Can We Add More RAP?  
A Study of Extracted Binder Properties from Plant Produced Mixtures with up to 25% RAP

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Submitted for Presentation at the 2010 TRB Annual Meeting and Publication in the Transportation Research Record: Journal of the Transportation Research Board

Word Count: 6632 words (3882 text, 2750 tables and figures)

March 2010
ABSTRACT

This paper presents the results of a study conducted by the New Hampshire Department of Transportation (NHDOT) in cooperation with three local paving contractors. Plant-produced HMA mixtures containing RAP percentages from 0% to 25% were obtained from seven different batch plants. A total of 28 mixtures were sampled and sent to the binder testing laboratories at NHDOT and Pike Industries, Inc. The virgin binders were also sampled and sent for binder testing. Binders were extracted and recovered from all of the mixtures and were tested to determine the PG binder grade and critical cracking temperature. The effect of the RAP at various percentages on the binder properties was evaluated. The high-end PG grades were found to remain the same or only increase one grade for the mixtures tested. The low-end PG grades also remained the same or only bumped one grade, and the critical cracking temperatures only changed by a few degrees for the mixtures examined in this study. The results of this study lead to a change in the implementation of the new NHDOT specification regarding the use of recycled asphalt binder in HMA.
INTRODUCTION
The use of reclaimed asphalt pavement (RAP) in Hot Mix Asphalt (HMA) has been steadily increasing in recent years. At the same time, researchers have been studying the effect of the RAP on the properties and performance of the mixture. There is still a significant amount that the industry does not understand about how the aged materials in RAP blend, or co-mingle, with the virgin materials and the extent of the effect on the properties and performance of the final mixture. Most agencies have relied on guidance from the federal level, results of national studies, and the local experience of paving engineers and contractors. As the economic forces have encouraged the use of more RAP, agencies have begun to investigate the use of RAP in more detail.

In New Hampshire, the use of RAP in HMA has become common practice over the last decade, with almost every asphalt mixture placed on state jobs containing some percentage of RAP. The NH state specifications for asphalt concrete containing RAP limited the amount of RAP to a maximum of 15% of the total batch weight for wearing course mixtures. Binder and base courses allowed 30% RAP from drum mixers, but only 20% from batch plants. Unknown RAP sources were also limited to 15% of the total batch weight (1).

With the rising costs of liquid asphalt that the industry has experienced recently, paving contractors in NH wanted to be able to increase the amount of RAP in state mixtures. NHDOT required a low-end PG grade bump for the higher RAP contents, based on national guidelines and recommendations. AASHTO M 323, Table 2 recommends the selection of virgin binder to be one grade softer than normal for mixes containing between 15% to 25% RAP. In New Hampshire, this requires changing the PG binder grade from -28 to -34. PG XX-28 binder is the standard material used in the New England region and is very easy to obtain. The PG -34 binder is more expensive to obtain and the use of the higher RAP percentages requiring the PG -34 binder would diminish the cost benefit of RAP use.

During meetings to discuss increasing the allowed use of RAP, Pike Industries, Inc. shared preliminary test data comparing the properties of virgin and RAP binders extracted from plant-produced mixtures. This information prompted a cooperative investigation by NHDOT and local paving contractors into how the properties of the asphalt binder change with the addition of different percentages of RAP. Plant-produced mixtures were sampled, and then the binder from these mixtures was extracted and recovered for testing in the laboratory. The results of the study lead to a change in the implementation of the new NHDOT specifications (2) with regards to the use of recycled binder in HMA. This paper presents the results of the study conducted during the past year.

Two similar studies have been conducted by other researchers; the summary of findings is presented in the following paragraphs. A study by the University of Rhode Island (3) studied the effect of RAP on binder properties by blending extracted RAP binder with virgin binder in various percentages. The results of BBR testing showed an increase in stiffness and a decrease in m-value for all temperatures with the addition of RAP. A change in the low temperature PG grade was not observed until a level of 30% RAP binder for the PG 58-28 virgin binder and a level of 75% for the PG 64-22 binder. The high-end binder grade was increased for all levels.

McDaniel, et al. (4, 5) conducted a study of plant produced mixtures at four RAP contents and two virgin binder grades. The addition of RAP increased the stiffness and critical cracking temperature of the binders that were extracted and recovered from the mixtures. For some mixtures, the indirect tensile strength of the mix increased with the addition of the RAP, but did not offset the increase in stiffness with respect to low temperature cracking. The
recommendation of the team from this study is to bump the low-end binder grade to improve the thermal cracking performance of the high RAP mixtures.

MATERIALS AND METHODS

Materials
Materials for this study were obtained from three different producers and seven asphalt batch plants. Asphalt binder extracted from a total of 28 mixtures was tested; information on the mixtures is summarized in Table 1. The virgin asphalt binders were sampled in-line from each of the plants during production of the test mixtures. There were two suppliers for the asphalt binders; the Pike and Continental binders were supplied by Pike Industries and the Brox binder was supplied by Aggregate Industries. The mixing temperature for both binder sources was 160°C. The plant produced HMA mixtures were sampled at each site by the producer and shipped to the testing laboratories.

All mixtures were Superpave 50 gyration, 12.5 mm NHDOT approved mixtures. The gradation for all the RAP percentages was kept constant at each plant. The RAP stockpiles at each plant had different asphalt contents, so the percentage of binder replacement is different at the various RAP contents. All of the RAP stockpiles were unknown source, except for the Pike-Poland plant where milled materials from a specific project were used. Table 2 summarizes the total reused binder (TRB) and percent binder replacement for each mixture. Equations (1) and (2) show the calculations for TRB and percent binder replacement, respectively.

\[
TRB = \frac{% \text{RAP in mix} \times \% \text{ac in RAP}}{100}
\]

\[
% \text{binder replacement} = \frac{TRB}{% \text{ac in mix}} \times 100
\]

Methods
The binder extraction, recovery, and testing were performed on duplicate samples by the NHDOT and Pike laboratories for six of the mix series. Two of the Pike mix series were only tested at the Pike laboratory. Only one replicate was performed at each laboratory. The specific testing procedures followed in each laboratory are summarized below.

NHDOT Procedure
Abson recoveries (AASHTO T 170) were performed by centrifuge using trichloroethylene as a solvent. The recovered binders were RTFO and PAV aged to maintain consistent testing procedures with the virgin binders. DSR testing was performed on the original, RTFO, and PAV aged binders. Both BBR and DTT were performed on the PAV aged binders (AASHTO T 313, T 314, and T 315). The PG grades of the recovered binders were determined using AASHTO M 320 Table 2, and the critical cracking temperatures (T_{cr}) were determined using AASHTO PP-42. The NHDOT uses an additional procedure to remove the last traces of trichloroethylene from the recovered binder to be tested as the “original” condition in the DSR. The procedure is as follows:

1. Place 35 g of asphalt in a rolling thin film oven bottle
2. Place bottle in oven at 163°C and rotate for 10 minutes
3. Remove bottle from oven and pour into 2 oz tin
4. Pour sample from tin into molds for testing on the DSR at desired temperature
Pike Procedure
Abson recoveries (AASHTO T170) were performed by centrifuge using trichloroethylene as a solvent. The high temperature PG grades were determined using the TA Instruments Navigator software for the DSR. The software requires that the binder be tested at two temperatures and then an Arrhenius calculation is used to determine the failure temperature. Testing on the original and RTFO binders was done at 58 °C and 64 °C or at 64 °C and 70 °C; therefore, high temperature PG grades above 70 are extrapolated. The low temperature PG grades were determined using AASHTO M 320 Table 1. The low-end failure temperatures for the binders were calculated using an Excel spreadsheet and BBR test results at two temperatures. The spreadsheet uses a linear regression to calculate the m-value failure temperature and a logarithmic regression to calculate the S failure temperature. The greater of these two temperatures is selected and 10 degrees is subtracted to determine the low-end failure temperature. The calculation of the low-end failure temperature was done for both the Pike and DOT data using the same Excel spreadsheet developed by Pike. DTT testing was not performed by Pike, so critical cracking temperature is not available from the Pike analysis.

RESULTS
This section presents the PG binder grade, low-end failure temperature, and critical cracking temperature results obtained from the testing of the virgin binder, extracted RAP binder, and the binders extracted from each of the mixtures.

Comparison of Virgin Binder and Mix
Figure 1 shows the comparison of the testing results for the virgin binder and the binder extracted from the virgin mix. The virgin binder and mixture were not available from the CPI-Litchfield plant. The high temperature PG grade, low temperature PG grade, low-end failure temperature, and critical cracking temperature are shown in graphs (a), (b), (c), and (d), respectively. The results from the DOT lab testing and Pike Lab testing are shown.

The DOT results show an increase of at least one PG grade on the high side after the binder goes through the mixing process for all plants (Figure 1a). The Pike results show an increase for all plants except for the Pike-Poland location; this location had an original DSR G*/sinδ value of 0.930 kPa at 70°C measured by Pike, just below the minimum 1.0 kPa criteria. Figure 1b shows that the low temperature PG grade remains the same for all of the DOT results. The Pike results show a drop of one PG grade for three locations; however, the BBR m-values for these three locations were 0.299, 0.299, and 0.294 at -18°C, just below the 0.300 minimum criteria. Figure 1c shows how little difference there is between the low-end failure temperatures. The one PG -34 binder showed a drop of two low temperature grades after running through the plant. The critical cracking temperatures for the virgin binders and mixtures are within a few degrees, as shown in Figure 1d.

RAP Binder Properties
The high PG grade, low PG grade, low-end failure temperature, and critical cracking temperature for the extracted RAP binders are shown in Figures 2a, 2b, 2c, and 2d, respectively. The extracted binders have high PG grades ranging from 76 to 94. The PG 76 RAP is the milled material; all others are unknown sources. The high PG grades determined from the Pike testing are lower than those determined from the DOT testing; some of this difference is likely due to
the use of extrapolation software by Pike (testing was not performed at the higher temperatures). The low PG grades for the RAP range from -10 to -22; with the milled material having the lowest low PG grade and low-end failure temperature. The milled material also has the best critical cracking temperature, as shown in Figure 2d.

**Comparison of RAP Mixtures**

*High PG Grade*

The high PG grades for each of the mixtures as determined from both the NHDOT and Pike binder testing are shown in Figure 3. The high PG grades increase only one binder grade with the addition of RAP for the mixtures tested. The NHDOT test results show this increase only occurred with one mixture and the grade bump was only apparent above the 20% RAP level. The Pike data shows this bump happening for several of the mixtures at 15% and 20% RAP levels.

*Low PG Grade and Low-end Failure Temperature*

Figures 4 and 5 show the low PG grades and low-end failure temperatures from the BBR results, respectively. The NHDOT analysis shows a higher low PG grade at the 15% RAP level for some mixtures and no change in grade for other mixtures. The Pike data shows a consistent low PG grade for most mixtures; one mixture showed a higher low PG grade at the 20% RAP level. One plant, Pike-Poland, showed a bump in the low PG grade for the 25% RAP mixture. The low-end failure temperatures calculated from the BBR testing show only a few degrees difference for most mixtures and between the DOT and Pike data. There appear to be some trends with the increasing RAP contents for several of the plants, but this is based only on one test and may not be statistically significant.

*Critical Cracking Temperature*

The critical cracking temperatures for the various RAP mixtures do not change by more than a few degrees, as shown in Figure 6. Some plants show an increasing $T_{cr}$ with the higher RAP percentages while others are flat or perhaps show a slight decrease (improvement) with higher RAP percentages. Each data point only represents a single test, so more testing is required to determine if these are statistically significant trends.

**Comparisons using Percent Binder Replacement**

*High-End Failure Temperature*

The change in the high-end failure temperature as a function of the percent binder replacement (Eq 2 and Table 2) is plotted in Figure 7. The continuous grade, or calculated failure temperature, instead of the 6° increment grade is used to calculate the change in failure temperature. Values greater than zero indicate that the high PG grade actually drops when RAP is added to the mixture. The data is scattered, but there is an apparent decreasing trend with higher percent binder replacements. The high temperature failure grade for the DOT results was not calculated, so this figure only shows the Pike data.

This graph also shows how different the percent binder replacement values can be for the various RAP percentages because of the asphalt content in the RAP and asphalt content of the total mixture. There are 15% RAP mixtures that have higher binder replacement percentages
than some of the 20% RAP mixtures and 25% RAP mixtures that have lower binder replacement percentages than the 20% RAP mixtures.

**Low-End Failure Temperature**  
The change in the low-end failure temperature as a function of the percent binder replacement is plotted in Figure 8. The continuous grade, or calculated failure temperature, instead of the 6° increment grade is used to calculate the change in failure temperature. Values greater than zero indicate an improvement in the low PG grade of the RAP mixture over the virgin mixture. It is interesting to note that at lower binder replacement percentages, the low-end failure temperature determined from the Pike testing actually improves. However, all of the NHDOT testing indicates an increase in the low-end failure temperature. The data is scattered, but there is an apparent decreasing trend with higher percent binder replacements.

**Critical Cracking Temperature**  
The change in the critical cracking temperature as a function of the percent binder replacement is shown in Figure 9. Values greater than zero indicate an improvement in critical cracking temperature of the RAP mixture over the virgin mixture. $T_{cr}$ was not determined in the Pike laboratory, so only results from the DOT testing are shown. Unexpectedly, there is an increasing trend in this data, indicating that adding RAP binder to the mixture might possibly improve the low temperature cracking properties. $T_{cr}$ identifies the temperature where the induced thermal stress exceeds the fracture stress. Thermal stresses are calculated from the stiffness versus time data measured in the BBR and the fracture stress is determined from the DTT test. Presumably, the RAP will change both the BBR stiffness and fracture strength; but the relative changes of each of these for certain RAP contents could result in a lower $T_{cr}$ for the binder.

It is important to note that these test results are based on testing the recovered, fully blended binder for the few mixtures evaluated as part of this study. The $T_{cr}$ measured on the recovered, blended binder may not accurately represent the behavior of the mixture in which the binder is not fully blended. Also, all of the mixtures tested in this study have binder replacement percentages below about 20%; this apparent trend may plateau or reverse at higher binder replacement percentages. It is also important to note that each point represents the results of only one test, so additional replicate testing and statistical analysis would be needed to verify these results. Finally, all RAP binders are not the same; they do not have the same characteristics, or behave the same way when blended. The findings in this study are based on the range of RAP binders encountered in this study. For practical purposes, this may be assumed to be representative of RAP binders in the New England Region, although there may be outliers not tested that may be extremely more or less aged than those encountered in this study.

**SUMMARY AND FINDINGS**  
This paper presents the results of a study to evaluate the extracted binder properties of RAP mixtures. A total of 28 plant mixtures were sampled and the asphalt binder was extracted, recovered, and tested for PG grade and critical cracking temperature. The study was limited to one mixture type (12.5 mm) and a limited range of virgin binders. It is also important to note that the results are based on a single test of fully blended, extracted binders and may not be representative of what happens with the mixture performance in the field. The findings from this study are as follows:
The high temperature PG grade remained the same, or only increased one grade for the various RAP percentages.

The low temperature PG grades remained the same, or only increased one grade from the virgin mixture. The low-end failure temperatures and critical cracking temperatures only change by a few degrees as the RAP percentages increase. Some plants show a slight decrease in these values with increasing RAP contents, while others show a slight increase.

The change in failure temperature as a function of percent binder replacement for both high and low temperatures is widely scattered, but shows the expected decreasing trend as the percentage of RAP binder increases in the mix.

The critical cracking temperature showed improvement as the percentage of RAP binder increased in the mixtures. More testing and analysis of various mixtures with replicate samples is needed to confirm this trend.

The percent binder replacement calculation is recommended for normalizing different mixtures with respect to the asphalt content of the RAP and the asphalt content of the mixture.

The NHDOT rewrote its RAP specifications while the study was being completed. The specifications use a ‘total reused binder’ value to delineate the different levels of the specification instead of the percent RAP by total mass of mix, which normalizes the specification with respect to the asphalt content of the RAP stockpile. The new specification for the 2009 construction season requires a grade reduction for mixes in all courses with between 0.8 and 1.0 percent total reused binder, unless the reduction is determined not to be required. As a result of this study, the NHDOT has conceded that the grade reduction is not required up to 1.0 percent total reused binder.

FUTURE WORK
Plans for future work on this study include additional plants, drum plants as well as batch plants, testing different binder grades, moving into higher RAP percentages and also low temperature performance testing on the mixtures.

ACKNOWLEDGEMENTS
This study would not have been possible without the help and cooperation of the NHDOT, Pike Industries, Inc., Continental Paving, Inc., and Brox Industries, Inc. In particular, the authors would like to acknowledge Alan Rawson, Alan Lugg, Brian Kulacz, and Melissa Sytek at NHDOT and Dave Duncan and Peter Moore at Pike Industries. Thanks also to Katherine Gray at UNH for her efforts in the literature review.

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Table 1. Plant Produced Mixture Information

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<sup>a</sup> Testing only performed at the Pike laboratory for these mixtures
### Table 2. Binder Replacement Values

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