study.

Loose mixtures were obtained from each contractor in five-gallon buckets. The first step was to heat the five-gallon bucket of mixture, with the lid on, for one hour at a temperature 10ºC lower than the plant discharge temperature. Next the bucket was heated at the same temperature for one hour with the lid off the bucket. After this second hour of heating, the temperature of the mixture was checked to confirm the center of the mixture was at least 75ºC (167 ºF). Next, the sample required to fabricate the appropriate mixture specimen was divided out to the proper mass.

In order to divide out the mixture, the loose mixture in the bucket was emptied into a large pan. Material was scooped from the pan in order to achieve the mass desired for a pre-determined specific specimen size. The massed specimen was then placed into an oven that was previously pre-heated to the appropriate compaction temperature. The entire dividing process took under 10 minutes to complete.

The massed specimens were then allowed to reach the compaction temperature (approximately 30 minutes in the compaction oven). Upon reaching the compaction temperature, the loose plant produced mixture specimens were then compacted. Each bucket of mixture was allowed to be heated only once and not allowed to be cooled and reheated again. The maximum reheating time was limited to 4 hours.

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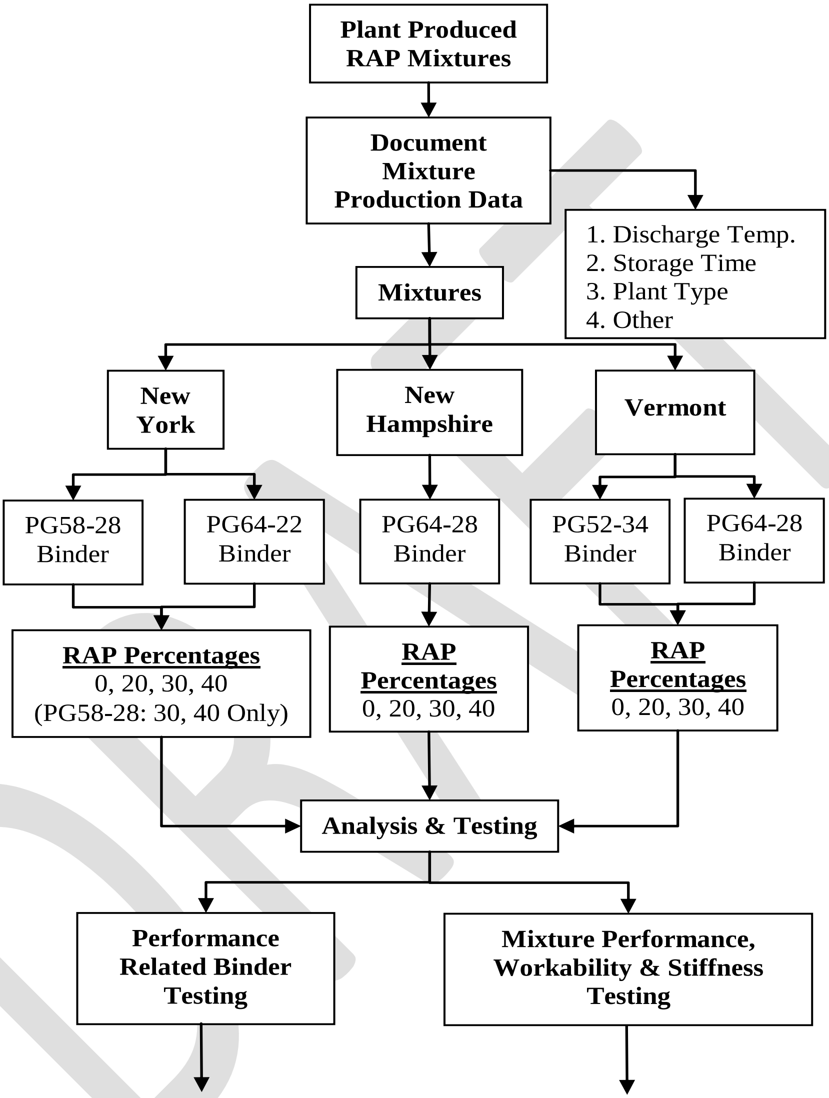

Figure 1. Experimental Plan

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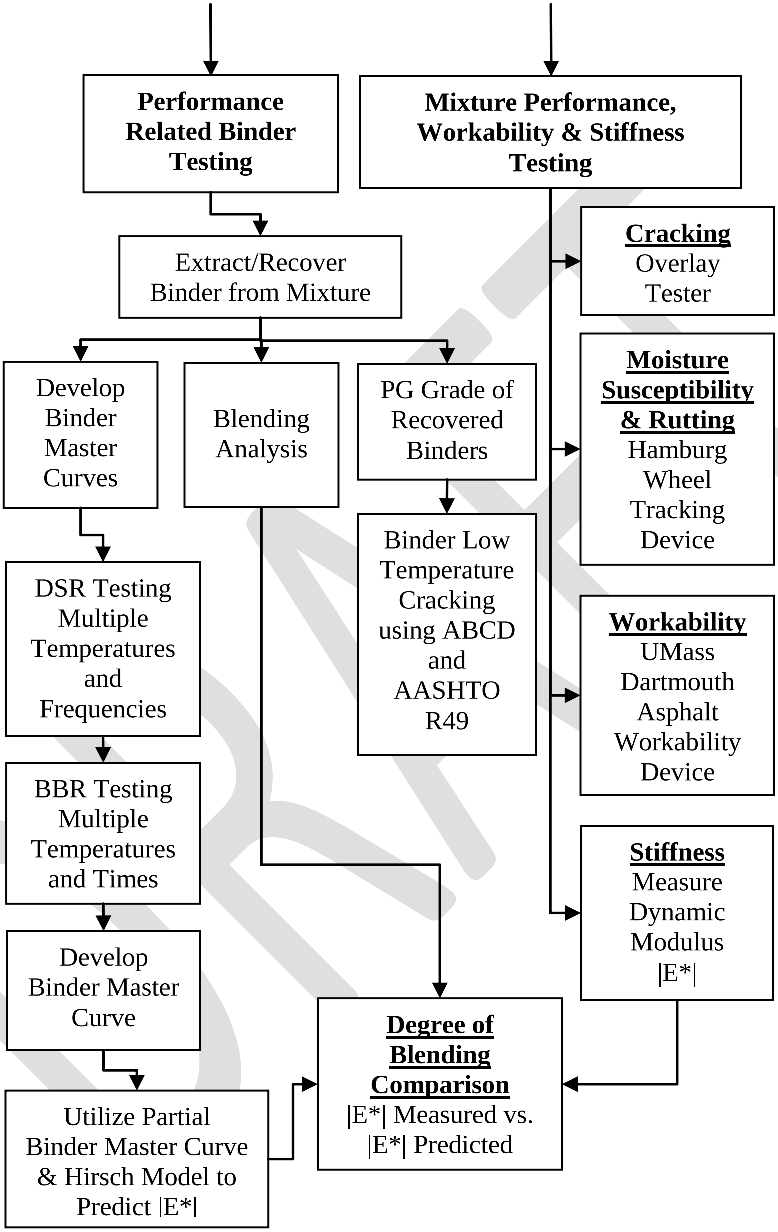

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Figure 2. Experimental Plan (continued)

State	PG Grade	Plant Type	% RAP	NMAS (mm)	Mixture Gradation								
					12.5	9.5	#4	#8	#16	#30	#50	#100	#200
NY	58-28	Drum	40	12.5	98.1	89.3	53.7	32.0	17.9	12.5	8.5	5.1	3.2
NY	58-28	Drum	30	12.5	97.5	91.2	59.5	33.3	21.2	14.7	9.7	5.8	5.3
NY	64-22	Drum	40	12.5	97.6	88.7	53.0	30.9	19.3	14.3	10.1	6.1	4.3
NY	64-22	Drum	30	12.5	95.0	85.8	54.4	30.2	22.7	16.5	11.6	7.8	6.0
NY	64-22	Drum	20	12.5	99.1	90.8	59.0	30.9	18.8	11.8	8.3	6.7	3.8
NY	64-22	Drum	0	12.5	99.8	90.8	68.3	42.3	26.8	18.9	13.2	5.2	3.8
NH	64-28	Drum	40	12.5	98.7	86.4	55.5	41.2	32.7	24.8	15.0	6.1	2.7
NH	64-28	Drum	30	12.5	98.7	86.5	56.2	41.9	33.5	25.8	16.0	6.9	3.6
NH	64-28	Drum	20	12.5	98.7	86.5	57.5	42.4	33.3	25.5	15.8	7.0	3.6
NH	64-28	Drum	0	12.5	98.6	85.8	58.3	42.5	32.4	24.7	15.5	7.2	3.6
VT	52-34	Batch	40	9.5	100	97.9	76.8	48.8	29.3	18.4	11.8	7.5	4.6
VT	52-34	Batch	30	9.5	100	98.6	75.0	48.1	29.5	18.7	11.7	7.4	4.5
VT	52-34	Batch	20	9.5	100	98.4	79.2	51.1	30.7	19.1	11.8	7.4	4.6
VT	52-34	Batch	0	9.5	100	98.8	78.8	51.1	31.4	19.3	10.7	6.1	3.8
VT	64-28	Batch	40	9.5	100	98.5	75.1	46.6	26.8	15.7	9.0	4.8	4.5
VT	64-28	Batch	30	9.5	100	97.8	77.5	48.9	29.0	17.8	11.0	7.0	4.3
VT	64-28	Batch	20	9.5	100	98.7	81.3	53.5	32.3	19.9	11.9	7.1	4.3
VT	64-28	Batch	0	9.5	100	99.6	76.9	48.8	29.7	18.0	9.9	5.5	3.3

Table 1. Plant Produced Mixture Gradations

State	PG Grade	% Binder	% RAP	RAP Binder Content, %	VMA	VFA	Agg. Temp. (^{o}F)	Discharge Temp. (^{o}F)	Compaction Temp. (^{o}F)	Silo Storage Time (hrs.)
NY	58-28	5.2	40	4.90	12.7	88.4	450	330	275	4
NY	58-28	5.2	30	4.93	13.7	81.1	410	305	275	3.5
NY	64-22	5.2	40	4.90	12.5	87.9	450	330	290	3
NY	64-22	5.2	30	4.93	13.0	85.1	410	305	290	2.75
NY	64-22	5.2	20	4.95	14.1	79.9	410	320	290	0.75
NY	64-22	5.2	0	--	12.6	89.3	375	310	290	2.75
NH	64-28	5.7	40	4.79	14.5	82.1	n/a	335	315	n/a
NH	64-28	5.7	30	4.79	14.4	81.3	340	335	315	1
NH	64-28	5.7	20	4.79	14.5	79.9	340	315	310	1.25
NH	64-28	5.7	0	--	14.9	74.8	340	330	300	6
VT	52-34	6.6	40	5.41	18.0	77.8	n/a	300	295	n/a
VT	52-34	6.6	30	5.41	17.7	82.5	n/a	320	320	n/a
VT	52-34	6.8	20	5.41	18.8	81.9	n/a	324	324	n/a
VT	52-34	6.7	0	--	20.2	76.3	n/a	340	340	n/a
VT	64-28	6.6	40	5.41	18.2	76.4	n/a	295	295	n/a
VT	64-28	6.6	30	5.41	19.1	75.9	n/a	322	310	n/a
VT	64-28	6.7	20	5.41	18.7	79.7	n/a	300	300	n/a
VT	64-28	6.5	0	--	20.3	71.5	n/a	330	300	n/a

Table 2. Plant Produced Mixtures –Properties and Production Information

Performance Related Binder Testing and Analysis

Binder from each plant produced mixture was extracted in accordance with Method A of AASHTO T164 “Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)” (5) and then recovered in accordance with AASHTO T170 “Recovery of Asphalt From Solution by Abson Method” (5). The effect of the production parameters on the rheological properties of the binders was examined by grading and constructing a master curve for each recovered binder. The master curve provides a relationship between binder stiffness (G*) and reduced frequency over a range of temperatures and frequencies. Accordingly, the master curve makes it possible to predict viscoelastic properties over a wide frequency range, beyond the range that actual measurements were carried out and also to predict viscoelastic properties at any temperature (6, 7, 8). The master curves of the recovered binder from the RAP mixtures were compared to the master curve of the recovered binder from the control mixture (for mixtures obtained at each plant) to evaluate the effect of RAP contents on the viscoelastic properties of the binders.

Finally, because of the concern in the industry that high RAP content might lead to a very stiff mixture that is susceptible to thermal cracking, the effect of the RAP binder on the low temperature cracking characteristics of the recovered binders was also evaluated utilizing two methods: the Asphalt Binder Cracking Device (ABCD) (AASHTO TP92) and AASHTO R49 “Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders.”

Performance Grade of Extracted Binders

All tank sampled and recovered binders were graded in accordance with AASHTO R29 “Grading or Verifying the Performance Grade of an Asphalt Binder” and AASHTO M320 “Standard Specification for Performance-Graded Asphalt Binder.” The results of the binder grading test are shown in Tables 3 and 4. The tank samples were graded to verify the grade of the virgin binder. The recovered binders were graded to determine the effect of plant type, percent RAP, the use of a soft binder, and production parameters on the grade of the fully blended binder (RAP and virgin). This was done by comparing the grade of the recovered binder from RAP mixtures to the grade of the recovered binder from mixtures with no RAP.

Based on examination of Tables 3 and 4, the following observations were made. The New York mixtures (drum plant) had minimal change in the low temperature grade of the binder up to RAP contents of 40% when a PG 58-28 was used. The high temperature binder grade increased by one grade at the 30 and 40% RAP contents for these mixtures. When a stiffer binder

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(PG64-22) was used, the high temperature grade again increased by one grade at RAP contents greater than 30%. Additionally, at a 40% RAP content, the low temperature grade experience a single grade loss, increasing from a -22°C to a -16°C.

For the New Hampshire mixtures (drum plant) there was no change in the binder grade up to 20% RAP content. At the 30 and 40% RAP content, the high temperature grade increased by a single grade. The low temperature grade did not change.

Table 3. Binder Grading Results – New York and New Hampshire Mixtures

Mixture	Type	Continuous PG Grade (°C)			PG Grade
		High	Low	Inter.	
New York 58-28	Tank 7/30/10	60.3	-30.8	17.2	58-28
	Tank 9/7/10	61.0	-34.6	18.5	58-34
	Extracted 30% RAP	69.6	-28.2	21.3	64-28
	Extracted 40% RAP	65.8	-29.3	20.5	64-28
New York 64-22	Tank 7/30/10	67.3	-26.0	22.1	64-22
	Tank 9/7/10	67.0	-25.5	21.9	64-22
	Extracted 0% RAP	67.5	-26.7	22.2	64-22
	Extracted 20% RAP	69.3	-25.9	26.6	64-22
	Extracted 30% RAP	70.9	-22.9	26.2	70-22
	Extracted 40% RAP	74.0	-18.3	26.1	70-16
New Hamp. 64-28	Tank	66.3	-29.5	19.9	64-28
	Extracted 0% RAP	66.8	-31.1	18.0	64-28
	Extracted 20% RAP	67.9	-30.0	20.9	64-28
	Extracted 30% RAP	70.6	-29.8	18.6	70-28
	Extracted 40% RAP	70.3	-29	20.3	70-28

For the Vermont mixtures (batch plant), there was no change in the low temperature grade for the PG64-28 and the softer binder PG52-34 (actual grade was PG52-28 as confirmed by tank grading). For the softer binder, the high temperature grade was increased by one grade at the 30 and 40% RAP contents. For the PG 64-28, there was a loss of one high temperature grade for all the mixtures, with minimal to no change in the low temperature grade.

Along with differences in plant type, there were also differences in storage time among the three different projects. For both drum plant projects (NY and NH), the mixtures were siloed for different time periods. Roughly averaged, the mixtures produced by both of the drum plants were siloed at

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temperatures exceeding 300°F for over 2 hours. Meanwhile, the mixtures produced at the batch plant in Vermont had zero silo storage time prior to sampling. As noted above, both drum plant projects (NY and NH) witnessed changes in both high and low temperature PG grade, while the batch plant (VT) project witnessed limited changes to either the high or low temperature grade. It would appear that stiffening, or lack of, witnessed in the asphalt binder grading may be a function of the length and temperature at which the material is stored, as well as the method of mixing (i.e. drum or batch plant).

Table 4. Binder Grading Results – Vermont Mixtures

		Continuous PG Grade (ºC)			
Mixture	**Type**	**High**	**Low**	**Inter.**	**PG Grade**
Vermont 52-34	Tank	56.3	-32.5	12.1	52-28
	Extracted 0% RAP	56.6	-30.1	10.3	52-28
	Extracted 20% RAP	57.8	-31.4	11.9	52-28
	Extracted 30% RAP	59.1	-32.0	11.2	58-28
	Extracted 40% RAP	59.8	-32.8	12.4	58-28
Vermont 64-28	Tank	64.4	-30.2	16.6	64-28
	Extracted 0% RAP	61.7	-28.7	16.8	58-28
	Extracted 20% RAP	60.9	-30.3	15.5	58-28
	Extracted 30% RAP	63.0	-28.5	17.4	58-28
	Extracted 40% RAP	61.9	-29.0	17.0	58-28

Low Temperature Cracking Resistance of Recovered Binders

The low temperature cracking resistance of the recovered binders was measured using the Asphalt Binder Cracking Device (ABCD) and AASHTO R49. The ABCD test method has recently been adopted as AASHTO TP92 and will be published in 2011 edition of the AASHTO Standards. Testing was conducted on binder in the as-recovered condition and after aging in the Pressure Aging Vessel (PAV). The results are shown in Table 5. For the New York and Vermont mixtures, the data indicated the softer binder improved the resistance to low temperature cracking. Since recovered binders represent full blending, the data indicates that if good blending occurs in the mixtures then a softer binder will help alleviate low temperature cracking potential of the mixture.

Similar trends in low temperature cracking performance on the PAV-aged extracted/recovered asphalt binders were found when evaluating the low temperature cracking properties utilizing the procedures outlined in AASHTO R49 (Table 5). However, there were major differences between the resultant critical cracking temperatures of the two procedures. On average, the ABCD

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test predicted low temperature cracking temperatures 7.9^{o}C colder than AASHTO R49 (as-received) and 5.2^{o}C colder for the PAV aged ABCD results. The maximum difference between ABCD and AASHTO R49 measurements was -10.8^{o}C and the minimum difference was -3.6 ^{o}C colder (as received) and -9.4^{o}C and -2.4 ^{o}C colder (PAV aged).

Table 5. Recovered Binders – Low Temperature Cracking Results

State	Base PG Grade Binder	% RAP	ABCD Temp, °C (As-Recovered)	ABCD Temp., °C (PAV Aged)	Critical Cracking Temp., °C AASHTO R49
NY	58-28	30	-36.2	-32.9	-30.3
		40	-37.3	-33.9	-30.2
	64-22	0	-33.8	-31.7	-25.5
		20	-32.5	-31.4	-22.0
		30	-32.3	-30.4	-24.0
		40	-32.1	-30.3	-24.3
NH	64-28	0	-35.7	-34.1	-28.0
		20	-34.6	-34.2	-28.3
		30	-33.2	-32.1	-29.6
		40	-36.2	-30.9	-28.5
VT	52-34	0	-44.2	-40.5	-34.5
		20	-41.8	-39.3	-35.3
		30	-41.5	-38.6	-34.7
		40	-41.7	-38.0	-31.7
	64-28	0	-39.2	-35.0	-28.4
		20	-37.1	-32.8	-29.1
		30	-36.4	-34.7	-28.2
		40	-38.0	-33.7	-28.5

Recovered Binder Master Curves

To completely characterize the stiffness characteristics of the recovered binders, master curves were constructed for the as-recovered and PAV aged binders. Master curves required Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) testing at multiple temperatures. The DSR testing was conducted in accordance with AASHTO T315 “Determining the Rheological Properties of Asphalt Binder Using Dynamic Shear Rheometer” (5). The complex shear modulus (G*) was measured using the DSR at the frequencies and temperatures listed in Table 6. The BBR testing was conducted in accordance with AASHTO 313 “Determining the Flexural Creep

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Stiffness of Asphalt Binder Using the Bending Beam Rheometer" (5). Creep stiffness, S(t), data was collected using the BBR at the loading times and temperatures listed in Table 6.

The data generated from the testing program listed in Table 6 were used to construct a master curve for each recovered binder. The master curve provided the relationship between G* and reduced frequency ω_r at the defining temperature T_d (6). T_d will be discussed later.

Table 6. Conditions Used in the Master Curve Testing.

	Intermediate Temperatures						**Low Temperature**
Test Device	Dynamic Shear Rheometer (DSR)						Bending Beam Rheometer (BBR)
Temperature, °C	10	22	34	46	58	70	-10, -16, -22, -28
Strain Level, %	0.1	1	1	5	10	10	n/a
Frequency (ω), rad/sec	0.100, 0.159, 0.251, 0.398, 0.631, 1.000, 1.59, 2.51, 3.98, 6.31, 10.0, 15.9, 25.1, 39.8, 63.1, 100						n/a
Time, sec.	n/a						8, 15, 30, 60, 120, 240

n/a= Not Applicable

Data were shifted so that the resulting master curve would fit the shape of the Christensen-Anderson model given below in Equation 1, which is a standard model applied to asphalt binders (7). Equations 1 through 5 show that this model has three unknown parameters that require determination, ω_c, R, and T_d. To obtain these parameters, an iterative process comparing the G* predicted by this model to the measured G* must be performed. The three parameters are varied in this process until least squares analyses provide the best values. The result is a master curve at T_d in the form of the Christensen-Anderson model that best fits the measured G*.

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

<u>Where:</u>

$G^*(\omega)$ = complex shear modulus

G_g = glass modulus assumed equal to 1GPa

ω_r = reduced frequency at the defining temperature, rad/sec

ω_c = cross over frequency at the defining temperature, rad/sec
ω = frequency, rad/sec
R = rheological index

Equation 1 shows that each reduced frequency ω_r will provide a predicted G* to be compared against the measured G*. Each ω_r is first computed from the testing frequency ω and the shift factor log a(T) using Equation 2. Log a(T) is the amount of shifting needed to shift the data to T_d. A plot of these shift factors versus temperature is a measure of how the viscoelastic properties of a binder changes with temperature (7).

$$\omega_r = \omega \times 10^{\log a(T)} \qquad [2]$$

Where:
ω_r = reduced frequency at the defining temperature, rad/sec
ω = frequency, rad/sec
Log a(T) = shift factor
T = temperature, °K

For temperatures above T_d, it was found that the shift factor for asphalt binders can be accurately described using a modified Williams-Landel-Ferry (WLF) equation shown as Equation 3 (6).

$$\log a(T) = \frac{-19(T - T_d)}{92 + T - T_d} \qquad [3]$$

However, for temperatures below T_d, the shift factor can be described more accurately by an Arrhenius function shown as Equation 4 (6).

$$\log a(T) = 13016.07\left(\frac{1}{T} - \frac{1}{T_d}\right) \qquad [4]$$

Where:
Log a(T) = shift factor
T = temperature, °K
T_d = defining temperature, °K

Equations 3 and 4 show that T_d divides the temperature data into two regions based on which shift factor is more appropriate, either WLF or the Arrhenius. They also show that T_d is not a standard temperature and will vary from binder to binder.

To construct the complete master curve, the BBR creep stiffness, S(t) was converted to G*. The simplest and most common relationship relating complex shear modulus to stiffness at a certain frequency is shown in Equation 5 (7).

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$$G^*(\omega) \approx \frac{S(t)}{3}, \quad \omega \approx \frac{1}{t} \qquad \text{(t: seconds, } \omega \text{ in rad/s)} \qquad [5]$$

It should be noted that the parameter, ω_c, is a function of a reference temperature which is usually 25°C (77 °F). Accordingly, all the master curves were shifted to the reference temperature of 25°C (77 °F) in order to compare the master curves of the different mixtures.

The Christensen-Anderson model is a very useful tool to compare mixtures because the master curve parameters (ω_c, R, and T_d) have specific physical significance (7). The cross-over frequency, ω_c, is a measure of the overall hardness of the binder. As the cross-over frequency decreases, the hardness of the binder increases. Comparing Tables 7 and 8 indicated that the hardness increases with PAV aging for all of the recovered binders.

Table 7. Binder Rheological Properties – As Recovered Condition

Mixture	**Base PG Grade Binder**	**RAP Content (%)**	**Rheological Properties**		
			R	**w_c, at 25 °C, rad/sec**	**T_d**
New York	58-28	30%	1.962	413.45	-12.49
		40%	1.841	1109.00	-13.57
	64-22	0%	2.146	170.41	-4.26
		20%	2.150	139.43	-3.47
		30%	2.224	95.06	-3.54
		40%	2.228	56.03	-3.45
New Hampshire	64-28	0%	2.053	744.93	-13.63
		20%	2.013	551.99	-12.66
		30%	2.087	296.81	-11.19
		40%	2.102	344.60	-12.27
Vermont	52-34	0%	2.709	380.95	-5.99
		20%	2.588	468.84	-5.80
		30%	2.528	466.37	-6.90
		40%	2.532	370.56	-4.76
	64-28	0%	2.134	557.22	-7.56
		20%	1.958	1219.77	-10.86
		30%	2.121	685.94	-8.72
		40%	1.990	1241.40	-11.63

Examining Tables 7 and 8 individually, it was expected that as the amount of RAP increased the recovered binder would become harder and the hardness of

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a RAP mixture could be reduced by using a softer binder. For the majority of mixtures tested, this trend held true. One example where the trend did not hold true was the 30% RAP New York mixture which was harder than the same mixture with 40% RAP utilizing the PG58-28 binder. This may be attributed to the higher discharge temperature associated with the 30% RAP mixture (330ºF versus 305ºF). Another example in the Vermont mixtures tested was the 40% RAP with PG64-28 binder which exhibited the least hardness. Again, this may be attributed to the lower discharge temperature relative to the discharge temperatures of the other Vermont mixtures. Table 7 also indicated that the Vermont mixtures designed with the softer PG52-34 binder were harder than the same mixtures prepared with the stiffer PG64-28 binder. This may be a result of the higher discharge temperature for the mixtures with the softer binder (PG52-34) as compared to the PG64-28 asphalt binder mixtures.

Table 8. Binder Rheological Properties – PAV Aged

Mixture	**Base PG Grade Binder**	**RAP Content (%)**	**Rheological Properties**		
			R	**w_c, at 25 °C, rad/sec**	**T_d**
New York	58-28	30%	2.791	1.52	6.14
		40%	2.631	6.58	3.88
	64-22	0%	2.627	2.68	5.44
		20%	2.642	2.01	6.26
		30%	2.668	1.45	5.81
		40%	2.924	0.24	12.56
New Hampshire	64-28	0%	2.623	10.17	-1.12
		20%	2.758	3.27	2.61
		30%	2.845	1.65	3.82
		40%	2.743	2.97	1.10
Vermont	52-34	0%	3.511	0.77	6.16
		20%	3.373	1.16	7.10
		30%	3.165	2.59	2.81
		40%	3.223	1.71	5.37
	64-28	0%	2.824	5.18	3.50
		20%	2.747	7.29	3.05
		30%	2.820	4.36	3.76
		40%	2.807	4.78	4.93

The rheological index, R, is an indicator of the rheologic type. As the value of R increases, the master curve becomes flatter indicating a more gradual transition from elastic behavior to steady-state flow. Normally, R is higher for oxidized asphalt (7). Comparison of Tables 7 and 8 showed that R increased with PAV aging of the recovered binders. Examining Tables 7 and 8 individually indicated that the New York and New Hampshire mixtures had a slight increase in R as the percent of RAP content increased. Also, the softer binder used with the New York mixtures reduced the R values slightly. For the Vermont mixtures the R values were higher for the softer binder which could be due to the higher discharge temperatures associated with the soft binders.

The defining temperature, T_d, is an indicator of the temperature dependency of the material. The temperature dependency increases as T_d increases. Tables 7 and 8 illustrate that the binders recovered from the RAP mixtures have slightly higher T_d compared to the binders recovered from the control mixture. Also, as the RAP content is increased, the temperature dependency increased slightly. The data indicated that the use of the softer binder can help reduce the temperature dependency of a mixture.

Procedure for Evaluating the Degree of Blending/Mixing

The degree of blending/mixing between the RAP and the virgin binders will have a significant impact on the volumterics and performance of HMA containing RAP. A method was developed by Bonaquist (2) to assess RAP and virgin binder blending by comparing the measured dynamic modulus |E*| of the mixtures with predicted dynamic modulus from binder testing of as-recovered binders (2). The former represents the as-mixed blending condition of the virgin binder with RAP, and the latter represents the fully blended condition. The |E*| is used in the method because it is highly sensitive to the stiffness of the binder (G*) in the mixture. A brief description of the steps involved in the method is described below:

Step I: Constructing Partial Master Curve at T_r

Since the measured |E*| were tested at temperatures ≥ 4°C, the DSR data, at temperatures ≥ 4°C, was used to construct a partial master curve for the extracted binders by fitting the data to the Christensen-Anderson model.

Step II: Calculating G Values Corresponding to the Test Temperature and Frequency of Measured E**

Using the partial master curve, G* values for any combination of frequency and temperature can be calculated. In order to evaluate the degree of blending, the reduced frequency is calculated at the test frequencies and temperatures used when measuring |E*|. Finally, utilizing the partial master curve from Step I and calculated reduced frequency, the G* value was then computed.

Step III: Predicting E Values Corresponding to G* using the Hirsch Model*

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The binder G* calculated in Step II was inputted in the Hirsch model (Equations 6 and 7) to calculate the predicted mixture dynamic modulus |E*| for fully blended conditions.

$$|E^*|_{mix} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3\,|G^*|_{binder}\left(\frac{VFA\ x\,VMA}{10{,}000}\right)\right] + \frac{1-P_c}{\left[\dfrac{\left(1-\dfrac{VMA}{100}\right)}{4{,}200{,}000}+\dfrac{VMA}{3VFA\,|G^*|_{binder}}\right]} \qquad [6]$$

$$P_c = \frac{\left(20+\dfrac{VFA\,x\,3\,|G^*|_{binder}}{VMA}\right)^{0.58}}{650+\left(\dfrac{VFA\,x\,3\,|G^*|_{binder}}{VMA}\right)^{0.58}} \qquad [7]$$

Where:

|E*|mix = mixture dynamic modulus, psi
VMA = Voids in mineral aggregates, %
VFA= Voids filled with asphalt, %

Step IV: Comparing Measured E Predicted E**

At each temperature and frequency of dynamic modulus test, a measured |E*| (provided by testing) and a predicted |E*| (provided by steps I to III) were collected. The predicted and measured |E*| were then compared statistically to determine if good or poor degree of blending exists. The confidence intervals at a level of significance of α = 0.05 was calculated for the measured and the predicted | E*| . If the two confidence intervals overlap, it is concluded that a good degree of blending exists. The procedure for measuring |E*| is described later in the paper.

Figures 3 through 8 present the degree of blending for the and New Hampshire and New York mixtures at 35°C (10Hz) and 20°C (10Hz and 1.0Hz). The same trend was consistent for the other temperatures and frequencies. The New Hampshire mixtures show good blending between the RAP and virgin binders at the different RAP contents. The discharge temperature for the 20 percent RAP was 8.4°C (15°F) lower than the discharge temperature for the control mixture. Nevertheless, a good degree blending for the 20 percent RAP was observed. All the New York mixtures exhibited a good degree of blending. However, the mixture with 30 percent RAP content produced with the softer binder, PG 58-28, did not have as good

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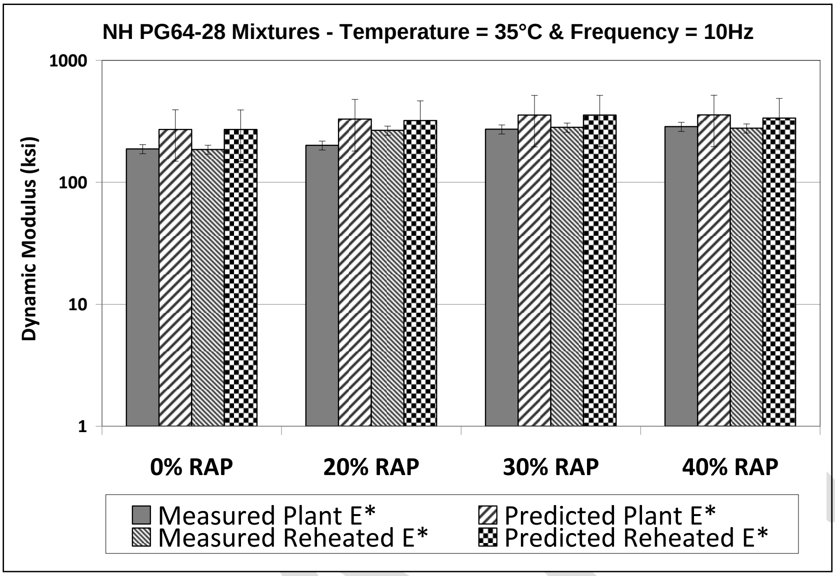

Figure 3. Degree of Blending Comaprison – NH Mixtures (35°C & 10Hz)

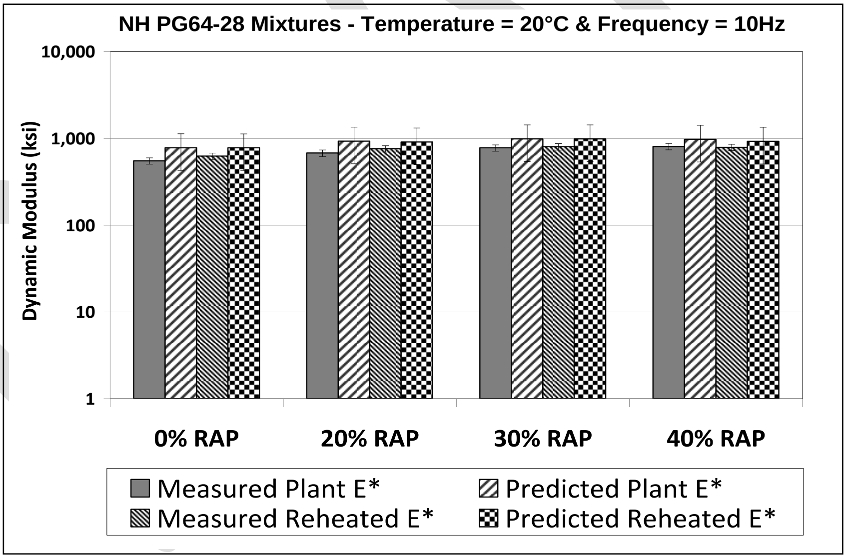

Figure 4. Degree of Blending Comaprison – NH Mixtures (20°C & 10Hz)

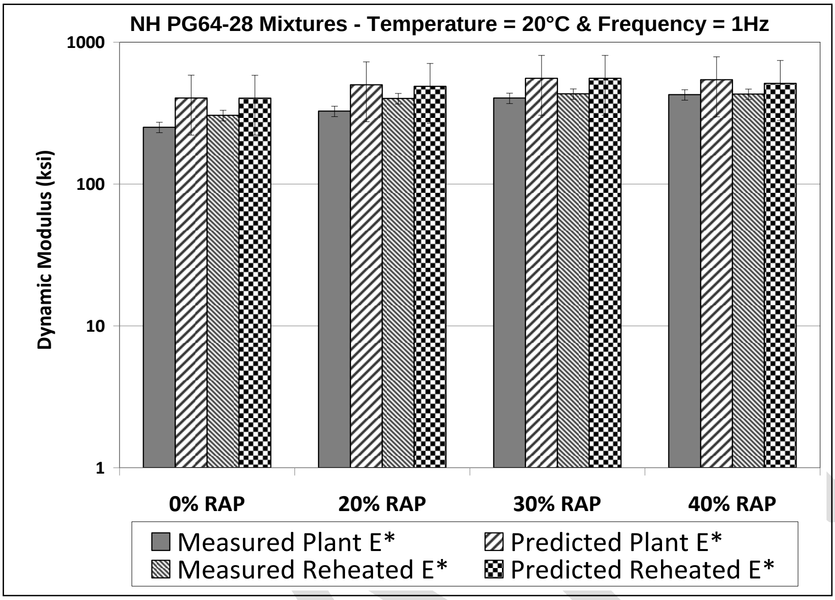

Figure 5. Degree of Blending Comaprison – NH Mixtures (20ºC & 1.0Hz)

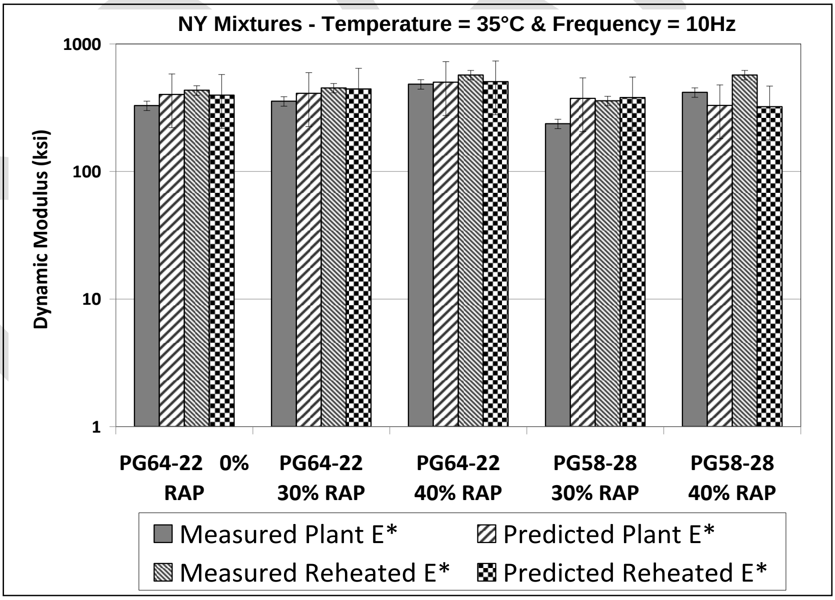

Figure 6. Degree of Blending Comaprison – NY Mixtures (35ºC & 10Hz)

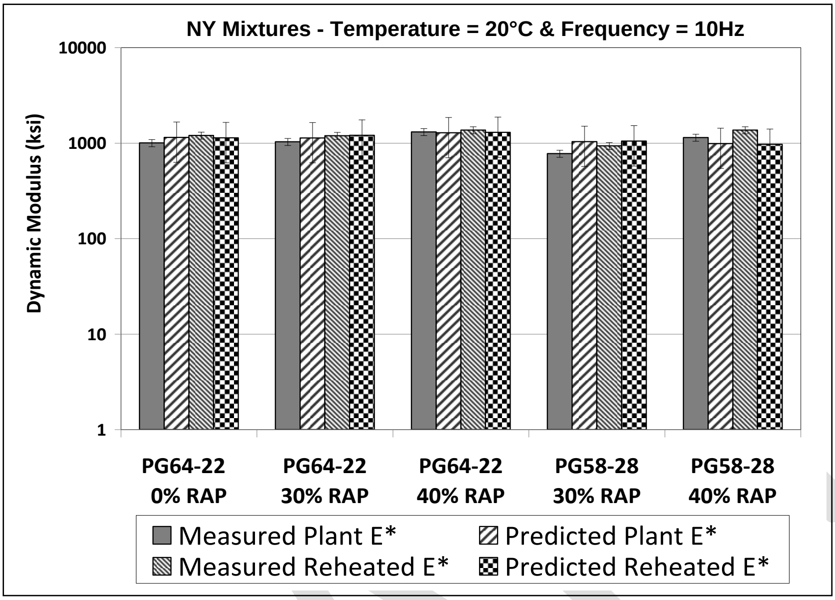

Figure 7. Degree of Blending Comaprison – NY Mixtures (20°C & 10Hz)

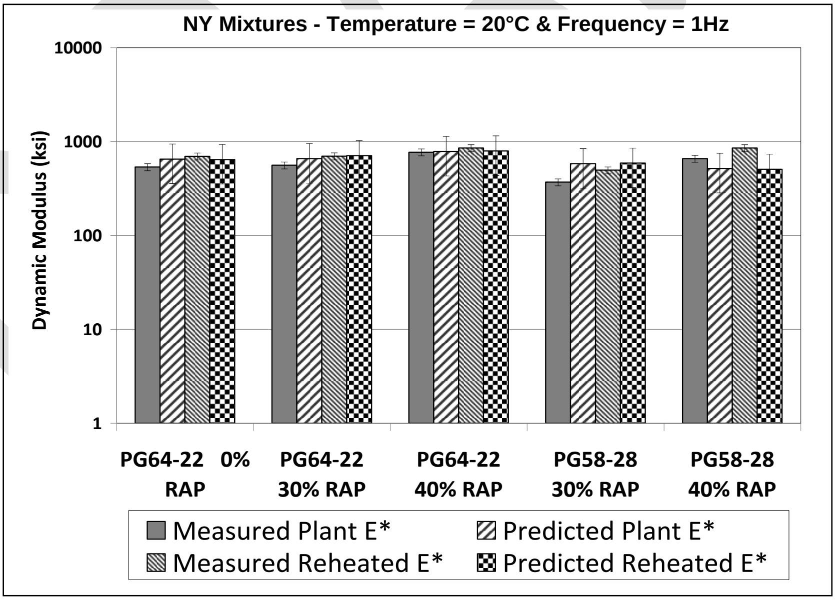

Figure 8. Degree of Blending Comaprison – NY Mixtures (20°C & 1.0Hz)

Mixture Performance Testing

a degree of blending as the other mixtures. Although the measured and predicted confidence interval for the |E*| overlapped, the difference in the mean values between the measured and predicted were higher in comparison to the other mixtures from New York. This may be attributed to the lower discharge temperature for this mixture relative to the other NY mixtures. It should be noted, however, that the 30 percent RAP content with the stiffer binder (PG 64-22) had as good degree of blending as the rest of the mixtures at the lower discharge temperature. For the majority of the Vermont mixtures there was a good degree of blending.

Performance Related Mixtures Testing and Analysis

Stiffness - Dynamic Modulus

In order to determine the dynamic modulus |E*|, test specimens were placed in the Asphalt Mixture Performance Test (AMPT) device and subjected to a sinusoidal (haversine) axial compressive stress at the different temperatures and frequencies. The resultant recoverable axial strain (peak-to-peak) was measured. From this data the dynamic modulus was calculated. Plant compacted and reheated specimens were prepared for dynamic modulus testing in accordance with AASHTO PP60 “Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor” (10). The final test specimens had an air void content of 7.0 ± 1.0%. Dynamic modulus testing was conducted in accordance with TP62 “Determining Dynamic Modulus of Hot-Mix Asphalt (HMA)” (10).

Each specimen was tested at temperatures of 4.4°C, 20°C, and 30 or 35°C (40ºF, 68ºF, and 86 or 95ºF) and loading frequencies of 25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, 0.1 Hz, and 0.01 Hz (30 or 35°C only) in accordance with AASHTO PP61 “Developing Dynamic Modulus Master Curves for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)” (10). A test temperature of 30°C was used as the high test temperature for the PG52-34 mixtures to ensure contact of the glued buttons to the specimen was achieved. The mixture master curves for each mixture were then developed from the dynamic modulus data at a reference temperature of 20ºC (68ºF).

Figure 9 illustrates the effect of RAP content on the stiffness of the New York mixtures. Generally, as the RAP content increased, the stiffness of the mixtures increased. This was true for the 30% and 40% RAP mixtures. However, the increase in the stiffness of the 30% RAP mixture was not significant in comparison to the control mixture. Moreover, the 20% RAP mixture had lower |E*| than the control mixture. This mixture was stored in the silo for a much shorter time. This illustrated the significance of storage time on the stiffness of the mixtures.

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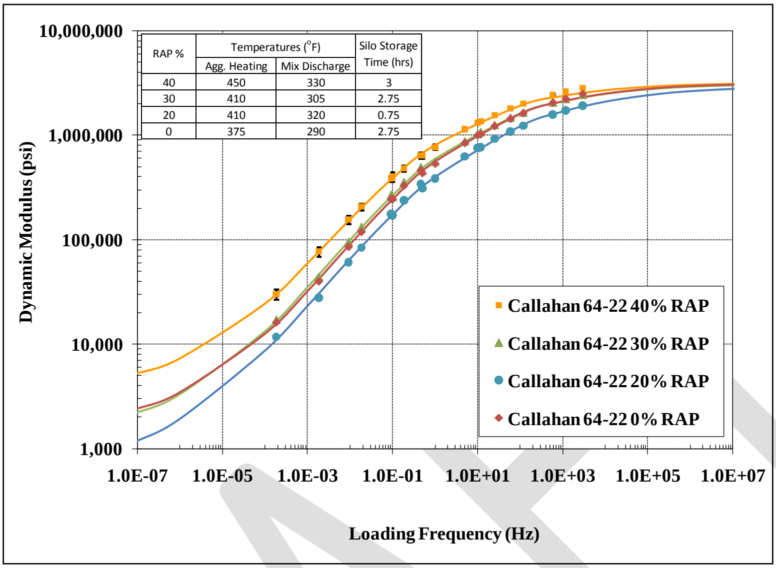

RAP %	Temperatures (°F)		Silo Storage Time (hrs)
	Agg. Heating	Mix Discharge	
40	450	330	3
30	410	305	2.75
20	410	320	0.75
0	375	290	2.75

Figure 9. Comparison of NY Mixture Master Curves with Varying Percentages of RAP.

Figure 10 indicated for the same mixture and same percentage of RAP (30%) with similar production parameters (aggregate temperature, discharge temperature and storage time), the use of a softer binder can mitigate the stiffing due to the addition of high percentages of RAP in the mixture. However, when RAP content increased to 40%, the master curves were much closer (Figure 11). A further review of the production data indicated that the NY 58-28 40% RAP mixture was stored for 1 hour longer than the NY 64-22 40% RAP mixture, possibly indicating that longer storage times may nullify the possible benefit of the softer asphalt binder. This data agrees well with the rheological properties ω_c and R of the extracted and recovered mixture binder which indicated recovered binder from the softer mixture had less hardness. This trend was noted for the New York mixtures, but not for the Vermont mixtures. The exact cause of this discrepancy is unknown. A softer binder grade was not used for the New Hampshire mixtures.

Figures 12 and 13 each show an example of two master curves for the same mixture. One set of specimens was compacted at the plant during production and the other was reheated using the procedure outlined previously

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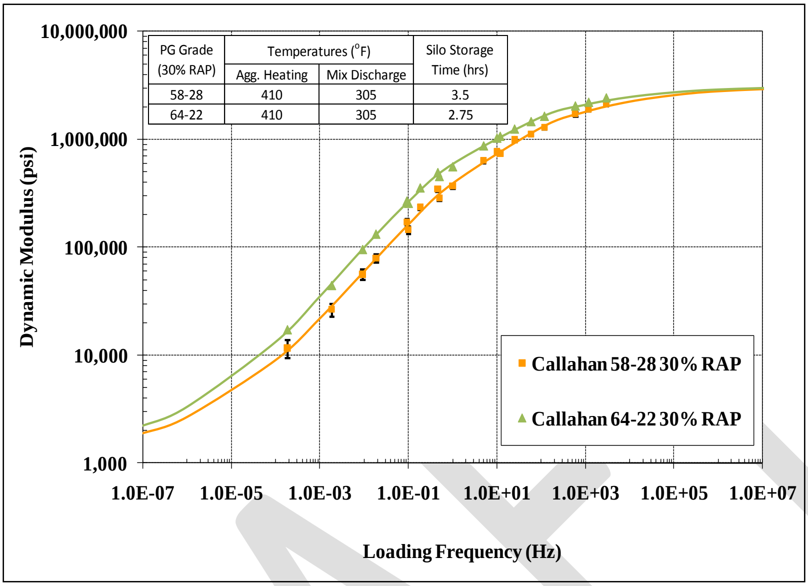
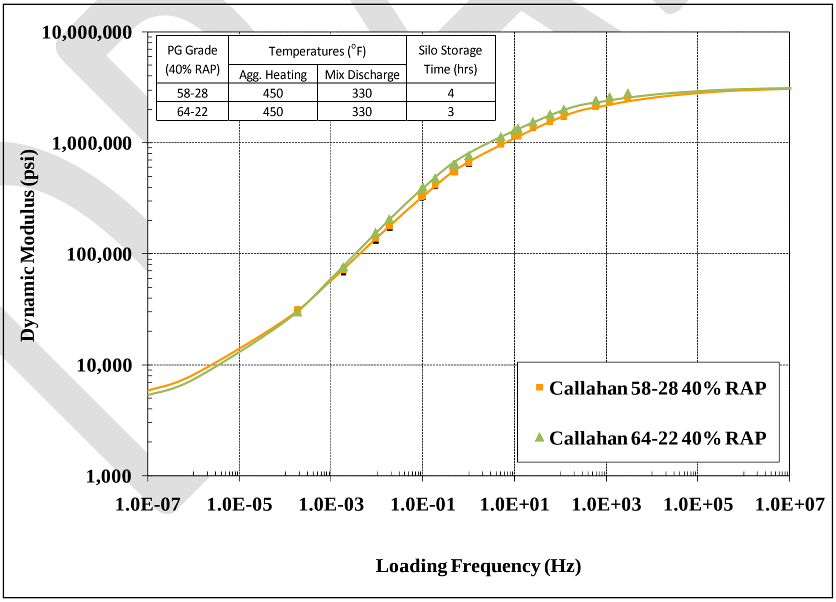


PG Grade (30% RAP)	Temperatures (°F)		Silo Storage Time (hrs)
	Agg. Heating	Mix Discharge	
58-28	410	305	3.5
64-22	410	305	2.75

Figure 10. Comparison of NY Mixture Master Curves of Similarly Produced Mixtures Fabricated with a Stiff and Soft Binder.



PG Grade (40% RAP)	Temperatures (°F)		Silo Storage Time (hrs)
	Agg. Heating	Mix Discharge	
58-28	450	330	4
64-22	450	330	3

Figure 11. Comparison of NY Mixture Master Curves of Similarly Produced Mixtures Fabricated with a Stiff and Soft Binder

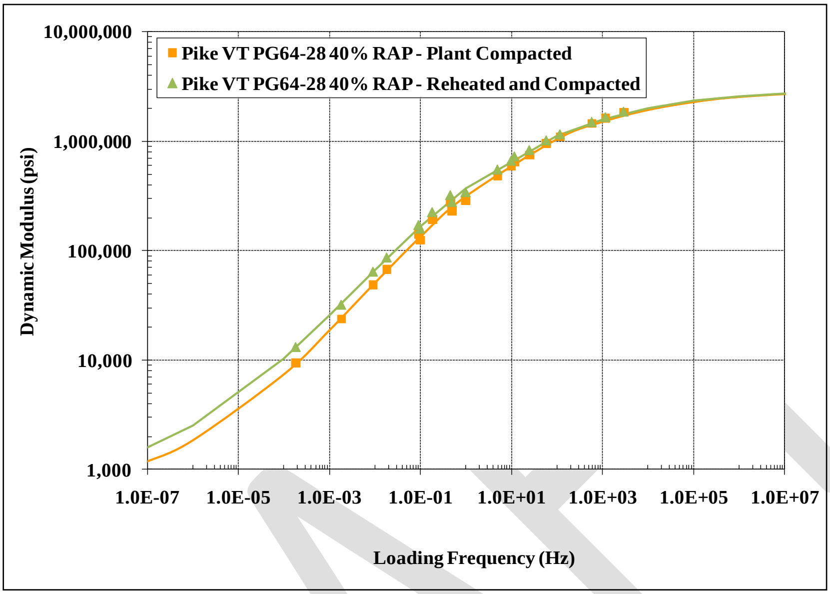


Figure 12. VT Mixture Master Curves Effect of Reheating Loose Mixture Compared to Mixture Compacted During Production.

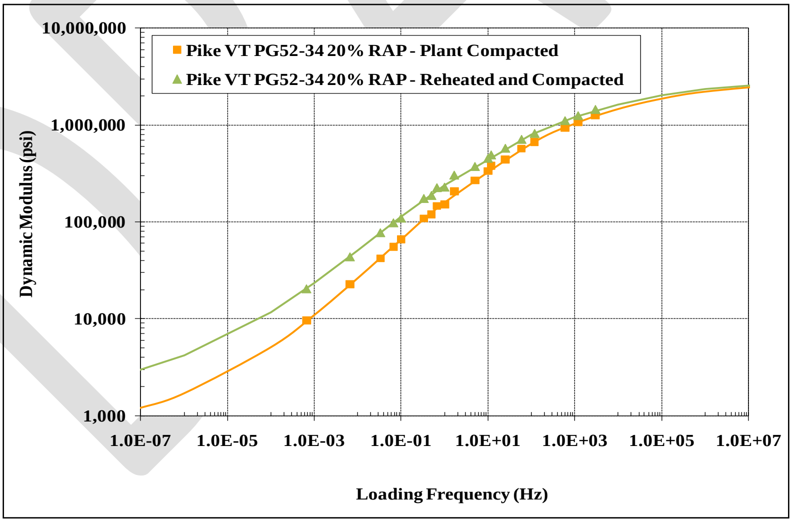


Figure 13. VT Mixture Master Curves Effect of Reheating Loose Mixture Compared to Mixture Compacted During Production.

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and compacted in the laboratory. The data indicated that the reheated mixture exhibited higher stiffness than the mixtures compacted at the plant. This trend was fairly consistent for the sets of mixtures tested. However, as Figure 14 indicates, as the RAP content increased, the magnitude of the reheating influence, as indicated by the ratio of the dynamic modulus between the reheated loose mix specimens and the plant QC lab compacted samples, decreased. When comparing all projects: The average dynamic modulus increased 33% when the Virgin mixtures were reheated; the average dynamic modulus increased 47% when the 20% RAP mixtures were reheated; the average dynamic modulus increased 27% when the 30% RAP mixtures were reheated; and the average dynamic modulus increased 12% when the 40% RAP mixtures were reheated.

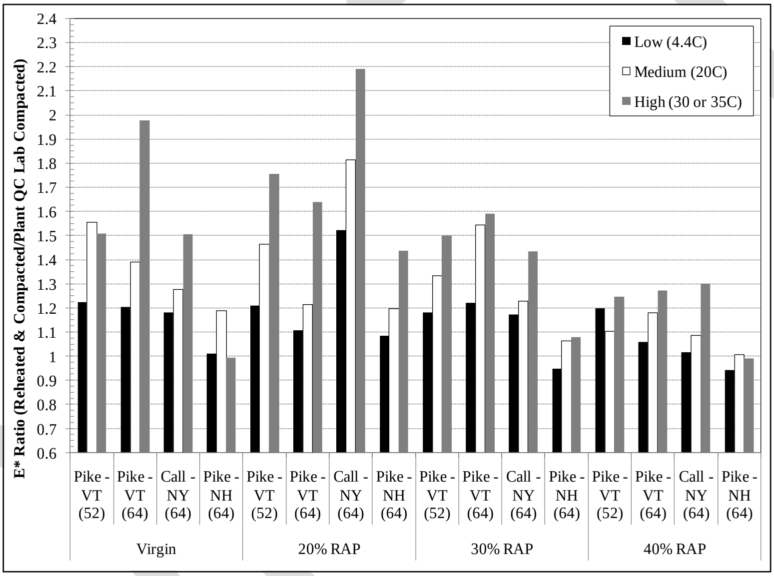

Figure 14. E* Aging Ratio Comparing the Increased Stiffness Due to Reheating Loose Mix vs Samples Prepared at Plant's QC Lab

This would indicate that the highly oxidized RAP binder is minimally affected by the additional reheating in the laboratory oven. The significance of this finding is that many times researchers do not report how the materials were handled prior to sample fabrication (i.e. – reheated or not, length of oven time, temperatures, etc.). However, as the data in Figure 14 would indicate, mixture modulus changes do occur and without proper knowledge of how the materials were handled, a literature review or State of the Practice report summarizing mixture performance may be misleading.

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Another impact of the reheating process is how the mixture modulus changes as the RAP content increases. As noted earlier, there was a clear increase in the mixture modulus, as determined by the dynamic modulus testing, with the addition of RAP. Overall, when averaging the dynamic modulus at the different test temperatures and loading frequencies, the increase in mixture modulus due to the addition of RAP followed the following trend:

- Plant QC Lab Compacted
  - 0 to 20% RAP: 8% increase in mixture modulus
  - 0 to 30% RAP: 29% increase in mixture modulus
  - 0 to 40% RAP: 49% increase in mixture modulus
- Loose Mix Reheated and Compacted
  - 0 to 20% RAP: 17% increase in mixture modulus
  - 0 to 30% RAP: 24% increase in mixture modulus
  - 0 to 40% RAP: 27% increase in mixture modulus

The comparisons above show that the reheating process also reduces the sensitivity to the mixture modulus changing due to the addition of RAP. This is most likely due to continued oxidation aging of the virgin binder present in the mixture.

Cracking Resistance Testing - Overlay Test Device

Mixtures were tested for their cracking resistance utilizing the Overlay Tester (OT). The OT device applies tension loading (in displacement control) to test specimens while recording load, displacement, temperature and time (11). It should be noted that this test is a crack propagation test, not a crack initiation test. This means that the test measures the mixture's ability to resist the propagation of a crack from the bottom of the specimen to the top due to a predetermined displacement.

For this study, the Texas Department of Transportation specification (Tex-248-F) for testing bituminous mixtures with the OT was followed (11). Specimens were fabricated from reheated loose plant produced mixture in the SGC and the specimens were then trimmed. The air void level of the trimmed specimens was 7.0±1.0%.

A joint opening (displacement) of 0.06 cm (0.025 inch), test temperature of 15°C (59°F), and a failure criteria of 93% reduction in the load measured during the first cycle or 1,200 cycles (whichever occurs first) were used. The average results of the testing are shown in Table 9. Generally, mixtures exhibiting more cycles to failure exhibit more cracking resistance.

The data from the OT test indicated that generally, the cracking resistance was reduced as the percentage of RAP in the mixture increased. This data agrees with the stiffness testing which indicated that the addition of RAP stiffened the resultant mixture. Stiffer mixes generally are more susceptible to cracking at moderate to high levels of deflection. Also, the data agreed with the rheological parameters obtained from constructing the master curves for the as-recovered and PAV aged binders. The rheological parameters such as ω_c illustrated the use of RAP would increase the stiffness of the mixtures.

Table 9. Cracking Test Results from Overlay Tester

Mixture	NMAS	Percent RAP	Binder Grade	Average OT Cycles to Failure
New York	12.5 mm	0%	PG64-22	111
		20%	PG64-22	121
		30%	PG64-22	90
		40%	PG64-22	22
		30%	PG58-28	70
		40%	PG58-28	13
New Hampshire	12.5 mm	0%	PG64-28	279
		20%	PG64-28	68
		30%	PG64-28	113
		40%	PG64-28	50
Vermont	9.5 mm	0%	PG52-34	1,200
		20%	PG52-34	1,200
		30%	PG52-34	217
		40%	PG52-34	112
		0%	PG64-28	1,032
		20%	PG64-28	127
		30%	PG64-28	126
		40%	PG64-28	44

Moreover, the data indicates that the use of the softer grade binder for the New York mixtures did not have the desired effect of improving the cracking resistance of the mixtures. However, the softer binder improved the cracking characteristics of the Vermont RAP mixtures. It should be noted that for the New York mixtures, the softer binder was only one grade softer than the stiffer binder while for the Vermont mixtures the softer binder was two grades softer than the stiffer binder.

Other general trends found from the OT results were that increased asphalt content resulted in higher cycles to failure. On average, the NY mixtures resulted in the lowest cycles to failure values and also had the lowest asphalt content (5.2%) of the projects evaluated. Meanwhile, the mixture with the highest cycles to failure, Vermont, also had the highest asphalt content (approximately 6.6%). Also, silo storage may have increased the aging, and therefore cracking susceptibility, of the asphalt mixtures. The Vermont mixtures, produced in the batch plant, did not undergo silo storage.

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Meanwhile, both the New York and New Hampshire projects underwent silo storage at elevated temperatures.

Rutting & Moisture Susceptibility– Hamburg Wheel Tracking Device

The effect of high RAP content and production parameters on the rutting and moisture susceptibility of the mixtures were evaluated in accordance with AASHTO T324 “Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)” (5).

Gyratory specimens were fabricated from loose plant produced mixture using the reheating procedure previously outlined to an air void level of 7.0±1.0% as required by AASHTO T324. Testing in the HWTD was conducted at a test temperature of 50ºC (122ºF). Testing terminated at 20,000 wheel passes or until visible stripping was noted. The rut depth versus numbers of passes of the wheel is plotted to determine the Stripping Inflection Point (SIP). The SIP gives an indication of when the test specimen begins to exhibit stripping (moisture damage). Table 10 shows the results of the moisture susceptibility testing.

The moisture susceptibility and rutting data indicated that all the Vermont mixtures performed poorly regardless of the binder utilized, amount of RAP, or production parameters. This might be the result of poor quality fine materials used. During the test it was observed that uncoated fine materials were coming out of the sample. All the New Hampshire mixtures passed the moisture susceptibility and rutting test, thereby indicating that the production parameters utilized were adequate in producing a moisture and rut resistant mixture. Also, the mixture incorporating RAP showed decreased rutting potential as the amount of RAP in the mixture increased. The New York mixtures incorporating RAP performed better that the control mixture in rutting and moisture susceptibility. Similar to the data for the New Hampshire mixtures, the addition of RAP to the mixtures decreased the amount of rutting. This correlates well with the stiffness data which indicated RAP mixtures were stiffer than control mixtures. Stiffer mixes will be less susceptible to permanent deformation. Moreover, since the mixtures passed the moisture susceptibility tests (with the exception of the 30% RAP mixtures) it indicated that the production parameters utilized were adequate in fabricating a mixture without an adhesion problem. Examination of the 30% RAP mixture data indicated that the discharge temperatures for these mixtures was lower (305°F) than all the mixtures that passed the moisture susceptibility test which were discharged above 320°F. This may have been the cause for these mixture failures. The use of a softer binder did not consistently or significantly improve or decrease the rutting potential or moisture susceptibility characteristics of the mixture.

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Finally, the results agreed with analysis for the degree of blending and the rheological properties from the Christensen-Anderson model. The good degree of blending should cause the binder in the mixture to be stiffer and accordingly harder to peal from the aggregates. This should improve the mixtures moisture and rut susceptibility.

Table 10. Moisture Susceptibility and Rutting HWTD Test Results

State	NMAS	% RAP	Binder Grade	Average Stripping Inflection Point	Avg. Rut Depth at 10,000 Cycles (mm)	Avg. Rut Depth at 20,000 Cycles (mm)
NY	12.5 mm	0	PG64-22	7,200	6.62	n/a
		20	PG64-22	NONE	1.93	3.17
		30	PG64-22	13,370	2.67	8.97
		40	PG64-22	NONE	1.55	2.13
		30	PG58-28	17,400	2.63	6.18
		40	PG58-28	NONE	2.12	3.37
NH	12.5 mm	0	PG64-28	NONE	2.15	3.61
		20	PG64-28	NONE	1.70	2.21
		30	PG64-28	NONE	0.49	0.61
		40	PG64-28	NONE	0.93	1.30
VT	9.5 mm	0	PG52-34	850	n/a	n/a
		20	PG52-34	1,600	n/a	n/a
		30	PG52-34	2,050	n/a	n/a
		40	PG52-34	1,450	n/a	n/a
	9.5 mm	0	PG64-28	1,350	n/a	n/a
		20	PG64-28	2,100	n/a	n/a
		30	PG64-28	2,650	n/a	n/a
		40	PG64-28	2,900	n/a	n/a

NONE = Mixture passed 20,000 cycle test with no SIP.
n/a = Test terminated prior to reaching specified cycle due to maximum deformation exceeding 20 mm.

Mixture Workability – Asphalt Workability Device (AWD)

Because of the potential decrease in mixture workability due to the incorporation of RAP in the mixtures, workability evaluations of each of the plant produced mixtures were completed. These evaluations were conducted using a HMA workability device developed by the University of Massachusetts Dartmouth Highway Sustainability Research Center (HSRC).

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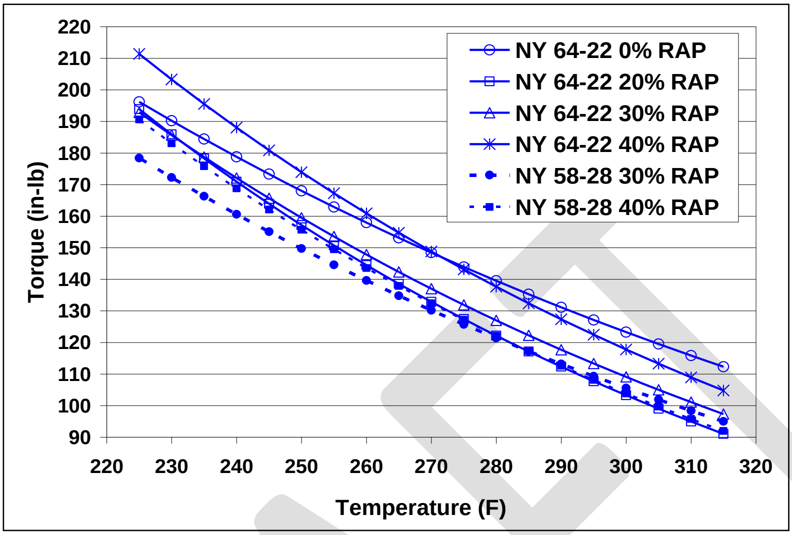

Figure 15. Workability Test Results - 12.5 mm New York Drum Plant Mixtures

This device is known as the Asphalt Workability Device (AWD) and has been used previously to evaluate high percentage RAP mixtures as well as mixture incorporating WMA additives (12*)*. The AWD operates on the torque measurement principles that have been previously established (13). Examination of the workability data shown in Figure 15 for the New York indicated that the addition of RAP to the mixtures decreased the mixture workability as compared to the respective control mixture without RAP. The workability reductions were generally larger as the amount of RAP increased. The workability data for the New Hampshire showed the same trend. The workability data for the Vermont mixtures did not follow any defined trend and the data is not presented. This may be attributed to overall lower mixture modulus, a coupled effect of softer asphalt binders, higher asphalt binder contents, and reduced (in this case no) additional aging due to silo storage.

Finally, the New York mixture data suggested that the use of the softer binder could improve the workability of RAP mixtures to a level comparable to the control mixture produced with the stiffer binder. This trend should be verified on a case-by-case basis.

Conclusions

In this study, plant produced mixtures were obtained from high RAP projects located in New York, New Hampshire and Vermont. The RAP percentages in

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the mixtures ranged from 0 to 40 percent. Production data such as plant type, mixing and discharge temperatures, and silo storage time were collected to determine their effect on the degree of blending between the RAP and virgin binders. Also, the effect of the production data on the workability and performance of the mixtures in terms of cracking, rutting, and moisture damage was evaluated. Based on the testing and the data analysis, the following conclusions were made:

1. The test results collected in this study showed that both plant production and silo storage practices, as well as how the material is handled prior to specimen fabrication (i.e. – reheating loose mix or not) will have an impact on the mixture performance. Therefore, to properly document research findings, it is important to also document how the mixtures were produced and handled prior to testing. In general, discharge temperatures and silo storage factors were found to highly influence mixture stiffness and cracking properties.

2. The master curve parameters (ω_c, R, and T_d) of the as-recovered and PAV aged recovered binders showed that as the amount of RAP increased the recovered binder would become harder and that the hardness of a RAP mixture could be reduced by using a softer binder. This agreed in general with the mixture tests.

3. The data indicated that the reheated mixtures exhibited significantly higher stiffness than the mixtures compacted at the plant. Also, the sensitivity of mixture stiffness to increased RAP content decreased when reheated as compared to the sensitivity (or change in dynamic modulus) found when evaluating the plant QC lab compacted specimens.

4. The analysis method used to evaluate the degree of blending between the RAP and virgin binders illustrated that certain production parameters (discharge temperature) may have an impact on the relative degree of blending between the RAP and virgin binders.

5. The Overlay Tester results showed that the cracking resistance was reduced as the percentage of RAP in the mixture increased. This data agrees with the stiffness testing of the mixtures and the rheological parameters obtained from constructing the master curves for the as-recovered and PAV aged binders. The rheological parameters such as ω_c illustrated the use of RAP would increase the stiffness of the mixtures.

6. The data indicated that the use of the softer grade binder for the New York mixtures did not have the desired effect of improving the cracking resistance

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of the mixtures. However, the softer binder improved the cracking characteristic of the Vermont RAP mixtures.

7. Among the New Hampshire and the New York mixtures, only the New York mixture with 30 percent RAP failed moisture damage in the HWTD. The discharge temperature for this mixture was lower (305°F) than all the mixtures that passed the moisture susceptibility test which were discharged above 320°F.

8. The workability data indicated that the addition of RAP decreased the mixture workability as compared to the respective control mixture without RAP. The workability reductions were generally larger at higher RAP contents. Data suggested that the use of the softer binder could improve the workability of RAP mixtures.

Acknowledgements

The authors would like to acknowledge the participating state agencies for the Transportation Pooled Fund Project TPF-5(230) “Evaluation of Plant-Produced High-Percentage RAP Mixtures in the Northeast” which are New Hampshire (Lead State), Maryland, New Jersey, New York, Pennsylvania, Rhode Island, and Virginia. Also the authors would like to acknowledge Callanan Industries in New York, Pike Industries, Inc. in New Hampshire and Vermont who produced and supplied the mixtures for this project. Pike Industries, Inc. also performed all of the binder extractions and recoveries for this study.

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