CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATIONS

SUMMARY OF BINDER EXTRACTION REVIEW

Existing extraction and recovery procedures were evaluated to determine their accuracy, precision, speed and ease when testing RAP. Different, existing solvents were also evaluated in the extraction/recovery process. The various combinations of extraction procedure, recovery procedure and solvent type were evaluated to determine how readily mixture component analysis (asphalt content and gradation) could be performed. The physical properties of the recovered binder were also determined to test the treatment's precision.

Based on the testing completed, it does not appear that the Abson recovery procedure is acceptable for determination of RAP properties. Coefficients of variation were very high for the RAP samples tested (38-69%). The stiffness of the recovered binder was also lowest for this treatment.

The Centrifuge-Rotavapor-Toluene/Ethanol and modified SHRP-Rotavapor-Toluene/Ethanol treatments were similar in many ways. Both treatments exhibited comparable precision (CV = 12%) and time of testing (six hours). The stiffness of the recovered binder was slightly different for the two treatments. Of the two, the Centrifuge-Rotavapor-Toluene/Ethanol treatment exhibited the highest stiffness. The gradations of the material extracted using the SHRP-Rotavapor-Toluene/Ethanol treatments were slightly finer than the other treatments. This was expected since the SHRP extraction procedure appears to remove more fines from the effluent than the Centrifuge extraction procedure. The retention of fines in the recovered binder may be causing the binder stiffness to be higher for the Centrifuge-Rotavapor-Toluene/Ethanol treatment. Likewise, the additional fines removed are likely causing the change in gradation for the SHRP-Rotavapor-Toluene/Ethanol treatment. Based on the results of the testing completed, it appears that the SHRP extraction and recovery (Rotavapor) procedure is the best choice. The SHRP extraction and recovery procedures are detailed in AASHTO TP2 with the modifications noted earlier. It appears that this extraction and recovery procedure is:

1. More repeatable than the Centrifuge-Abson procedure, and equally repeatable compared to the Centrifuge-Rotavapor procedure,
2. Equally time-consuming as the Centrifuge-Rotavapor procedure, but slightly more time-consuming than the Centrifuge-Abson procedure (six hours compared to four hours), and
3. Comparable in asphalt content determination and gradation to the Centrifuge-Abson and Centrifuge-Rotavapor procedures.

Of all the parameters, accuracy is the most difficult to define. It appears that the modified SHRP-Rotavapor procedure removes more residual solvent than the Centrifuge-Abson procedure and more fines than the Centrifuge-Abson or Centrifuge-Rotavapor procedures. These two factors would suggest that the SHRP-Rotavapor procedure provides a more accurate representation of the RAP binder properties.

Because of the concern with the toxicity of extraction solvents, it is attractive to use alternative solvents, such as the n-propyl bromide solvent. The testing here indicated higher variability in the properties of binders recovered with the alternative solvent, but the variability was still much improved over that of the Centrifuge-Abson procedure.

The binder test methods themselves were found to be applicable to testing the recovered binder. (The recovered binders tested under Task 4 were linear.)

RAP Binder Blending Procedure

Based on the experimental data, blending of RAP binders can be accomplished by knowing the desired final grade (critical temperatures) of the blended binder physical properties (and critical temperatures) of the recovered RAP binder and one of the following two variables:

1. Physical properties (and critical temperatures) of virgin asphalt binder, or
2. Percentage of RAP in the mixture

The following steps should be followed to determine the physical properties and critical temperatures of the RAP binder. These are illustrated through flow charts in Appendix C.

1. The RAP binder should be recovered using the modified AASHTO TP2 method (described previously) with an appropriate solvent (either a toluene/ethanol combination or an n-propyl bromide solvent have been determined to be acceptable). At least 50 g of recovered RAP binder are needed for testing.
2. Perform binder classification testing using the tests in AASHTO MP1. Rotational viscosity, flash point and mass loss tests are not needed.
   2.1 Perform original DSR testing on the recovered RAP binder to determine the critical high temperature, T_c(High), based on original DSR values where $G^*/\sin\delta$ = 1.00 kPa. Calculate the critical high temperature as follows:

2.1.1 Determine the slope of the Stiffness-Temperature curve as the change in $\Delta Log(G^*/\sin\delta) / \Delta T$.

2.1.2 Determine T_c(High) to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{Log(1.00) - Log(G_1)}{a} \right) + T_1$$

where,

G_1 is the $G^*/\sin\delta$ value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 2.1.1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the $G^*/\sin\delta$ *value closest to the criterion (1.00 kPa) to minimize extrapolation errors.*

3. Perform RTFO aging on the remaining RAP binder.

4. Perform RTFO DSR testing on the RTFO-aged recovered RAP binder to determine the critical high temperature (based on RTFO DSR). Calculate the critical high temperature (based on RTFO DSR) as follows:

4.1 Determine the slope of the Stiffness-Temperature curve as the change in $\Delta Log(G^*/\sin\delta)/\Delta T$.

4.2 Determine T_c(High), based on RTFO DSR, to the nearest 0.1°C using the following equation:

$$T_c(High) = \left(\frac{Log(2.20) - Log(G_1)}{a}\right) + T_1$$

where,

G_1 is the G*/sinδ value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 4.1

Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*/sinδ *value closest to the criterion (2.20 kPa) to minimize extrapolation errors.*

5. Determine the critical high temperature of the recovered RAP binder as the lowest of the Original DSR and RTFO DSR critical temperatures. Determine the high temperature performance grade of the recovered RAP binder based on this single critical high temperature.

6. Perform intermediate temperature DSR testing on the RTFO-aged recovered RAP binder to determine the critical intermediate temperature, T_c(Int), based on PAV DSR.

   6.1 Determine the slope of the Stiffness-Temperature curve as ΔLog(G*sin δ)/ΔT.

   6.2 Determine T_c(Int) to the nearest 0.1°C using the following equation:

$$T_c(Int) = \left(\frac{Log(5000) - Log(G_1)}{a}\right) + T_1$$

where,

G_1 is the G*sin δ value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 6.1

*Note: Although any temperature (T_1) and the corresponding stiffness (G_1) can be selected, it is advisable to use the G*sin δ value closest to the criterion (5,000 kPa) to minimize extrapolation errors.*

7. Perform BBR testing on the RTFO-aged recovered RAP binder to determine the critical low temperature, $T_c(S)$ or $T_c(m)$, based on BBR Stiffness or m-value.

7.1 Determine the slope of the Stiffness-Temperature curve as ΔLog(S)/ΔT.

7.2 Determine $T_c(S)$ to the nearest 0.1°C using the following equation:

$$T_c(S) = \left(\frac{Log(300) - Log(S_1)}{a} \right) + T_1$$

where,

S_1 is the S-value at a specific temperature, T_1

a is the slope of the Stiffness-temperature curve described in 7.1

Note: Although any temperature (T_1) and the corresponding stiffness (S_1) can be selected, it is advisable to use the S- value closest to the criterion (300 MPa) to minimize extrapolation errors.

7.3 Determine the slope of the m-value-Temperature curve as Δm-value/ΔT.

7.4 Determine $T_c(m)$ to the nearest 0.1°C using the following equation:

$$T_c(m) = \left(\frac{0.300 - m_1}{a} \right) + T_1$$

where,

m_l is the m-value at a specific temperature, T_1

a is the slope of the curve described in 7.3

Note: Although any temperature (T_l) and the corresponding m-value (m_l) can be selected, it is advisable to use the m- value closest to the criterion (0.300) to minimize extrapolation errors.

7.5 Select the higher (less negative) of the two low critical temperatures $T_c(S)$ and $T_c(m)$ to represent the low critical temperature for the recovered asphalt binder, $T_c(Low)$. Determine the low temperature performance grade of the recovered RAP binder based on this single critical low temperature.

Once the physical properties and critical temperatures of the recovered RAP binder are known, two blending approaches may be used. In one approach (designated Method A) the asphalt technologist knows the percentage of RAP that will be used in an asphalt mixture and needs to determine an appropriate virgin asphalt binder for blending. In the second approach (Method B) the asphalt technologist seeks to determine the maximum percentage of RAP that can be used in an asphalt mixture while still using the same virgin asphalt binder grade. Both approaches assume that the specifying agency will specify the performance grade of the blended binder. (These methods are also shown as flow charts in Appendix C and are described in detail for technicians in the companion Technicians' Manual (Appendix E).)

METHOD A – Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)

If the final blended binder grade, desired percentage of RAP and recovered RAP properties are known, then the properties of an appropriate virgin asphalt binder grade can be determined. Consider the following example:

- The specifying agency requires a blended binder grade of PG 64-22 or better.
- The RAP percentage in the mixture is 30%.
- The recovered RAP properties are as indicated in Table 99.

By rearranging the equations described earlier, the critical temperatures of the virgin asphalt binder can be determined:

$$T_{Virgin} = \frac{T_{Blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)}$$

where: T_{Virgin} = critical temperature of the virgin asphalt binder

T_{Blend} = critical temperature of the blended asphalt binder (final desired)

%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)

T_{RAP} = critical temperature of recovered RAP binder

Using these equations for the high, intermediate and low critical temperatures, the properties of the virgin asphalt binder needed to satisfy the assumptions could be determined. These values are indicated in Table 100 and Figures 76 – 78.

As indicated in Table 100 and Figure 76, the minimum high temperature grade of the virgin asphalt binder should be 54.3°C to satisfy the requirements of the blended grade (PG 64-

22) using the RAP in Table 99 at 30%. This means that a PG 58-xx grade would be needed to ensure that the minimum required value of 54.3°C would be achieved.

Table 100 and Figure 77 indicate that the minimum low temperature grade of the virgin asphalt binder should be –26.4°C (-16.4°C -10°C factor in AASHTO MP1) to satisfy the requirements of the blended grade (PG 64-22) using the RAP in Table 99 at 30%. This means that a PG xx-28 grade would be needed to ensure that the minimum required value of –26.4°C would be achieved.

From Table 100 and Figures 76 and 77, a PG 58-28 asphalt binder would be selected as the virgin asphalt binder for use in a mixture using 30% of the RAP described in Table 99. To meet the intermediate temperature grade (G*sin δ) in Figure 78, the virgin asphalt binder would need to have a critical intermediate temperature no higher than 22.6°C. Since the maximum critical intermediate temperature for a PG 58-28 binder is 19°C, the selected binder should easily meet all blended binder requirements.

It should be noted that the actual high temperature grade required for the virgin asphalt binder is 54.3°C. It is possible that a PG 52-28 binder could be used, provided that the actual high temperature was at least 54.3°C. However, material variability (RAP or virgin binder) and testing variability (Recovery and DSR testing) make this choice questionable.

METHOD B – Blending with a Known Virgin Binder Grade (RAP Percentage Unknown)

If the final blended binder grade, virgin asphalt binder grade and recovered RAP properties are known, then the allowable RAP content can be determined. Consider the following example:

- The specifying agency requires a blended binder grade of PG 64-22 or better.

- The virgin binder grade is a PG 58-28 (critical temperatures in Table 101).
- The recovered RAP is a PG 82-10 (critical temperatures in Table 101).

By rearranging the equations described earlier, the percentage of RAP can be determined:

$$\%RAP = \frac{T_{Blend} - T_{Virgin}}{T_{RAP} - T_{Virgin}}$$

where: T_{Virgin} = critical temperature of the virgin asphalt binder

T_{Blend} = critical temperature of the blended asphalt binder (final desired)

%RAP = percentage of RAP expressed as a decimal (i.e., 0.30 for 30%)

T_{RAP} = critical temperature of recovered RAP binder

Using these equations for the high, intermediate and low critical temperatures, the percentage of RAP needed to satisfy the assumptions can be determined. These values are indicated in Table 102 and Figures 79 – 81.

As indicated in Table 102 and Figure 79 a percentage of RAP between 14% and 36% should satisfy the high temperature requirements of the blended grade (PG 64-22) using the RAP and virgin asphalt binders in Table 101. Note that to achieve the minimum PG 64-xx grade, the percentage of RAP is rounded up. To achieve a maximum PG 64-xx grade (that is, a PG 70-xx grade is not desired), the percentage of RAP is rounded down.

Table 102 and Figure 80 indicate that a RAP percentage between 6% and 40% should satisfy the low temperature requirements of the blended grade (PG 64-22) using the RAP and virgin asphalt binders in Table 101. Note that to achieve the minimum PG xx-22 grade, the percentage of RAP is rounded down. To achieve a maximum PG xx-22 grade (that is, a PG xx-28 grade is not desired), the percentage of RAP is rounded up.

From Table 102 and Figures 79 and 80, a RAP percentage between 14% and 36% would satisfy all the requirements of a blended PG 64-22 binder. If the maximum high temperature grade was not a concern, the RAP percentage could be increased to 40% without changing the desired low temperature grade of the blended asphalt binder.

To meet the intermediate temperature grade (G*sin δ) in Figure 81, the RAP percentage would need to be less than 66%.

Testing Reliability Issues

Variability in test results typically can come from one of three sources: materials, sampling and testing. Often, variability in testing is attributed to the material being tested when, in reality, sampling or testing errors may have contributed to the variability in the test results.

Good sampling practices can effectively minimize variability in test results caused by sampling. Adherence to the proper test methods may minimize testing variability, but it still will be present. If sampling variability can be reduced by good sampling practices and testing variability can be properly accounted for, then material variability can be quantified.

Testing of recovered RAP asphalt binders can occur in either the recovery procedure or in the binder test procedure (i.e., DSR, BBR tests). Variability due to the combined effects of the recovery procedure and high temperature DSR testing is indicated in Table 103 for two RAPs tested in the first phase of this research project.

The data in Table 103 indicates that the test results from three separate recoveries indicated a change in the critical high temperature by as much as 2.1°C. The d2s limit defining the acceptable range of two test results (95% confidence limit) was 2.5°C for the Kentucky RAP and 0.7°C for the Florida RAP.

Applying a tolerance of 2.5°C to the critical high temperature of the RAP binder in Tables 99 and 101 changes it from 86.6°C to 84.1°C. The effect on the blending would change the virgin binder critical high temperature from 54.3°C to 55.4°C in Method A – a change of approximately 1°C, but no change in the virgin binder grade. The effect on blending would also change the minimum RAP percentage from 14% to 15% in Method B. In either instance, because the RAP is being blended with virgin asphalt binder at percentages of (typically) 40% or less, variability in test results due to the recovery procedure and subsequent testing is decreased.

It should be noted that Table 103 provides an indication of single laboratory testing variability associated with the modified AASHTO TP2 procedure. Since this is a new procedure, multi-laboratory variability has not been determined. It should also be noted that no low temperature variability (single laboratory) was determined from the two RAP sources.

Other sources (33) describe multi-laboratory testing variability associated with the Superpave binder tests. This information is readily available from the AASHTO Material Reference Laboratory Program. However, this testing variability is based on samples that are typically taken from the asphalt binder tanks, not recovered from an asphalt mixture sample. It is expected that the testing variability will increase as the binder is subjected to the recovery procedure.

Until testing variability can be sufficiently established for recovered asphalt binders, the user agency may wish to add a factor of safety to ensure that the final blended asphalt binder grade is achieved. Based on the 2.5°C change in the critical high temperature of the recovered RAP binder (Kentucky), an increase/decrease of no more than 2.0°C in the critical temperatures of the desired binder grade should be sufficient. Therefore, an agency requiring a PG 64-22 blended asphalt binder would fix the critical high temperature at 66°C instead of 64°C. The critical low temperature of the blended binder would be -14°C rather than -12°C. These adjustments may or may not result in a change in the virgin asphalt binder grade required or the percentage of RAP used in the mixture.

Discussion of AASHTO MP1A Blending

At the time of this experiment, the critical low temperature of an asphalt binder was determined principally from the BBR Stiffness and m-value. Blending equations were determined during the experiment to accommodate estimations of BBR Stiffness and m-value of blended asphalt binders.

Recently, however, a research team involved with the Asphalt Binders Expert Task Group developed a new procedure for determining the critical low temperature of an asphalt binder (34). This procedure uses BBR data to generate a thermal stress curve, and uses direct tension data to determine failure stress at one or more temperatures. The point at which the failure stress intersects the thermal stress curve is the critical low temperature of the asphalt binder. This procedure was forwarded to AASHTO as an alternate to the performance graded asphalt binder specification. It has been designated as AASHTO MP-1A.

The equipment, procedure and analysis software have only recently been finalized. Consequently there was no time in the research to examine the concept of low temperature blending charts using the alternate method of determining critical low temperature (AASHTO MP-1A). However, a separate research effort being conducted at the Asphalt Institute as part of the FHWA's National Asphalt Training Center II contract is examining the concept of low temperature blending using the MP-1A procedure. That final report should supplement the findings of this research.

BINDER EFFECTS STUDY

Analysis of Effect of RAP on Binder Grade

The binder effects study indicated that the binder grade changed as RAP percentage increased, but the high temperature grade changed more rapidly than the low temperature grade. For low temperatures the temperature difference between the original (virgin) binder and the RAP blends is indicated in Table 104 below. The data is also graphically represented in Figures 82 and 83.

Table 104 and Figure 82 indicate that the Arizona RAP has a greater influence than the Florida and Connecticut RAP on the low temperature grade of the blended asphalt binder. This was expected since the Arizona RAP had an actual low temperature grade 10°C warmer than the Florida and Connecticut RAP.

Table 104 and Figure 83 indicate that at 10% RAP the average low temperature grade of the blended asphalt binder changes by less than 1.0°C. At 20% RAP, the average low temperature grade of the blended asphalt binder changes by approximately 2.5°C. Figure 83 also indicates that the PG 52 asphalt binder is slightly more affected by the RAP than the PG 64 asphalt binder.

For high temperatures the temperature difference between the original (virgin) binder and the RAP blends is indicated in Table 105. The data is also graphically represented in Figures 84 and 85.

Table 105 and Figure 84 indicate that, as with the low temperature grade, the Arizona RAP has a greater influence than the Florida and Connecticut RAP on the high temperature grade of the blended asphalt binder.

Table 105 and Figure 85 indicate that at 10% RAP the average high temperature grade of the blended asphalt binder changes by approximately 3.0°C. At 20% RAP, the average high temperature grade of the blended asphalt binder changes by approximately 5-7°C. Figure 85 also indicates that the PG 52 asphalt binder is slightly more affected by the RAP than the PG 64 asphalt binder.

The slopes of the lines in Figures 83 and 85 indicate that the percentage of RAP has twice the effect on the high temperature grade of the asphalt binder as it does on the low temperature grade. This can also be seen in Table 106 where the change in temperature is calculated for various RAP percentages corresponding to the limits in the Mix ETG recommended tiers and the binder effects experiment. Table 107 indicates the percentage of RAP required to cause a specified change in critical temperature.

Table 106 indicates that following the ETG guidelines, 0-14% RAP could have changes of 1.6°C in the low temperature grade and 4.2°C in the high temperature grade of the blended asphalt binder. Assuming the virgin asphalt binder is produced with some "margin" on the low temperature and high temperature grade, the final blended grade should be substantially the same as the virgin asphalt binder grade. *(The binder grade "margin" assumes that an asphalt binder is produced approximately 2°C from the minimum critical temperature. In other words, a PG 64-22 asphalt binder would be produced with actual critical temperatures of 66°C and -24°C.)*

Assuming the 2°C margin indicated above, the 15% RAP limit before a change in binder grade is required appears reasonable. A virgin asphalt binder with more "margin" may allow a higher percentage of RAP before a grade change is required. For example, a mixture using a PG 64-22 with a 4°C margin on the low temperature grade (i.e., a PG 64-26 binder) could use 25% RAP without a change in the virgin asphalt binder grade. Conversely, a virgin asphalt binder with less "margin" may allow a lower percentage of RAP before a grade change is required.

The data in Tables 104 and 105 suggest that the Arizona RAP has a greater effect than the Florida and Connecticut RAP on the blended asphalt binder grade. This appears to be particularly true for the low temperature grade (Table 104) where it appears that the Arizona RAP changes the low temperature grade twice as fast as the Florida and Connecticut RAP. Separating the RAP stiffness into two groups yields the data in Tables 108 and 109. Tables 110 and 111 indicate the percentage of RAP required to cause a specified change in critical temperature.

The data in Tables 107, 110 and 111 indicate that, in general, the ETG recommendations are appropriate. A 2°C change in the critical low temperature is caused by the addition of 16.7% RAP. A 3°C change in the critical low temperature is caused by the addition of 24.2% RAP. When the RAP stiffness increases (Table 110, Arizona RAP), the RAP percentages are 11.0% and 16.0% to create a change in the critical low temperatures of 2°C and 3°C, respectively. When the RAP stiffness decreases (Table 110, Florida and Connecticut RAP), the RAP percentages are 22.7% and 32.8% to create a change in the critical low temperatures of 2°C and 3°C, respectively. This data suggests that the ETG recommendations can also be modified depending on the low temperature stiffness of the recovered RAP binders. A possible modification to the recommendations could be made based on the data in Tables 107 and 110. That modification is shown in Table 112. Table 112 is used to select binder grades in the accompanying proposed AASHTO specification revisions (Appendix F), Guidelines (Appendix D) and Technicians' Manual (Appendix E).

BLACK ROCK STUDY

The black rock study offers compelling evidence that blending does occur between the old, hardened RAP binder and the virgin added binder. At low RAP contents, certainly 10% or less, there is not enough RAP present to significantly change the mixture properties. At 40% RAP, however, the effects were significant. At the higher RAP content, samples representing actual practice more closely resembled samples representing total blending than those representing black rock. This confirms both the concept of blending charts and the establishment of a tiered approach to RAP usage. At low RAP contents, no changes are necessary, but as the RAP content increases, the need to use a blending chart does also.

It does not seem reasonable that total blending would actually happen in the field. Findings from this research, however, strongly suggest that actual practice achieves a situation much closer to total blending than to no blending (black rock).

The application of these findings to current practice would support continuation of a tiered approach to RAP usage.

MIXTURE EFFECTS STUDY

The mixture effects study looked at RAP contents ranging from 0 to 40%. Shear testing, indirect tensile testing and beam fatigue were used to analyze the effects of increasing the RAP content on the mixture properties.

The shear testing indicated that the complex shear modulus of the mixtures increased exponentially with RAP content, in most cases. Deformation decreased as the RAP content increased and shear strain decreased as RAP ratio increased. All of these changes indicate the stiffening effect of the RAP on the mixture properties. The effects become especially significant between 20 and 40% RAP.

Indirect tensile testing supports these findings as well. Increasing the RAP content increases the low temperature stiffness of the mix. The samples with 10% RAP were typically similar to the control samples (0% RAP). At higher RAP contents, the effects of the RAP become significant.

Beam fatigue testing reveals similar conclusions. As the RAP content increases, beam fatigue life, as measured by cycles to failure, decreases. Again there was no significant effect of the RAP at the 10% level, but higher percentages of RAP became more significant. The beams made with softer binder exhibited greater fatigue life, as expected. This supports the concept of using a softer virgin binder with higher proportions of RAP.

These results combined suggest that mixtures with higher percentages of RAP can be expected to be stiffer and therefore more resistant to permanent deformation. This increased stiffness, however, can lead to a decrease in low temperature and fatigue cracking resistance, *unless compensated for by changes in the binder properties.*

These findings also correlate well with the results of the black rock study and the binder effects study in support of a tiered approach to the use of RAP. All of these studies suggest strongly that there is indeed a threshold level of RAP below which the effects of the RAP are insignificant. This is clearly the case at 10% RAP. At the 20% RAP level, effects were sometimes significant, but not always. At the 40% level, the effects of the RAP were quite apparent, in most cases. This suggests that an upper limit for the threshold of between 15 and 20% would be reasonable.

While a tiered approach is not novel or innovative, it is practical. Its use allows for the relatively easy implementation of low levels of RAP. If the economics of using RAP justify further expense at the mix design phase, additional testing and/or adjustments to the binder grade can be performed to take into account the increased effects of the RAP at higher addition rates.

PLANT VS. LAB COMPARISON

The plant vs. lab mini-experiment was done to ensure that the laboratory approach used in this study had some validity. If the results of the lab-prepared testing differed greatly from the results of testing plant-produced mix with the same components, applying these laboratory findings to actual projects would be questionable. Only one RAP and its plant-mix were investigated in this mini-experiment.

The results of this limited study indicate that the laboratory approach for preparing samples was representative of plant-produced mix. The plant-produced mixes tended to be slightly stiffer than the lab mixes, but not significantly stiffer. This can increase the confidence level when applying the results of this research project to actual construction.

EFFECTS OF RAP HANDLING

The findings of the mini-experiment on the effects of time and temperature on RAP properties support the conventional recommendations to limit heating time and temperature. Heating the RAP for long periods of time at high temperatures (16 hours at 150°C) resulted in changes in the binder properties, which could lead to changes in mixture properties. For some RAP-virgin binder combinations, however, heating for long time periods at relatively low temperatures had no detrimental effect.

This was not an exhaustive study, by any means. It was also limited by the use of binder test results as surrogates for extensive mixture testing, due to concerns about mix testing variability masking the effects of heating. Nonetheless, the findings do concur with other recommendations that RAP be heated at low temperatures (110°C) for short periods of time (5).

If circumstances require longer heating times, comparisons should be made of mixes heated for long periods versus those heated for recommended times to determine if any detrimental changes occurred. Comparisons of the volumetric properties of multiple samples could be used on a project by project, or material by material, basis to demonstrate the effects of prolonged heating. This may be preferable to the binder testing done here since few contractors have access to binder equipment, though they do have access to a gyratory compactor.

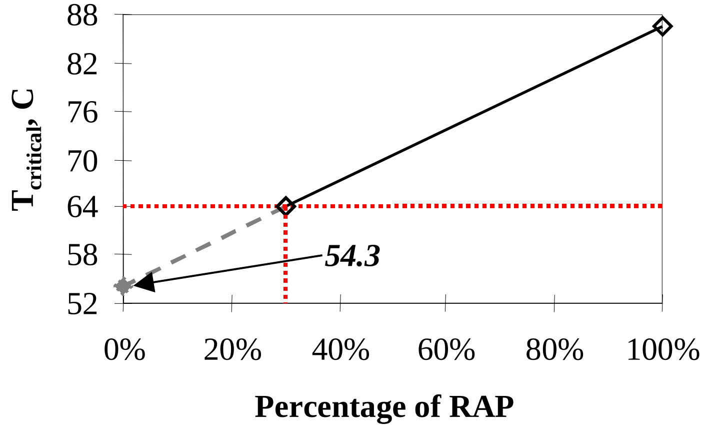

Figure 76. High Temperature Blending Chart (RAP Percentage Known)

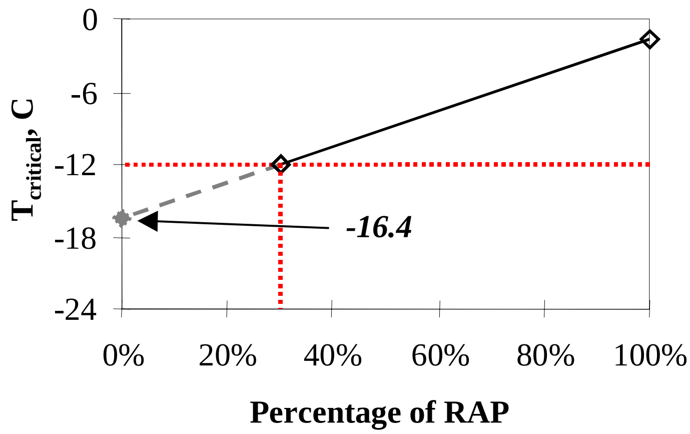

Figure 77. Low Temperature Blending Chart (RAP Percentage Known)

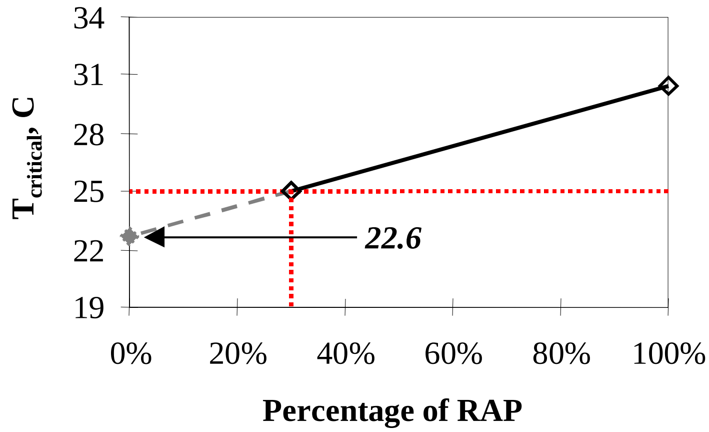

Figure 78. Intermediate Temperature Blending Chart (RAP Percentage Known)

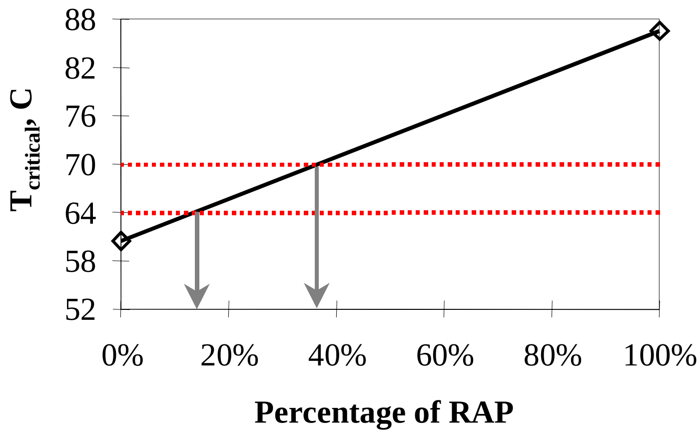

Figure 79. High Temperature Blending Chart (RAP Percentage Unknown)

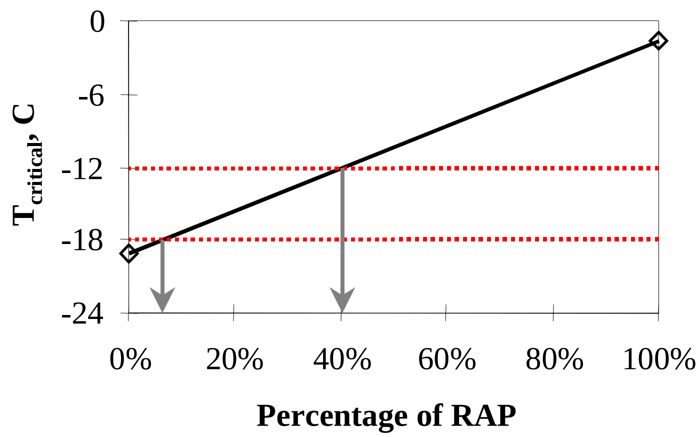

Figure 80. Low Temperature Blending Chart (RAP Percentage Unknown)

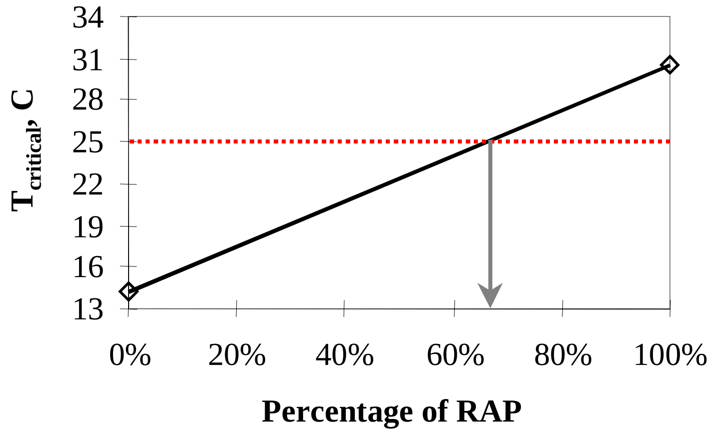

Figure 81. Intermediate Temperature Blending Chart (RAP Percentage Unknown)

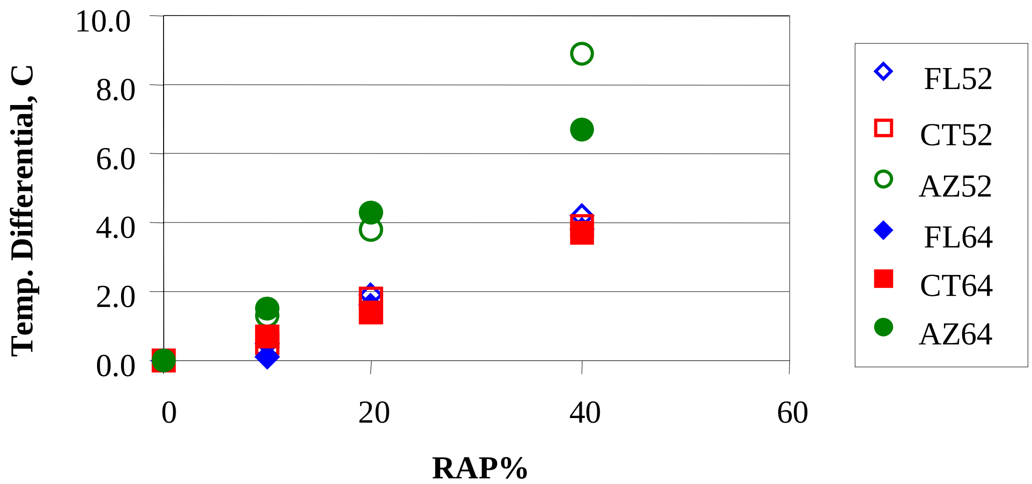

Figure 82. Individual Change in Low Temperature Grade with Addition of RAP

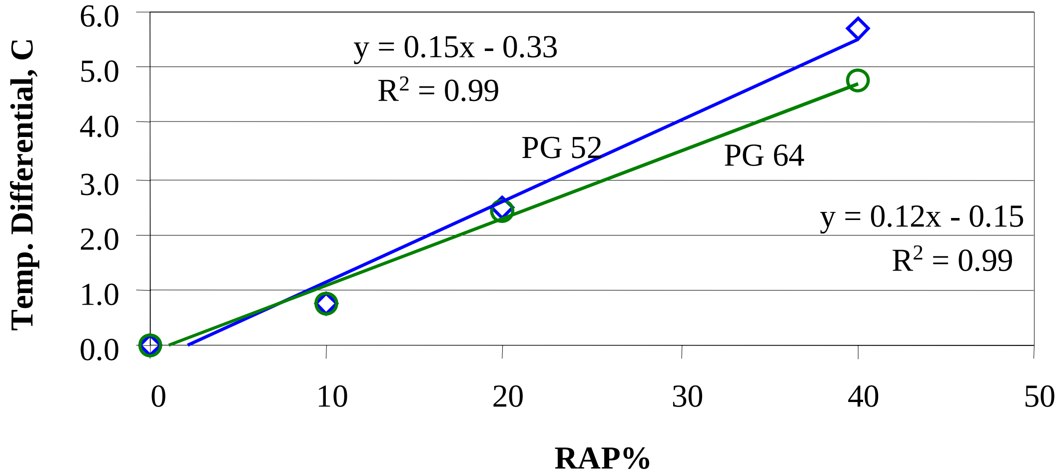

Figure 83. Average Change in Low Temperature Grade with Addition of RAP

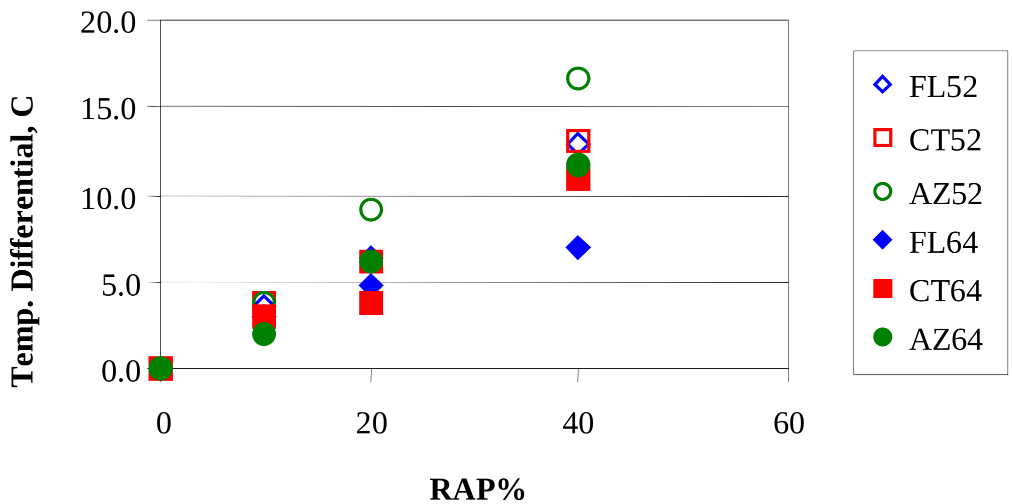

Figure 84. Individual Change in High Temperature Grade with Addition of RAP

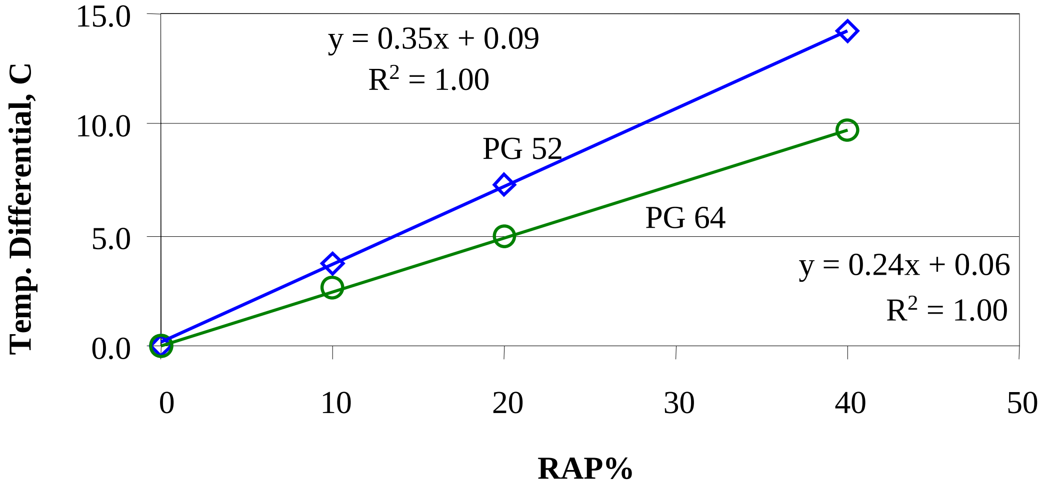

Figure 85. Average Change in High Temperature Grade with Addition of RAP

Table 99. Critical Temperatures of Recovered RAP Binder

Aging	Property	**Critical Temperature, °C**	
Original	DSR G*/sinδ	High	**86.6**
RTFO	DSR G*/sinδ	High	88.7
PAV	DSR G*sinδ	Intermediate	**30.5**
	BBR S	Low	-4.5
	BBR m-value	Low	**-1.7**
	PG	Actual	PG 86-11
		MP1	PG 82-10

Table 100. Estimated Critical Temperatures of Virgin Asphalt Binder

Aging	Property	Critical Temperature, °C	
Original	DSR G*/sinδ	High	**54.3**
RTFO	DSR G*/sinδ	High	53.4
PAV	DSR G*sinδ	Intermediate	**22.6**
	BBR S	Low	-15.2
	BBR m-value	Low	**-16.4**
	PG	Actual	PG 54-26
		MP1	PG 58-28

Table 101. Critical Temperatures of Virgin and Recovered RAP Binders

		Critical Temperature, °C		
Aging	Property	Temp. Range	Virgin Binder	RAP Binder
Original	DSR G*/sinδ	High	**60.5**	**86.6**
RTFO	DSR G*/sinδ	High	61.0	88.7
PAV	DSR G*/sinδ	Intermediate	**14.2**	**30.5**
	BBR S	Low	-22.2	-4.5
	BBR m-value	Low	**-19.0**	**-1.7**
	PG	Actual	PG 60-29	PG 86-11
		MP1	PG 58-28	PG 82-10

Table 102. Estimated Percentage of RAP to Achieve Final Blended Grade

			Percentage of RAP to Achieve:	
Aging	Property	Temp.	**PG 64-22**	**PG 70-28**
Original	DSR G*/sinδ	High	**13.4%**	**36.4%**
RTFO	DSR G*/sinδ	High	10.8%	32.5%
PAV	DSR G*sinδ	Intermediate	**66.3%**	**---**
	BBR S	Low	57.6%	23.7%
	BBR m-value	Low	**40.5%**	**5.8%**

Table 103. Testing Variability of Modified AASHTO TP2 Method (with Toluene/Ethanol)

	G*/sinδ, kPa							
	Kentucky				**Florida**			
	64ºC	70ºC	76ºC	**T_c**	64ºC	70ºC	76ºC	**T_c**
Rep 1	21.76	9.23	4.06	**86.0**	7.10	3.10	1.42	**78.6**
Rep 2	24.24	9.60	4.01	**85.3**	7.11	3.07	1.39	**78.4**
Rep 3	27.30	11.55	5.01	**87.4**	7.79	3.37	1.51	**79.0**
Average	24.43	10.13	4.36	**86.2**	7.33	3.18	1.44	**78.7**
σ (1s)	2.27	1.02	0.46	**0.9**	0.32	0.13	0.05	**0.2**
CV (1s%)	9%	10%	11%	**1%**	4%	4%	4%	**0.3%**
d2s	6.41	2.88	1.30	**2.5**	0.91	0.38	0.14	**0.7**
d2s%	26%	28%	30%	**3%**	12%	12%	10%	**1%**

Table 104. Change in Low Temperature Grade of Virgin Asphalt Binder with Addition of RAP

		Change in Critical Low Temperature , °C			
		0% RAP	10% RAP	20% RAP	40% RAP
PG 52-34	FL	0.0	+0.5	+1.9	+4.2
	CT	0.0	+0.5	+1.8	+3.9
	AZ	0.0	+1.3	+3.8	+8.9
	Average	**0.0**	**+0.8**	**+2.5**	**+5.7**
PG 64-22	FL	0.0	+0.1	+1.6	+3.8
	CT	0.0	+0.7	+1.4	+3.7
	AZ	0.0	+1.5	+4.3	+6.7
	Average	**0.0**	**+0.8**	**+2.4**	**+4.7**

Table 105. Change in High Temperature Grade of Virgin Asphalt Binder with Addition of RAP

		Change in Critical High Temperature, °C			
		0% RAP	10% RAP	20% RAP	40% RAP
PG 52-34	FL	0.0	+3.6	+6.4	+12.8
	CT	0.0	+3.8	+6.2	+13.1
	AZ	0.0	+3.7	+9.1	+16.6
	Average	**0.0**	**+3.7**	**+7.2**	**+14.2**
PG 64-22	FL	0.0	+2.9	+4.8	+7.0
	CT	0.0	+2.9	+3.7	+10.8
	AZ	0.0	+2.0	+6.2	+11.6
	Average	**0.0**	**+2.6**	**+4.9**	**+9.8**

Table 106. Change in Critical Temperature with Addition of RAP (Average of All RAPs)

	Low Temperature, °C			High Temperature, °C		
RAP	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
14%	+1.8	+1.5	**+1.6**	+5.0	+3.4	**+4.2**
15%	+1.9	+1.7	**+1.8**	+5.3	+3.7	**+4.5**
25%	+3.4	+2.9	**+3.2**	+8.8	+6.1	**+7.5**
26%	+3.6	+3.0	**+3.3**	+9.2	+6.3	**+7.7**
40%	+5.7	+4.7	**+5.2**	+14.1	+9.7	**+11.9**

Table 107. Percentage of RAP to Cause Change in Critical Temperature (Average of All RAP)

	Low Temperature, %RAP			High Temperature, %RAP		
Temp., °C	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
2.0	15.5	17.9	**16.7**	5.5	8.1	**6.8**
3.0	22.2	26.3	**24.2**	8.3	12.3	**10.3**
4.0	28.9	34.6	**31.7**	11.2	16.4	**13.8**
6.0	42.2	51.3	**46.7**	16.9	24.8	**20.9**

Table 108. Change in Critical Low Temperature with Addition of RAP

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
RAP	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
14%	+1.2	+1.0	**+1.1**	+2.7	+2.5	**+2.6**
15%	+1.3	+1.1	**+1.2**	+3.0	+2.7	**+2.8**
25%	+2.4	+2.1	**+2.2**	+5.3	+4.4	**+4.8**
26%	+2.5	+2.2	**+2.4**	+5.5	+4.5	**+5.0**
40%	+4.0	+3.5	**+3.8**	+8.7	+6.9	**+7.8**

Table 109. Change in Critical High Temperature with Addition of RAP

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
RAP	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
14%	+4.6	+3.2	**+3.9**	+5.9	+3.9	**+4.9**
15%	+5.0	+3.5	**+4.2**	+6.3	+4.2	**+5.2**
25%	+8.2	+5.6	**+6.9**	+10.5	+7.2	**+8.8**
26%	+8.5	+5.8	**+7.2**	+10.9	+7.5	**+9.2**
40%	+13.0	+8.8	**+10.9**	+16.8	+11.7	**+14.2**

Table 110. Percentage of RAP to Cause Change in Critical Low Temperature

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
Temp., °C	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
2.0	21.3	24.1	**22.7**	10.9	11.1	**11.0**
3.0	30.9	34.6	**32.8**	15.2	16.9	**16.0**
4.0	40.4	45.2	**42.8**	19.6	22.8	**21.2**
6.0	59.4	66.2	**62.8**	28.3	34.6	**31.4**

Table 111. Percentage of RAP to Cause Change in Critical High Temperature

	Florida, Connecticut RAP (PG xx-22)			Arizona RAP (PG xx-10)		
Temp., °C	PG 52	PG 64	**Average**	PG 52	PG 64	**Average**
2.0	5.8	8.2	**7.0**	4.8	7.6	**6.2**
3.0	8.9	12.9	**10.9**	7.2	10.9	**9.0**
4.0	12.0	17.5	**14.8**	9.6	14.3	**12.0**
6.0	18.3	26.8	**22.6**	14.3	20.9	**17.6**

Table 112. Binder Selection Guidelines for RAP Mixtures

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (i.e., select a PG 58-28 if a PG 64-22 would normally be used)	20 – 30%	15 – 25%	10 – 15%
Follow recommendations from blending charts	>30%	>25%	>15%

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

BINDER EFFECTS STUDY

The following conclusions and recommendations can be made from this research:

1. The modified AASHTO TP2 procedure, using either a combination of toluene (85%) and ethanol (15%) or an n-propyl bromide as solvent, is the preferred recovery procedure for RAP because of the repeatability and accuracy of the test results.
2. After recovery, the RAP binder should be tested in the DSR to determine the critical high temperature where the high temperature stiffness ($G^*/\sin\delta$) of the unaged recovered RAP binder is 1.00 kPa.
3. The remaining recovered RAP binder should be RTFO-aged prior to further testing. No PAV aging of the recovered RAP binder is necessary.
4. After RTFO-aging, the RAP binder should be tested in the DSR to determine the critical high temperature where the high temperature stiffness ($G^*\sin\delta$) of the RTFO-aged recovered RAP binder is 2.20 kPa. The RAP binder should also be tested in the DSR to determine the critical intermediate temperature where the stiffness ($G^*\sin\delta$) of the RTFO-aged recovered RAP binder is 5,000 kPa. The RAP binder should also be tested in the BBR to determine the critical low temperature where either the BBR Stiffness of the RTFO-aged recovered RAP binder is 300 MPa or the BBR m-value is 0.300.
5. Linear blending equations using critical temperatures appear to be appropriate for estimating the properties of the blended asphalt binder. Detailed procedures using these linear equations are provided in the accompanying Technicians' manual.

6. The critical temperatures (and performance grade) of the virgin asphalt binder can be determined from the linear blending equations if: (a) the percentage of RAP is known; (b) the critical temperatures of the recovered RAP binder are known; and (c) the critical temperatures of the desired blended binder are known.
7. The percentage of RAP to be used in a mixture can be determined from the linear blending equations if: (a) the critical temperatures of the virgin asphalt binder are known; (b) the critical temperatures of the recovered RAP binder are known; and (c) the critical temperatures of the desired blended binder are known.
8. The critical temperatures (and performance grade) of the blended asphalt binder can be determined from the linear blending equations if: (a) the percentage of RAP is known; (b) the critical temperatures of the recovered RAP binder are known; and (c) the critical temperatures of the virgin asphalt binder are known.
9. The RAP percentages suggested by the Asphalt Mixtures Expert Task Group [1] appear to be substantially correct. Based on the research findings, the ETG recommendations appear to represent a "middle ground." One possible refinement to the recommendations would also consider the stiffness of the RAP binder. Depending on the low temperature stiffness of the RAP, percentages of up to 20%, depending on the RAP binder stiffness, can be used without change to the virgin asphalt binder grade. RAP percentages greater than 15 to 30%, again depending on the RAP stiffness, can be used by following the blending equations and charts. RAP percentages between these extremes can be used by decreasing the high and low temperature grade of the virgin asphalt binder by one grade (i.e., using a PG 58-28 instead of a PG 64-22).
10. Blends containing 40% RAP were successfully tested in the research. At this high level, however, some non-linearity begins to appear in the blending equations. Users should exercise caution in the use of the linear blending equations (or charts) for percentages of RAP greater than 40%.

11. Testing variability was discussed, but insufficient data was available from this research to provide a systematic method of properly accounting for testing variability. Users should be cognizant of the variability in test results caused by the recovery and binder testing procedures. Further research in this area is warranted.
12. Blending using the new procedure for determining the critical low temperature of an asphalt binder, based on thermal stress curves developed from the BBR test and failure stress determined from the direct tension test, was discussed. Further research in this area is warranted to determine how to adjust the low temperature equations for determining blended asphalt binder properties.

BLACK ROCK STUDY

Based on experimental design, testing, and analyzing the data in this study the following conclusions can be drawn:

1. RAP does not act as a black rock. Test results have shown that mixtures containing RAP have properties much closer to those of the total blending case; at high RAP levels a significant amount of partial blending is occurring. Therefore, using blending charts in the design of mixtures containing RAP is a valid approach.
2. The Superpave performance tests, including shear tests and indirect tensile tests, were able to differentiate between black rock and two other mixtures cases (total blending and standard practice) at a high RAP ratio (40%), providing statistically valid evidence that RAP is not a black rock.
3. For all three shear tests, there was no significant difference among mixture cases at the low RAP ratio (10%) but there was a significant difference between the black rock case and the

other mixture cases at the high RAP ratio (40%). At low RAP contents, there is not enough hardened RAP binder present to change the mix properties.

4. Indirect tensile testing also supported this conclusion. The 10% RAP blends did not indicate a significant difference between the cases. At the 40% level, however, there was a noticeable difference between the actual practice and total blending cases versus the black rock case. At the higher percentages of RAP, the low temperature properties show behavior that approaches total blending.
5. The findings of this research project strongly suggest that the Mixtures ETG recommendation of a 15% threshold, below which no change in binder grade is required, appears reasonable. It is only at higher RAP levels that statistically significant differences between the mixture cases were measured. This limit could perhaps be raised to 20%, depending on the stiffness of the recovered RAP binder. A selection chart based on recovered RAP grade is offered.

MIXTURE EFFECTS STUDY

Evaluation of various RAP contents from 0 to 40% leads to the following conclusions.

1. The complex shear modulus of mixtures increased exponentially with RAP content in most cases.
2. Addition of a high stiffness RAP will create a mixture that is stiffer than a mixture made with a medium stiffness RAP.
3. Shear deformation and accumulated shear strain generally decreased as RAP content increased.
4. Low temperature mixture stiffness values increased with increasing RAP content.
5. Increasing RAP content or RAP stiffness decreases a mixture's resistance to low temperature

cracking, if no adjustments are made in the virgin binder grade.

6. The addition of up to 10% RAP into an asphalt mixture will not significantly affect the high or low temperature stiffness of the mixture. The addition of over 20% RAP does have a significant effect on the stiffness.
7. Increasing RAP content has very little effect on low temperature tensile strength of a mix.
8. As RAP content increased, beam fatigue life, measured by cycles to failure, decreased when no adjustments were made to the virgin binder grade.
9. Beams made with softer binder generally exhibited longer fatigue life.

MINI-EXPERIMENTS

Plant vs. Lab Comparison

1. No significant difference was found between samples of plant-produced HMA and specimens prepared in the laboratory using the protocols of this study.
2. The procedures used in this project do a reasonably good job of replicating field practice.
3. The conclusions of this project should be applicable to actual plant-produced mixtures.

Effects of RAP Handling

1. No significant changes occurred in the binder properties of RAP that was heated for 2 hours at either 110 or 150°C.
2. Higher temperatures and longer heating times could bring about changes in the RAP binder properties.

3. To reduce the possibility of changing the RAP binder properties and, possibly, the resulting mixture properties, the time of heating RAP in the laboratory should be limited to 2 hours or less at 150°C or less.

OVERALL CONCLUSIONS

The results of the black rock, binder effects and mixture effects studies all point to a threshold level of RAP of between 10 and 20%. At the 10% level, the effects of the RAP were not significant. At the 20% level, the effects were sometimes significant and at 40% the effects were usually significant. A 15% level may be a reasonable middle ground, although there is evidence to support raising this level to 20%, especially if changes are made in the binder stiffness. Changing the virgin binder grade based on the recovered RAP stiffness would counteract some of the apparently detrimental effects of RAP on fatigue and low temperature properties, both of which are largely binder dependent. Procedures based on the combined results of the different parts of this research are offered in the companion Guidelines for specifying agencies (Appendix D) and Manual for technicians (Appendix E). Suggestions for moving the results of this research are given in Appendix F, the Implementation Plan.

SUGGESTED RESEARCH

There are a number of questions remaining about the use of RAP in the Superpave system that will require more research to resolve. The following topics are among those questions.

Field verification of the findings of this project is needed. The test site in Connecticut is an excellent starting point, since the binder and RAP from that project have been extensively tested. The actual mixtures used in this research do not correspond to the field mixtures, however, since a common virgin aggregate and virgin binders were used for the purposes of this lab evaluation. Additional projects incorporating RAP and control sections without RAP should be placed in the field and monitored over time. Incorporation of differing percentages of RAP in the mixtures would help to verify the three-tiered approach recommended by the Mixtures Expert Task Group and largely verified here. This additional testing and evaluation may also help to verify the effect of RAP stiffness on binder grade selection and the validity of a table such as that suggested in Table 112.

Additional testing is needed in multiple laboratories to establish the variability of recovered RAP binder properties after extraction using the modified SHRP extraction and recovery procedures recommended in this research. Ruggedness and precision and bias testing is also needed.

The issue of recycling modified binders remains a question regardless of the mix design system used. Modified binders have been used for long enough now that pavements incorporating those binders are or soon will be in need of rehabilitation. How will RAP with a modified binder behave when added to a new mix, especially if that new mix also includes a modifier? Will compatibility issues become a concern? This study did not include binder modifiers in either the RAP materials or the virgin binders.

The effect of recycling agents was also not investigated during this research; it was determined to be beyond the scope of the project. The effect of these agents should be investigated. Perhaps an approach similar to that used in the black rock study could be used to assess the effects of rejuvenators. If recycling agents do act as rejuvenators, they would presumably make RAP act even less like a black rock and more like total blending. This effect should be considered when selecting the amount of RAP to incorporate or when selecting the virgin binder grade.

Lastly, a test method that can evaluate any mixture based on fundamental engineering properties should be developed and used to evaluate all mixtures, including those containing RAP. If the industry had a true performance test, the establishment of tiers and recommendations on changes in binder grade would be irrelevant. Any mixture could be designed and evaluated for its long-term performance. This is a lofty goal but should be an ultimate goal.

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APPENDIX A
ANNOTATED BIBLIOGRAPHY

Review of Current Practice: Literature Review (Task 1)

Literature searches on Reclaimed Asphalt Pavement, extraction and testing procedures were conducted through the Purdue Technical Information Service (TIS). TIS searched the following databases for information: Transportation Research Information Service (TRIS), Scisearch, EI Compendex, Pascal, NTIS, Energy Science & Technology JICST-Eplus, McGraw-Hill Publications, Inspec, Fluidex, Inside Conferences, Wilson Applied Science & Technology Abstracts, RAPRA Rubber & Plastics, Apilit, General Science Fulltext, API Encompass: News, Federal Research in Progress, Conference Papers Index, Geobase, Spin, Georef, Chemical Engineering & Biotechnology Abstracts, Mechanical Engineering Abstracts, Geoarchive, Abstracts in New Technologies & Engineering, Metadex, Tulsa (Petroleum Abstracts), Engineered Materials Abstracts, Ceramic Abstracts, World Translations Index, Materials Business File, Polymer Online, Meteorological & Geophysical Abstracts, and World Surface Coatings Abstracts.

The initial search for the key words “reclaimed” or “recycle” or “extract” and “asphalt” or “bituminous” or “pavement” or “binder” revealed over 3,000 items. The search criteria were then narrowed and the search was limited to items published in English in the years 1990 through 1997. It was felt that this time period was reasonable since the Superpave test methods to be analyzed in this study were not developed prior to 1990. Many changes have occurred in test methods and extraction/recovery procedures since that time. This search still resulted in 1,082 items. Summaries of the most relevant documents are provided below in different categories.

Extraction and Recovery Methods

Solvent Removal from Asphalt

B.L. Burr, R.R. Davison, C.L. Glover and J.A. Bullin. Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 1-8.

This study compared the Abson and Rotavapor recovery methods at different temperatures for several asphalt viscosities. Trichloroethylene was used and solvent concentrations were measured after recovery using gel permeation chromatography.

Neither method was found to remove solvent adequately, though more solvent was removed at higher temperatures or with longer recovery periods. The Abson method was found to remove less solvent for high viscosity binders. The solvent hardened the asphalt; greater hardening was observed with longer exposure periods and higher temperatures. The Abson method was found to leave enough solvent in the recovered binder to produce significant softening, as measured by changes in the viscosity. More solvent could be recovered through longer recovery times and higher temperatures, but this would result in greater solvent hardening. The rotavapor method was found to remove more solvent, but was less repeatable than the Abson method.

Hardening was also observed, to a lesser extent, when volatile fractions of the asphalt were lost. Asphalts that had been aged through the Rolling Thin Film Oven (RTFO) did not exhibit this hardening, presumably because the volatiles were lost during aging.

Evaluation of Solvents for Extraction of Residual Asphalt from Aggregates

C.A. Cipione, R.R. Davison, B.L. Burr, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1323, Transportation Research Board, Washington, D.C. (1991) pp. 47-52.

The research compared the use of various solvents for removing asphalt from aggregates. The addition of alcohol to the solvent was also investigated. Several experiments were performed. The experiments compared the ability of different solvents to remove residual material. The different extraction methods and aggregate sources were compared for their effectiveness. The experiments also investigated the effect of moisture on the ability of solvents to remove residual asphalt, as well as the effects of adding different amounts of alcohol to the solvents.

The results of the experiments indicated that ASTM D-2172 Method A modified by using trichloroethylene (TCE)/ethanol was best at removing residual asphalt. It also suggested that moisture did not have a significant effect on the solvent. The study on the addition of alcohol to solvents showed that TCE with 15% ethanol was most effective in asphalt removal, and agitation increased the efficiency further. When the same amount of solvent was used, the TCE system removed significantly more hard-to-remove material than the toluene system did. It was also concluded that TCE/ethanol and pyridine are comparable in solvent power for hard-to-remove material, but seemed to remove different material preferentially. The authors also indicate that no solvent removes asphalt completely. Furthermore, the material that is easier to remove is probably better for predicting cracking.

Asphalt Hardening in Extraction Solvents

B.L. Burr, R.R. Davison, H.B. Jemison, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1323, Transportation Research Board, Washington, D.C. (1991) pp. 70-76.

This research investigated the effects of light, oxygen and temperature on the hardening of asphalt in solvents. The object was to quantify the amount of hardening with respect to time of exposure, temperature and concentration of dissolved asphalt. The experiment was performed on various solvents and asphalts. Some solutions were deoxygenated by bubbling with CO_2 or N_2, some had oxygen bubbled through to attain CO_2 saturation, and some solvents were direct from the bottle. Dark, low hood light and strong fluorescent light were used. Recoveries were conducted using the rotavapor apparatus at either near room temperature under vacuum or at higher temperatures under atmospheric pressure. The solvents tested were TCE, $CHCL_2$, CH_2CH_2, TCE/ethanol, toluene, and CCL_4. The solutions in different conditions were observed using gel permeation chromatography (GPC).

From the results, it seemed that prehardened asphalt still hardened in solvent at about the same rate as tank asphalt. Some oxygen-containing samples hardened considerably, and light seemed to accelerate hardening. In the TCE/ethanol sample, there was a gradual increase in hardening with decreasing asphalt concentration. The results appear to indicate that solvent hardening occurs to about the same degree in most solvents. The hardening is more rapid at the beginning, and then slows as time passes. One conclusion is that extracting at room temperature and completing the recovery process as quickly as possible can minimize solvent hardening.

New Apparatus and Procedure for the Extraction and Recovery of Asphalt Binder from Pavement Mixtures

B.L. Burr, C.J. Glover, R.R. Davison and J.A. Bullin. Transportation Research Record, No. 1391, Transportation Research Board, Washington, D.C. (1993) pp. 20-29.

This research was focused on presenting the SHRP extraction and recovery method and comparing it with modified versions of two commonly used procedures. The methods studied are the SHRP extraction method, and modified version of ASTM D-2172 A and ASTM D-2172 B. The modification in Method A was the substitution of toluene for trichloroethylene (TCE), with ethanol added in later washes; and the difference in Method B was that the solvents were varied for some experiments. It was recognized during the research that because properties of asphalt change when mixed with aggregates, there is no way of knowing the properties that the extracted asphalt is supposed to possess, i.e. "the 'correct' result is never known."

The results showed that the SHRP method and Modified Method A produced similar results and precision, while the Modified Method B extraction results were less reproducible with respect to average viscosities. Modified Method B had a low asphalt removal efficiency, leaving large amounts of asphalt on the aggregates. The SHRP method was slightly more efficient in removing asphalt compared to the Modified Method A. The authors concluded that the SHRP and Modified Method A procedures were able to provide better asphalt samples that have nearly unchanged properties. However, there are other considerations, such as the requirement of considerable operator attention and lab space.

Aging of Asphalt on Paved Roads- Characterization of Asphalt Extracted from the Wearing Courses of the Belgrade-Nis Highway

M. Smiljanic, J. Stefanovic, Hans-J. Neumann, I. Rahimaian and J. Jovanovic. Journal: Erdol and Kohl, Vol. 46, No. 6, Hamburg, Germany. (1993) pp. 238-244.

This paper presents the findings of tests to characterize asphalt binders extracted from eight paved road samples from different parts of Belgrade. These samples were related to different levels of roadway distress. The goal of the research was to correlate properties in aged asphalt with the damage on the road.

In this research, the penetration, softening point, Fraas breaking point and number average molecular weight were determined. Elemental analysis and thermal analysis were performed. The asphaltene content was also determined. Thermogravimetry was used as the method for measuring the accelerated aging of asphalt. The test was performed at 250^{o}C, as opposed to 165^{o}C for conventional methods.

The conclusions drawn from the research include the confirmation that aging of asphalt is a hardening process involving an increase in softening point and Fraas point and decrease in penetration. The more damage there is in the pavement, the greater the changes in the properties of the asphalt. Thermal analysis of the samples also showed that there is less oxidation susceptibility where the roads are better preserved.

Recycling Agents and Blended Binders

Evaluating Recycled Asphalt Binders by the Thin-Film Oven Test

A. Samy Noureldin and Leonard E. Wood. Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 20-25.

In this research, long-term performance was evaluated, and the homogeneity, incompatibility and hardening rate in hot-mix-recycled bituminous pavement were identified. The effects of artificial laboratory aging on a virgin binder and three rejuvenated binders were determined.

The binder used was an AC-20, and the recycled binders were restored to the AC-20 classification range. The experiment examined the effects of binder type (virgin and three recycled binders restored using different agents) and time of exposure in the thin film oven test (TFOT) (0, 2, 5 and 10 hrs). During the preparation of samples, actual field conditions were simulated, so virgin aggregate was added to the RAP followed by the rejuvenator, except Mobilsol-30, which was added before the virgin aggregate.

The findings indicated that rejuvenated binders might have different aging behaviors than virgin binders of the same consistency. Penetration and viscosity measurements on a rejuvenated binder were not adequate to ensure long-term performance. The results indicated additional criteria and test conditions need to be developed to ensure success of hot-mix-recycled pavement. The TFOT was identified as a good tool to determine the hardening rate, possible nonhomogeneity and incompatibility that may occur with a rejuvenated binder. It was noted that in order to ensure good-quality recycled asphalt pavement with acceptable performance, careful selection and testing of a recycling agent is essential.

Viscosity Mixing Rules for Asphalt Recycling

J.M. Chaffin, R.R. Davidson, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1507, Transportation Research Board, Washington, D.C. (1995) pp. 78-85.

Forty-seven blends of aged asphalts and softening agents were blended at multiple levels of aged material content. It was found that for 45 of the blends, the relationship between viscosity of the blends at 60°C and the proportion of aged material can be described using the Grunberg model. Blends using low-viscosity asphalts as softening agents exhibited significantly different behavior from blends using commercial recycling agents. The low-viscosity asphalt softening agents had viscous interaction parameters close to or greater than zero. All of the blends using commercial recycling agents had interaction parameters less than zero. The value of the interaction parameter is a strong function of the viscosity difference between the aged asphalt and recycling agent. A normalized Grunberg model was developed to eliminate this dependency. An average normalized interaction parameter can be used to generate a "universal" mixing rule for commercial-type recycling agents.

Viscoelastic Characterization of Blended Binders

Hamid R. Soleymani. Ph.D. Dissertation, University of Saskatchewan, Saskatoon, Canada (September 1997) 223 pp.

Research was conducted to study the properties of laboratory-aged binders blended with two soft asphalt cements and two recycling agents. The main objective of this research was to characterize the blended binders with PG testing parameters (G^*, δ, S and m-value). The other objective of this research was to investigate the temperature and loading time dependencies of blended binders with their master curves. The relationships between master curve parameters of blended binder with proportion of recycling agent were studied. The master curve parameters, rheological index (R) and crossover frequency (ω_c), were based on the SHRP A-002A model for asphalt cement, which suggested a hyperbolic equation for the master curve of asphalt cements. The blended binders were characterized at a wide range of temperatures from -30 to 70°C. All blended binders were tested with the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR).

Based on the results of this research, a linear relationship was shown to be adequate for prediction of PG testing parameters (log G*, δ, log S, and m-value). Two methods were proposed for the selection of soft asphalt cements/recycling agents in recycled mixtures. The first method was based on a linear relationship for PG binder performance criteria (G*/sinδ, G*sinδ, S and m-value). The second method was based on a linear relationship of the critical temperatures, the temperatures at which the PG criteria were just satisfied. The relationship of master curve parameters (R and ω_c) of the blended binders was studied. A linear relationship was accurate enough for prediction of these parameters of blended binders with the proportion of recycling agents in the blends. The temperature dependency of shift factors was studied based on defining temperature (T_d) from the William, Landel and Ferry (WLF) Equation. The defining temperature decreased as the proportion of recycling agent in the blend decreased and the binders aged.

The results of this study can be used for selection of asphalt cement/recycling agent to rejuvenate the aged asphalt cement in RAP. In addition, results can be used for producing a specific PG asphalt cement by blending different asphalt cements.

Effect of Composition on Asphalt Recycling Agent Performance

G.D. Peterson, R.R. Davison, C.J. Glover and J.A. Bullin. Transportation Research Record, No. 1436, Transportation Research Board, Washington, D.C. (1994) pp. 38-46.

The purpose of this research was to find out the types of materials suitable for use as asphalt recycling agents. Experiments were performed for re-blended asphalts with different components mixed in controlled amounts and artificially aged. Tank asphalts were hardened by bubbling oxygen though molten asphalt, then aging in the Pressurized Oxygen Vessel (POV). The factors to be studied were the effect of oil on aging of aromatic fractions; effect of metals and asphaltenes on aging; and effect of oils, waxes, and asphaltenes on re-blended asphalt aging. The zero shear complex viscosity, measured in the dynamic shear rheometer, and carbonyl area, which indicates amount of oxidation, were measured for aged and unaged blends.

The results from the experiments showed that asphaltenes had practically no effect on the oxidation rate, but did increase hardening rate. Aged material containing high amounts of asphaltenes, when recycled, had increased hardening susceptibility, but better temperature susceptibility. Highly aromatic recycling agents produced pavements that were superior to the original pavement. Small amounts of wax had no effect, but waxes and saturates unquestionably affect the ductility negatively.

An Integrated Approach for Determining Additive Requirements in Hot Mix Recycling

V.P. Sevas, A.C. Edler, M.A. Ferreria and E.J. Van Assen. <u>Sixth International Conference on Structural Design of Asphalt Pavements</u>, Vol. 1, Ann Arbor, Michigan. (1987) pp. 23-33.

An integrated approach including chemical composition and fluxing power methods was used for selection of the type and amount of recycling agent for hot asphalt recycling.

In chemical composition, first an open column chromotography method was used to fractionate aged bitumens and recycling agents, but because of the time consumed and large sample sizes required, the High Performance Liquid Chromatography (HPLC) method was used instead. In this study, ten recycling agents, seven new bitumens and three aged asphalt cements were fractionated by HPLC, and the chemical fractions including asphaltenes, saturate and aromatic + resins were determined.

To determine the physical requirements for a recycling agent, the fluxing power method was used. In this method, the penetration of blended binders with differing amounts of recycling agent was measured and the slope of fluxing lines were obtained. The steeper the slope of the fluxing lines the greater the fluxing power of the agent for restoring aged extracted binders. Chemical composition data were used in conjunction with fluxing power requirements to design and produce laboratory and field recycled mixes.

Design of Recycled Asphalt Pavements and Selection of Modifiers

R.L. Dunning and R.L. Mendenhald. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 35-46.

The purpose of this paper is to discuss the design of recycled asphalt pavement with emphasize on the criteria required to reconstitute an aged asphalt. Recommended specification requirements for a modified binder include a flash point of 200°C, a viscosity range of 90 to 300 cP at 60°C, and a composition of at least 9 percent polar compounds and 60 percent aromatic compounds.

The amount of modifier required to soften an asphalt to a predetermined viscosity may be calculated within limits by using equations based upon plots of log-log (viscosity) versus log[559.7-(%modifier)] and log-log(viscosity) versus [559.7+2 (%modifier)].

Practical Aspects of Reconstituting Deteriorated Bituminous Pavements

D.D. Davidson, William Cenessa and S.J. Escobar. American Society for Testing and Materials, STP 662, Recycling of Bituminous Pavements, ASTM, Philadelphia, PA (1977) pp. 16-34.

The objective of this paper was to provide practical guidelines, which can be used to reconstitute deteriorated asphalt pavements. Two elements involved in recycled mix design, including restoration of durability and desirable consistency to the aged asphalt and determination of the proper mix design, were studied in this research.

In the first element, some physical and chemical specifications were proposed for reclaiming agents. These specifications include viscosity, flash point, volatility, compatibility, chemical composition and specific gravity. For recycled mix design, various steps were suggested through this research:

- Basic properties of the pavement to be recycled must be determined.
- The Asphalt Institute formula was shown to be adequate for determining the asphalt demand of the aggregate.
- Recycling Agent may be selected.
- Viscosity or penetration blending graphs should be used for checking the amount of recycling agent in the recycling pavement.

Design Approaches for Mixtures Containing RAP

Guidelines for the Design of Superpave Mixtures Containing Reclaimed Asphalt Pavement (RAP) Superpave Mixture Expert Task Group. Federal Highway Administration, Washington, D.C. (1997) 5 pp.

This guideline is the result of an FHWA Superpave Mixture Expert Task Group activity to make specific recommendations for inclusion of RAP into Superpave mixture design procedures.

This guideline suggests that, in the design of Superpave mixtures with RAP, aggregate in the RAP be handled as aggregate and asphalt binder in the RAP be considered as part of the blended asphalt binder. All aggregate requirements for the aggregate blend (virgin and RAP) must be satisfied. For adjusting the asphalt binder grade, this guideline divided the design of mixtures containing RAP into three tiers as follows:

1) ≤ 15% RAP by weight of total mixture

The asphalt binder grade for the mixture is selected for the environmental and traffic conditions as required for a mixture with all virgin materials. No grade adjustment is made to compensate for the stiffness of the asphalt binder in the RAP.

2) 16% to 25% RAP by weight of total mixture

The selected binder grade for the new asphalt binder is one grade lower than the grade required for a virgin asphalt binder at both the high and low temperatures.

3) > 25% RAP by weight of total mixture

The binder grade for the new asphalt binder is selected using an appropriate blending chart for high and low temperatures.

Designing Recycled Hot Mix Asphalt Mixtures Using Superpave Technology

Prithvi S. Kandhal and Kee Y. Foo. Progress of Superpave (Superior Performing Asphalt Pavement): Evaluation and Implementation, STP 1322, American Society for Testing and Materials, West Conschocken, PA (1997).

This research project was undertaken to develop a procedure for selecting the Performance Grade (PG) of virgin asphalt binder to be used in recycled mixtures. Three aged asphalt binders recovered from reclaimed asphalt pavement (RAP) and three performance grade (PG) binders, PG 64-22, PG 58-22 and PG 52-28, were physically blended in different proportions to obtain various recycled binders. The recycled binders were subjected to a temperature sweep using the dynamic shear rheometer near high pavement service temperatures (that is, measuring $G^*/\sin\delta$ or rutting factor at various temperatures) to determine their high temperature grade and near the intermediate service temperatures (that is, measuring G*sinδ or fatigue factor at various temperatures) to determine their intermediate temperature grade.

It was concluded that the construction of a "temperature sweep" blending chart is very time consuming. It involves conducting a temperature sweep on both aged asphalt binder in the RAP as well as the proposed virgin asphalt binder to determine the temperature at which G*/sinδ equals 1.0 kPa. The inconvenience of running temperature sweep tests can be eliminated by constructing a "specific grade" blending chart. In this blending chart, the Y-axis is a log-log scale (similar to viscosity or penetration blending charts). The information needed to construct a "specific grade" blending chart is the G*/sinδ of both the aged asphalt binder and the virgin asphalt binder at the high pavement service temperature.

Preliminary Mixture Design Procedure for Recycled Asphalt Materials

T.W. Kennedy and Ignacio Perez. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 47-67.

This paper summarizes the findings of a study to evaluate the strength, fatigue and elastic characteristics of recycled asphalt pavement materials and to develop a preliminary mixture design procedure. Mixtures with different types and amounts of additives for three recycling projects in Texas were evaluated. The primary methods of evaluation were the static and repeated-load indirect tension tests.

Estimates of tensile strength, resilient elastic and fatigue characteristics of recycled mixtures were obtained. The necessary steps for the design of recycled asphalt mixtures have been subdivided into three categories; general, preliminary design and final design. Some recommended values for the indirect tensile test were proposed for recycled mixtures.

Some other findings of this study were:

- The engineering properties of the recycled mixtures evaluated in this study generally were slightly better than those of conventional mixtures.
- Satisfactory mixtures can be obtained with recycled mixtures.

Development of Low-Temperature Blending Charts for Recycled Asphalt Binders Using the Superpave Binder Specification Parameters

Hussain Bahia, Robert Peterson and David Ross. <u>Development of Low Temperature Blending Charts for Recycled Asphalt Binders Using the Superpave Binder Specification Parameters</u>, FHWA Report DTFH-61-95-C-00055, National Asphalt Training Center II Project (1996).

This study was initiated by the FHWA to establish guidelines for selecting Performance Graded asphalts for mixtures containing RAP material. This report summarizes the results of an experiment at the Asphalt Institute and also refers to another study carried out by the Transportation Center of the University of Saskatchewan, Canada (Soleymani).

Comparing a linear and non-linear model for prediction of PG parameters of blended binders showed that a linear model can be used for this purpose. Two alternative methods have been recommended based on the results of the mentioned studies. These methods differ in the concept used to define a blending chart. The first is based on the concept of limiting temperature. The second is based on testing at the testing temperatures appropriate for the target grade (design grade).

Black Rock Issue

Modifier Influence in the Characterization of Hot-Mix Recycled Material

Samuel H. Carpenter and John Wolosick. <u>Transportation Research Record</u> 777, Transportation Research Board, Washington, D.C. (1980) pp. 15-21.

This paper investigates the influence of the recycling agent diffusion process on the recycled mixture. A recycled material with 2.6-mm penetration at 25°C was used in this study. A standard modifier (Paxole 1009) was chosen to rejuvenate the aged mixture. Two sets of material were tested. The rejuvenated samples were made by blending the modifier into the extracted asphalt cement and the combination was added to aggregate recovered from the original Reclaimed Asphalt Pavement (RAP). The recycled samples were prepared by adding the same proportion of modifier to the recycled material without extraction of the asphalt cement from the RAP. Two series of material were characterized with resilient modulus, creep compliance and Marshall stability. The test data support a softening effect caused by the diffusion of the modifier into the old asphalt cement.

In a validation study, the asphalt cements of recycled samples were recovered in two different stages at an appreciable time following mixing; these were characterized as inner and outer layers. The outer and inner layers were not of the same consistency, but they approached the same consistency after more than 60 days following mixing. Therefore, the diffusion process must be recognized and accounted for in the prediction of lab and in field performance.

Test for Efficiency of Mixing of Recycled Asphalt Paving Mixtures

Teh-Chang Lee, Ronald Terrel, and Joe Mahoney. Transportation Research Record 911, Transportation Research Board, Washington, D.C. (1983) pp. 51-60.

The main objective of this research was to develop a technique and necessary test equipment needed to establish the ability of a mixing operation to produce an intimate mixture consisting of Reclaimed Asphalt Pavement, modifying agent and new asphalt.

The researchers examined the resilient modulus, as a classical engineering testing method, for determining the efficiency and time dependency of recycling agents in recycled mixtures. They concluded that the resilient modulus test appears to be sensitive enough to the recycling agent content but not sensitive enough to detect small changes in the mixture. Therefore, the researchers used a dye chemistry technique for this purpose.

In the dye chemistry technique, a small amount of dye chemical was added with the recycling agent and then developed dye in the mixture was detected by visual examination or by using other measuring methods. The investigators found that the dye chemistry method provides additional insight into how a recycling agent disperses with time. Standard laboratory samples were prepared and maintained at room temperature for 1, 5, 10 and 30 days and up to 6 months after compaction of samples. The laboratory and field dye chemistry results showed that the diffusion of a recycling agent through a mix is a function of mixing time and the potential of further dispersion of a recycling agent with time is only local.

Rejuvenator Diffusion in Binder Film for Hot-Mix Recycled Asphalt Pavement

Ahmad Samy Noureldin and Leonard E. Wood. Transportation Research Record 1115, Transportation Research Board, Washington, D.C. (1987) pp. 51-61.

The objective of this study was to determine the extent to which certain types of rejuvenators diffuse into the hardened asphalt film coating the aggregate and effect of its properties during a specific period of time.

A partial extraction technique that had the effect of dividing the asphalt film into microlayers was used. The recovered binders from each microlayer were characterized by means of consistency tests. In this study, one RAP, one new aggregate and three types of recycling agents (AC-2.5, AE-150 and Mobilsol-30) were selected. In the stage extraction method, the amount of solvent for extraction of binder in recycled mixtures was added to mix in increments of 200, 200, 300 and 700 ml in order to extract the asphalt film in four stages. Some findings from this study are as below:

- Stage extraction of the hard asphalt film from the RAP indicated a non-uniform consistency distribution. The outer microlayer of binder film was the hardest, the second microlayer was less hardened and the third layer appeared to retain its original consistency.
- Stage extraction of binder rejuvenated by recycling agents without addition of virgin aggregate indicated that the rejuvenators are most effective at softening the hardened binder on the outer two microlayers of the asphalt film.

Laboratory and Field Performance of Recycled Asphalt Pavements

Mixture Properties of Recycled Central Plant Materials

J.A. Epps, D.N. Little, R.J. O'Neal and B.M. Galling. "Mixture Properties of Recycled Central Plant Materials," American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA 1997, pp. 68-103.

The objectives of this research were to:

a.) define the material properties of central plant recycled mixes in Texas,

b.) compare properties of these recycled mixes with conventional paving mixtures normally used in Texas,

c.) evaluate the performance of the pavements containing central plant recycled mixes, and

d.) compare the performance of pavement constructed with recycled and conventional paving mixtures.

Hveem, Marshall, resilient modulus, indirect tensile, direct tensile and water sensitivity properties were reported for recycled mixtures compacted both in the laboratory and under normal field procedures. The material properties of central plant recycled mixes indicated that, through proper mixture design, these mixtures can meet conventional design criteria. The short-term performance evaluation of the recycled pavement, based on Serviceability Index and Pavement Rating Score, indicated that they showed satisfactory performance.

Laboratory Performance of Recycled Asphalt Concrete

R.L. Terrel and D.R. Fritchen. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 104-122.

This research used a practical laboratory test system for evaluating the performance of recycled asphalt pavement. One old asphalt pavement was selected for this study. The amounts of two different recycling agents to be used were determined with viscosity blending charts, and the laboratory samples were prepared. The laboratory recycled samples were conditioned in freeze-thaw. The performance of the laboratory samples was determined by measuring the resilient modulus (M_r).

The addition of both types of rejuvenating agent softened the old mixes in terms of decreasing the modulus. The results of this research also indicated that the performance of recycled asphalt concrete pavement is comparable to the performance of standard new asphalt concrete pavements.

Recycling Old Asphaltic Pavement with Sulfur

W.C. McBee, T.A. Sullivan, and Don Saybk. American Society for Testing and Materials, Recycling of Bituminous Pavements, STP 662, ASTM, Philadelphia, PA (1977) pp. 123-141.

In this study, the feasibility of using sulfur to soften or reduce the viscosity of the oxidized asphalt binder in old asphaltic pavements was demonstrated. On a laboratory scale, three sources of RAP were investigated. With all three materials, mixes incorporating the addition of 1.25 weight percent sulfur (16 to 26 weight percent of the binder) to the reclaimed asphalt material were designed.

The laboratory testing results showed that recycled mixtures softened with sulfur plus additional asphalt had higher than normal stiffness values, which means greater fatigue life for the recycled mixtures. A series of constant-stress amplitude flexural fatigue tests showed that recycling by the addition of asphalt-paxale, sulfur-asphalt or sulfur alone can provide a pavement material with fatigue behavior equal or superior to that of a typical asphaltic concrete system.

Durability of Recycled Asphalt Concrete Surface Mixes

Osama Abdulshafi, Bozena Kedzierski, and Michael G. Fitch. Ohio Department of Transportation, Columbus, OH (1997) 109 pp.

This study was designed to evaluate the durability of HMA surface mixtures produced in the state of Ohio that contain varied amounts of RAP and included evaluations of both the binders and the mixtures. The binder evaluation included determination of the viscosity and infrared spectroscopy characteristics of laboratory aged samples; virgin, RAP and blended virgin plus RAP samples were analyzed. Uncompacted mixture samples containing 0, 10, 20 and 30% RAP were oven-aged until the recovered binder properties (Abson process) matched those from standard binder aging methods. Specimens were then prepared from these mixtures by Marshall compaction and analyzed for bulk specific gravity, theoretical maximum specific gravity, resilient modulus, AASHTO T-283 moisture sensitivity, indirect tensile strength and indirect tensile creep modulus.

Infrared spectroscopy indicated that the RTFO and PAV procedures produced aged binders that differ in chemical composition from those recovered from oven-aged mixtures. The results also indicated that the aged RAP binder does not completely blend with the virgin asphalt cement. Mixtures containing RAP showed an increase in the resilient modulus, increase in indirect tensile strength and increase in indirect creep modulus as the percentage of RAP increased. The mixtures containing RAP also showed slight improvement in the resistance to moisture damage. A procedure for the selection of the percent RAP was recommended.

Five-Year Experience of Low-Temperature Performance of Recycled Hot Mix

K.K. Tam, P. Joseph, and D.F. Lynch. Transportation Research Record, No. 1362, Transportation Research Board, Washington, D.C. (1992) pp. 56-65.

This research looked into the thermal cracking of recycled hot-mix (RHM) and confirmed the belief that RHM is less resistant to thermal cracking than non-recycled mixes. The results were obtained through laboratory and field evaluation. The research also compared the use of two types of results as methods of evaluation. The thermal cracking properties of the mixes were analyzed using the limiting mix stiffness and pavement fracture temperature criteria. RHM specimens were produced from plant mixes and individual mix components in the laboratory. These RHM mixtures covered different recycling ratios. Penetration grade asphalt cements (85/100 to 300/400) were used in the RAP mixtures.

The research showed that the Fracture Temperature (FT) criteria correlated well with field data and are more suitable and reliable for evaluating low temperature performance of hot mixes than limiting stiffness. It also correlated well with recovered penetration values and followed the expected trends of behaviors. The limiting stiffness method needs to be examined further and modified accordingly before it can be used for predicting low temperature behavior. The research also showed that RHMs are more prone to thermal cracking than conventional mixes. In order to minimize low temperature cracking and obtain better accuracy of predicting fracture temperature, recycling ratios should be limited to 50/50, an appropriate virgin asphalt cement should be selected for a desirable recovered mix penetration, the fracture temperature method should be used for mix evaluation, and more data needs to be obtained to support the use of laboratory samples for prediction or evaluation of low temperature performance in the field, both for RHM and conventional mixes.

Laboratory Evaluation of Recycled Asphalt Pavement Using Nondestructive Tests

A. Samy Noureldin and Leonard E. Wood. Transportation Research Record, No. 1269, Transportation Research Board, Washington, D.C. (1990) pp. 92-100.

This research was focused on characterizing the performance of recycled hot-mix asphalt pavement compared to virgin mix using pulse velocity, resilient modulus and Marshall stability tests. The binder in the RAP was restored to an AC-20 designation using three different agents. The percentage rejuvenator used was determined using the Asphalt Institute curves, and was verified by extraction, recovery and testing. The salvaged and virgin aggregates were combined to a fixed gradation, and mixes containing 5.5, 6, and 6.5% asphalt were prepared.

The test results show that the virgin mixture stiffness and strength values were generally higher than those of recycled mixtures. AE-150 may not be a good rejuvenator as the stiffness and strength values of the recycled mixture with AE-150 were very low. Pulse velocity test parameters were not sensitive to binder content or binder type present in mixtures. Resilient modulus test results were sensitive to both, and can be used for the design of asphalt mixtures and the evaluation of recycling agent used. The Marshall stability test was adequate for identifying binders with potential for producing high stability mixtures, and pulse velocity and modulus of elasticity measurement could be used for pavement thickness design considering their low variability.

Recyclability of Moisture Damaged Flexible Pavements

Serji N. Amirkhanian and Bill Williams. Journal of Materials in Civil Engineering, Vol. 5, No. 4, American Society of Civil Engineering, New York (1993) pp. 510-530.

The objective of this research was to evaluate asphalt concrete mixtures, which had been damaged by moisture, using test data from lab-prepared Marshall specimens. Also evaluated in this study were the South Carolina Department of Highways and Public Transportation (SCDHPT) procedures using RAP from field cores to design recycled mix instead of using milled RAP from actual paving.

The mix design for the virgin specimens was prepared using the Marshall method with an optimum asphalt content of 5.25%. The SCDHPT Marshall mix design was used for the recycled Marshall specimens. Hydrated lime and liquid antistrip agents were used. Some specimens were partially vacuum saturated according to the Root-Tunnicliff moisture-conditioning test. All specimens, wet and dry, were tested for resilient modulus and indirect tensile strength. A visual stripping rating was also performed on the moisture-conditioned specimens.

Statistical analysis of the results showed that the indirect tensile strength ratios and resilient moduli ratios of moisture-damaged asphalt concrete samples were significantly higher than those of virgin materials. The tensile strength ratio and resilient modulus ratios were higher for virgin materials, but not significantly. There were no significant differences in the specimens containing milled RAP and cored RAP. It was also found that antistripping agents were effective in recycled concrete mixtures. The results indicated that mixes containing up to 15% RAP are not more susceptible to moisture damage than virgin mixes and that the reuse of moisture-damaged RAP mixtures does not necessarily increase the risk of moisture damage for the new pavement.

Performance of Recycled Hot-Mix Asphalt Mixtures in Georgia

Prithvi S. Kandhal, Shridhar S. Rao, Donald E. Watson, and Brad Young. Transportation Research Record, No. 1507, Transportation Research Board, Washington, D.C. (1995) pp. 67-77.

The purpose of this research was to evaluate the performance of recycled pavements and compare them to virgin asphalt pavements. Field projects in Georgia were selected for the first part of this research such that the recycled and virgin sections used the same virgin aggregates in the mixture, were produced by the same HMA plant, were placed and compacted by the same equipment and crew, and were subjected to the same traffic and environment. The extraction of aged asphalt from the mixtures was done using the ASTM D2172 Method A procedure using trichloroethylene (TCE), while the recovery process was that recommended by SHRP. Tests performed on the recovered asphalt included viscosity at 60°C, penetration at 25°C, and dynamic shear rheometer (DSR) at 64°C and 22°C. Tests conducted on the cores were air void content, resilient modulus at 25°C and indirect tensile test at 25°C. Mix from cores of the virgin and recycled pavements was reheated and recompacted in the Corps of Engineers gyratory to determine the gyratory stability index (GSI), gyratory elasto-plastic index (GEPI) and roller pressure.

The results of the first part of the research showed that the pavement sections were performing satisfactorily, and there were no significant differences between the properties of the virgin and recycled sections in terms of air voids or resilient modulus measured on cores as well air voids, GSI and confined dynamic creep modulus for the recompacted mixes. There were significant differences in the indirect tensile strength, GEPI and roller pressure values. Recovered binder test results showed no significant differences for viscosity, penetration, rutting factor ($G^*/\sin \delta$) or fatigue factor ($G^* \sin \delta$).

The second part of the research involved studying projects with only recycled wearing courses and projects with only virgin wearing courses. Measurements taken from these projects included rut depth, cracking and density. Asphalts recovered from the cores were tested for penetration at 25°C and viscosity at 60°C.

The results of the second part of the research showed that there were no significant differences in the properties of virgin and recycled pavements in terms of rutting, cracking or density. The overall performance of the virgin and recycled pavements was comparable based on visual inspection. The conclusion of the research was that recycled pavements generally perform as well as virgin pavements, implying that the current Georgia DOT specifications, procedures and quality control are satisfactory.

Behavior of Recycled Asphalt Pavements at Low Temperatures

M. Sargious and N. Mushule. "Behaviour of Recycled Asphalt Pavements at Low Temperatures." Canadian Journal of Civil Engineering, Vol. 18, National Research Council of Canada, Ottawa (1991) pp. 428-435.

In this study, a mixture containing 45.2% reclaimed asphalt pavement and 54.8% virgin materials was compared to a 100% virgin mixture designed to meet the same initial properties. Laboratory properties including resilient modulus, modulus of elasticity, coefficient of thermal expansion, thermal conductivity and specific heat were compared in what is termed the experimental analysis. A finite element computer program called FETAB was used in the theoretical analysis to analyze the performance of the recycled and virgin mixtures if they were used in a variety of thicknesses and over different subgrades. The program considers the influence of mixture properties as well as pavement properties to determine the thermal stresses that would build up in various pavement cross sections due to a change in temperature from 20 to -40^{o}C.

In both the theoretical and experimental analyses, the recycled mixture/pavement was found to perform better than the virgin control in terms of low-temperature cracking. This may have been due to the fact that a softer asphalt (400/500) was used in the recycled mixture than in the control (150/200). The recycled mixture also had a higher coefficient of thermal conductivity, higher tensile strength and lower coefficient of thermal contraction. The authors noted that further research was needed.

The Mechanical Properties of Recycled Asphalt Mixes

A.F. Stock and S.J. Sulaiman. Highways and Transportation, Vol. 42, No. 3, Journal of the Institution of Highways and Transportation, London (1995) pp. 19-24.

This paper presents the results of a program of mechanical tests designed to evaluate mixes, mix design approach, and quality of recycled mixes. The tests were performed on mixes containing increasing amounts of recycled asphalt up to 70%. Tests performed were the Marshall stability and flow, dynamic stiffness and flexural strength. During the preparation of the samples, the recycled material was heated at temperatures limited to 100^{o}C so as to avoid binder run-off. The hot mix was placed in a large mold and compacted. The compacted samples were then cut into manageable pieces from which cores and test samples were cut. This ensured that the samples were provided from one batch of mix.

The results from the Marshall test showed that there was no significant difference in the stabilities of the mixes with varying proportions of RAP up to 50%. The mix with 70% RAP showed significantly higher stability. The differences in flow were also not significant. This implied that the mixing and compaction technique used produced samples with uniform density and mechanical properties. There were also no significant differences in the dynamic stiffness of mixes with up to 70% RAP, for a range of temperatures from -5^{o}C to 25^{o}C, and for loading rates between 0.1 and 10 Hz. The RAP also does not influence the flexural strength for temperatures in that range. The strain at failure increased with RAP content, but was not likely to lead to premature failure.

Performance of Recycled Asphalt Concrete Overlays in Southwestern Arizona

Mustaque Hossain, Dwight G. Metcalf, and Larry A. Scofield. Transportation Research Record, No. 1427, Transportation Research Board, Washington, D.C. (1993) pp. 30-37.

The research studied recycled asphalt concrete overlays as a rehabilitation strategy. Eight test sections were observed for roughness, frictional properties and cracking. Overlays containing 50/50 blends of virgin and recycled materials and all virgin materials were placed in two thicknesses, 51mm and 102 mm. The thinner overlays were constructed over existing surfaces and over milled surfaces (mill and replace). The test sections were in a dry, no-freeze zone.

In this research, roughness and frictional characteristics were used to indicate present serviceability. Roughness was measured by the Mays ride meter, and frictional characteristics were measured using the Mu meter. The structural pavement performance was evaluated using visual distress survey (PAVER) and falling weight deflectometer. Rut depth, bulk density and air voids were also measured.

The research concluded that the overlays performed satisfactorily throughout their service lives. The recycled pavements performed as well as the virgin pavements. The thicker overlays performed better in terms of cracking, but showed more rutting, due to densification. The mill and replace strategy did not provide increased life, but for those pavements, the recycled mix performed better than the virgin mix. Pavements of both thicknesses required rehabilitation after ten years of service.

Evaluation of Recycled Projects for Performance

Harold R. Paul. Asphalt Paving Technology, Vol. 65, Journal of the Association of Asphalt Paving Technologists, St. Paul, Minnesota (1996) pp. 231-254.

This report summarizes a performance evaluation comparing recycled and conventional projects over a five-year period. Five recycled pavement sections were paired with virgin pavements constructed during the same time period by the same contractor, if possible, and with similar mix designs, cross sections and traffic. RAP contents ranged from 20 to 50%.

The pavement performance was analyzed in terms of serviceability, Pavement Condition Rating, (PCR) and structural strength (Dynaflect). Cores were analyzed to determine specific gravity, asphalt content and recovered binder properties (penetration, viscosity and ductility).

The findings indicate that the recycled pavements performed as well as conventional pavements from six to nine years after construction. No significant differences were found between the recycled and virgin pavements as measured by PCR or upper pavement strength (excluding subgrade differences). The recovered binders revealed no significant difference in penetration, viscosity or ductility.

Recycling of Asphalt Mixtures Containing Crumb Rubber

B.E. Ruth, M. Tia, G. Jonsson, and J.C. Setze. Florida Department of Transportation, Report No. FL/DOT/MO/D510717, Tallahassee, FL (1997) 221 pp.

This study was conducted to evaluate the effects of recycling asphalt mixtures that contain Crumb Rubber Modifier. The study is reviewed here due to its use of a procedure to simulate a recycled mixture by oven-aging it in the laboratory. Mixtures were evaluated using various percentages of RAP with three different sizes of CRM at three different concentrations of rubber. Mixtures were prepared meeting a typical Florida DOT gradation modified to represent a milled mixture. The mixtures, which contained the CRM modifier, were aged for 14 days in a convection oven at 85^{o}C to simulate field aging. The artificial RAP was then combined with additional aggregate and asphalt to produce mixtures, which were then evaluated in terms of Rice densities and GTM compaction-densification tests.

Among other results, the study found that there was no statistical difference between mixtures with and without CRM in terms of compacted mixture properties. The inclusion of RAP with age-hardened CRM did not significantly influence the shear resistance of one type of mixture, but did affect the air void content, due to significant increases in the Rice density. This increase in the Rice density was concluded to be due to binder absorption and a possible loss of volatiles.

Field Validation of Laboratory Aging Procedures for Asphalt Aggregate Mixtures

C.A. Bell, M.J. Fellin and A. Weider. Asphalt Paving Technology, Vol. 63, Journal of the Association of Asphalt Paving Technologists, St. Paul, Minnesota (1994) pp. 45-80.

This paper summarizes the work to validate the short-term and long-term oven aging techniques developed under SHRP to simulate aging during the construction process and during field service. Field samples were used during this study to compare to laboratory-produced samples of the original construction materials that were intended to simulate actual aging behaviors. The diametral resilient modulus was used to evaluate the effects of different aging times and handling procedures.

The results presented in this study support the conclusion that oven aging for four hours at 135^{o}C is representative of the type of aging that occurs during mixing and placement. Two days of oven aging at 85^{o}C represents aging typical of up to five years, and four days at 85^{o}C appears to simulate up to 15 years for Wet-No Freeze and seven years in Dry-Freeze climates.

Guidelines for Wet-Freeze and Dry-No Freeze could not be developed because of a lack of suitable projects with samples of the original materials that were sufficiently old. Oven aging at 85^{o}C was considered more reliable than aging at 100^{o}C because aging at the higher temperature can damage the samples.

Evaluation of Fatigue Properties of Recycled Asphalt Concrete

Elton R. Brown. Sixth International Conference on Structural Design of Asphalt Pavements, Vol. 1, Ann Arbor, Michigan. (1987) pp. 305-322.

In this study, samples of aged asphalt concrete were obtained from three locations. These samples were blended with new aggregate and new asphalt materials to produce six different recycled mixtures. The flexural fatigue properties of recycled samples, two conventional mixtures and blends of recycled mixture and new material were evaluated.

Test results indicate that recycled mixtures can be designed to perform as well as conventional mixtures when tested in flexural fatigue. The properties of blended asphalt binders in the recycled mixture should be similar to the properties of a new asphalt binder to provide satisfactory results.

Recycled mixtures performed better than conventional mixtures in fatigue when analyzed for a thin layer of asphalt concrete placed over a base course; however, the conventional mixtures performed better than the recycled mixtures when the data were analyzed for thick layers such as full depth asphalt concrete.

Fundamental Properties of Recycled Asphalt Mixes

V. P. Servas, M.A. Ferreira, and P.C. Curtayne. Sixth International Conference on Structural Design of Asphalt Pavements, Vol. 1, Ann Arbor, Michigan. (1987) pp. 455-465.

This study has two sections; a laboratory based evaluation of recycled base mixes and the use of a heavy vehicle simulator test to determine the behavior of recycled asphalt base layers. A laboratory study was carried out to determine the properties of asphalt mixes composed of different proportions of reclaimed material, meeting the design criteria of conventional mixes. It was found that the proportion of reclaimed material had no effect on permanent deformation and fatigue resistance. This study took no account of either the durability characteristics of recycled mixes or the effect of recycling additives.

The heavy vehicle simulator was used to test recycled asphalt base layers. The results of this accelerated testing suggested that the field behavior of recycled base mixes is comparable to that of conventional asphalt.

Pavement Recycling Executive Summary and Report

U.S. Department of Transportation, Federal Highway Administration, Report No. FHWA-SA-95-060, Washington, D.C. (1996) 119 pp.

The FHWA initiated a project in mid-1992 to assess the current state-of-practice of recycled HMA production. The scope of this project included site visits to 17 State highway agencies (SHAs), with at least two SHAs in each FHWA region. Field contacts included discussions with design, research, and construction individuals from SHAs, contractors, and industry. This report summarizes the state-of-practice for the use, materials mix design, structure design, construction and performance of recycled HMA pavement.

Based on this report, it was estimated that 45 million tons of RAP are generated annually with approximately 33 percent of the RAP being reused in HMA productions. There are practical limitations on the amount of RAP that can be incorporated into a recycled HMA. Some of these limitations include plant technology and the amount of fine material in the RAP. However, some specifications or special provisions provide further limitations on RAP usage. These limitations are an obstacle that limits recycled HMA production. In most cases, restrictions were based on past projects that did not perform well. However, it was found that there was limited research or analysis to explain the poor performance. Other agencies placed limitations on RAP based on their judgment. Some of the reasons for low limits of RAP in specifications cited include:

- The RAP variability was perceived to be too high to use in HMA production, or recycled HMA production is too variable.
- Blending soft asphalt cement or rejuvenating agent with salvaged binder can be accomplished in the laboratory. Some engineers, however, do not believe that blending occurs during production and placement.
- The quality of recycled HMA has not been proven through performance evaluation. Pavement performance evaluations conducted by the Washington State DOT and updated with their PMS system show that recycled HMA performs as well as conventional HMA. Most of the SHAs indicated that recycled HMA performance is equivalent to conventional HMA when the recycled HMA meets mixture requirements of conventional HMA.

Some other conclusions from this study are:

- The major obstacle to increased RAP usage is limitations placed in standard specification, supplemental specifications and special provisions.

- Those SHAs that perform an evaluation of RAP and report its composition in plans, specifications and estimates generally permit greater percentages of RAP in all HMA mixtures.
- As with poor-performing conventional HMA, poor recycled HMA performance can be related to poor mixture design procedures or use of control and acceptance procedures that do little to ensure the quality of the recycled HMA.
- The recycled HMA mixture design procedure outlined in the Asphalt Institute's Manual Series No. 2 and No. 20 is a technically viable method for establishing ingredient properties of a recycled mixture.
- To minimize the amount of recovery and testing performance, up to 15 percent RAP in all mixtures could be permitted without changing to softer grade asphalt cement. With a RAP content of more than 15 percent, the selection of the new type of asphalt cement or recycling agent added to recycled HMA should be based on a viscosity blending chart or equivalent procedure or formula.
- Additional training should be provided to increase the awareness of proper mixture design and analysis, product equipment and handling procedures, performance evaluation and quality control plans.
- Research needs include the use of RAP with modified asphalt cements and use of RAP in the Superpave binder specifications and mixture design and analysis system.

Production Variability Analysis of Hot-Mixed Asphalt Concrete Containing Reclaimed Asphalt Pavement

Mansour Solaimanian and Thomas W. Kennedy. University of Texas at Austin, Department of Civil Engineering, Research Report #2828-1F, Austin, TX (1995).

This study was to evaluate the production and construction variability of HMAC containing high quantities of RAP material, including an analysis of the variability in RAP stockpiles and variability of plant-produced HMA with 20 to 50% RAP. The researchers found that projects with high percentages of RAP showed greater variability than HMA without RAP. The variability affected asphalt content and gradation determinations more than density. Variability in the RAP material was manifested in variability in the plant-produced mix; that is, projects with more variation in RAP asphalt content or stiffness showed more variability in the asphalt content and stiffness of the plant-mix as well.

The Quality of Random RAP: Separating Fact from Superstition

Robert M. Nady. Focus on HMAT, Summer 1997, Vol. 2, No. 2, National Asphalt Pavement Association, Lanham, MD pp. 14-17.

This paper reports on an evaluation of the variability of milled RAP versus unclassified (stockpiled random) RAP in Iowa. RAP from both sources is found to be quite uniform in terms of gradation and asphalt content. There were differences between the two types, such as the generally finer gradation noted for the milled RAP. Explanations for the uniformity of a given source are offered and include consistency of the historical state gradation specifications, routine quality control testing, and RAP processing equipment.

APPENDIX B
STATISTICAL ANALYSIS OF BLACK ROCK DATA

Table B-1. Summary of Comparison of Means, Frequency Sweep, Complex Shear Modulus
RAP Source: Florida

Binder Type	RAP Content	Aging	Test Temp.,°C	Frequency Hz	Mix Case			Significance
					A	B	C	
PG 52-34	10%	N	20	0.01				A=B=C
PG 52-34	10%	N	20	10				A=B=C
PG 52-34	10%	N	40	0.01				A=B=C
PG 52-34	10%	N	40	10				A=B=C
PG 64-22	10%	N	20	0.01				A=B=C
PG 64-22	10%	N	20	10	*	*		A=B, A=C, B≠C
PG 64-22	10%	N	40	0.01	*		*	A=B, A=C, B≠C
PG 64-22	10%	N	40	10				A=B=C
PG 52-34	40%	N	20	0.01				A≠B, B≠C, A=C
PG 52-34	40%	N	20	10				A≠B, B≠C, A=C
PG 52-34	40%	N	40	0.01				A=B=C
PG 52-34	40%	N	40	10				A≠B, B≠C, A=C
PG 64-22	40%	N	20	0.01				A≠B≠C
PG 64-22	40%	N	20	10				A=B=C
PG 64-22	40%	N	40	0.01				A=B=C
PG 64-22	40%	N	40	10		*	*	A=C, B=C, A≠B

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-2. Summary of Comparison of Means, Frequency Sweep Data, Complex Shear Models
RAP Source: Connecticut

Binder Type	RAP Content	Aging	Test Temp.,°C	Frequency Hz	Mix Case			Significance
					A	B	C	
PG 52-34	10%	L	4	0.01				A=B=C
PG 52-34	10%	L	4	10				A=B=C
PG 52-34	10%	L	20	0.01	*		*	A=C, B=C, A≠B
PG 52-34	10%	L	20	10		*	*	A=B, B=C, A≠C
PG 52-34	10%	N	20	0.01				A≠B, A≠C, B=C
PG 52-34	10%	N	20	10				A≠B, A≠C, B=C
PG 52-34	10%	N	40	0.01				A=B, A≠C, B≠C
PG 52-34	10%	N	40	10		*	*	A=B, B=C, A≠C
PG 64-22	10%	L	4	0.01				A=B=C
PG 64-22	10%	L	4	10				A=B=C
PG 64-22	10%	L	20	0.01	*		*	A=C, B=C, A≠B
PG 64-22	10%	L	20	10				A=B=C
PG 64-22	10%	N	20	0.01				A≠B, A≠C, B=C
PG 64-22	10%	N	20	10				A=B=C
PG 64-22	10%	N	40	0.01				A=B, A≠C, B≠C
PG 64-22	10%	N	40	10	*	*		A=B, B=C, A≠C
PG 52-34	40%	L	4	0.01				A≠B, A≠C, B=C
PG 52-34	40%	L	4	10	*		*	A=C, B=C, A≠B
PG 52-34	40%	L	20	0.01				A≠B, A≠C, B=C
PG 52-34	40%	L	20	10				A≠B, A≠C, B=C
PG 52-34	40%	N	20	0.01				A≠B≠C
PG 52-34	40%	N	20	10				A≠B, A≠C, B=C
PG 52-34	40%	N	40	0.01				A=B=C
PG 52-34	40%	N	40	10				A≠B≠C
PG 64-22	40%	L	4	0.01				A≠B, A≠C, B=C
PG 64-22	40%	L	4	10				A≠B, A≠C, B=C
PG 64-22	40%	L	20	0.01				A≠B≠C
PG 64-22	40%	L	20	10				A=B=C
PG 64-22	40%	N	20	0.01				A≠B≠C
PG 64-22	40%	N	20	10				A≠B, A≠C, B=C
PG 64-22	40%	N	40	0.01				A≠B, B≠C, A=C
PG 64-22	40%	N	40	10				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-3. Summary of Comparison of Means, Frequency Sweep Data, Complex Shear Modulus
RAP Source: Arizona

Binder Type	RAP Content	Aging	Test Temp.,°C	Frequency Hz	Mix Case			Significance
					A	B	C	
PG 52-34	10%	N	20	0.01		*	*	A≠B, B=C, A=C
PG 52-34	10%	N	20	10				A=B=C
PG 52-34	10%	N	40	0.01				A=B=C
PG 52-34	10%	N	40	10				A=B=C
PG 64-22	10%	N	20	0.01				A=B=C
PG 64-22	10%	N	20	10				A≠B, B=C, A≠C
PG 64-22	10%	N	40	0.01				A=B=C
PG 64-22	10%	N	40	10				A=B, A≠C, B≠C
PG 52-34	40%	N	20	0.01		*	*	A=B, B=C, A≠C
PG 52-34	40%	N	20	10		*	*	A=B, B=C, A≠C
PG 52-34	40%	N	40	0.01				A=B=C
PG 52-34	40%	N	40	10				A≠B, B=C, A≠C
PG 64-22	40%	N	20	0.01				A≠B, A=C, B≠C
PG 64-22	40%	N	20	10	*		*	A≠B, B=C, A=C
PG 64-22	40%	N	40	0.01				A=B, B≠C, A≠C
PG 64-22	40%	N	40	10				A≠B, A=C, B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-4. Summary of Comparison of Means, Simple Shear Test, Maximum Shear Deformation
RAP Source: Florida

Binder Type	**RAP Content**	**Aging**	**Test Temp.,°C**	**Mix Case**			**Significance**
				A	**B**	**C**	
PG 52-34	10%	N/A	20				A=B=C
PG 52-34	10%	N/A	40		*	*	A=B, B=C, A≠C
PG 64-22	10%	N/A	20				A=B=C
PG 64-22	10%	N/A	40				A=B=C
PG 52-34	40%	N/A	20		*	*	A≠B, A=C, B=C
PG 52-34	40%	N/A	40		*	*	A≠B, A≠C, B=C
PG 64-22	40%	N/A	20				A≠B≠C
PG 64-22	40%	N/A	40				A≠B, A≠C, B=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-5. Summary of Comparison of Means, Simple Shear Data, Maximum Shear Deformation
RAP Source: Connecticut

Binder Type	RAP Content	Aging	Test Temp, °C	Mix Case A	Mix Case B	Mix Case C	Significance
52-34	10	L	4				A=B=C
52-34	10	L	20				A=B=C
52-34	10	N	40			NA	A=B
52-34	10	N	20				A=B=C
64-22	10	L	4				A=B=C
64-22	10	L	20				A≠B, B=C,A≠C
64-22	10	N	20				A≠B, B=C,A≠C
64-22	10	N	40			NA	A=B
52-34	40	L	4				A≠B, B=C,A≠C
52-34	40	L	20				A≠B, B=C,A≠C
52-34	40	N	20				A≠B, B=C,A≠C
52-34	40	N	40				A=B=C
64-22	40	L	4				A≠B, B=C,A≠C
64-22	40	L	20				A≠B, B=C,A≠C
64-22	40	N	20				A≠B≠C
64-22	40	N	40				A≠B, B=C,A≠C

* Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-6. Summary of Comparison of Means, Simple Shear Data, Maximum Shear Deformation

RAP Source: Arizona

Binder Type	**RAP Content**	**Aging**	**Test Temp.,°C**	**Mix Case**			**Significance**
				A	**B**	**C**	
PG 52-34	10%	N	20				A=B=C
PG 52-34	10%	N	40				A=B=C
PG 64-22	10%	N	20				A=B=C
PG 64-22	10%	N	40				A=B, A≠C, B≠C
PG 52-34	40%	N	20				A≠B, A≠C, B=C
PG 52-34	40%	N	40				A≠B, A≠C, B=C
PG 64-22	40%	N	20				A≠B≠C
PG 64-22	40%	N	40				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-7. Summary of Comparison of Means, Repeated Shear at Constant Height, Shear Strain
RAP Source: Florida

Binder Type	RAP Content	Aging	Test Temp.,°C	Mix Case			Significance
				A	B	C	
PG 52-34	10%	N	52		*	*	A≠B, A=C, B=C
PG 64-22	10%	N	58				A=B=C
PG 52-34	40%	N	52		*	*	A≠B, A=C, B=C,
PG 64-22	40%	N	58				A=B=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-8. Summary of Comparison of Means,Repeated Shear at Constant Height Data, Shear
RAP Source: Connecticut

Binder Type	**RAP Content**	**Test Temp, ^{o}C**	**Mix Case**			**Significance**
			A	**B**	**C**	
52-34	10	52				A=B=C
64-22	10	58				A=B=C
52-34	40	52				A=B=C
64-22	40	58				A≠B,B=C, A≠C

* Cases with same symbol or shading are not significantly different at a 5% confidence level
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-9. Summary of Comparison of Means, Repeated Shear at Constant Height, Shear Strain
RAP Source: Arizona

Binder Type	**RAP Content**	**Aging**	**Test Temp.,°C**	**Mix Case**			**Significance**
				A	**B**	**C**	
PG 52-34	10%	N	52				A=B=C
PG 64-22	10%	N	58				A=B=C
PG 52-34	40%	N	52				A≠B, B=C, A≠C
PG 64-22	40%	N	58				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-10. Summary of Comparison of Means, Indirect Tensile Strength, Stiffness
RAP Source: Connecticut

Binder Type	RAP Content	Test Temp.,°C	Mix Case A	Mix Case B	Mix Case C	Significance
PG 52-34	10%	-20				A=B=C
PG 52-34	10%	-10				A=C, A≠B, B≠C
PG 52-34	10%	0				A=B=C
PG 64-22	10%	-20				A=B=C
PG 64-22	10%	-10				A=B=C
PG 64-22	10%	0				A=B=C
PG 52-34	40%	-20				A≠B, A≠C, B=C
PG 52-34	40%	-10				A≠B, A≠C, B=C
PG 52-34	40%	0				A≠B, A≠C, B=C
PG 64-22	40%	-20		*	*	A=B, B=C, A≠C
PG 64-22	40%	-10				A=B=C
PG 64-22	40%	0				A≠B,A≠C, B=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-11. Summary of Comparison of Means, Indirect Tensile Strength, Stiffness
RAP Source: Arizona

Binder Type	RAP Content	Test Temp.,°C	Mix Case			Significance
			A	B	C	
PG 52-34	10%	-20				A=B=C
PG 52-34	10%	-10				A=B=C
PG 52-34	10%	0				A=B=C
PG 64-22	10%	-20		*	*	A≠B, A=C, B=C
PG 64-22	10%	-10				A≠B, A≠C, B=C
PG 64-22	10%	0				A=B=C
PG 52-34	40%	-20				A≠B, A≠C, B=C
PG 52-34	40%	-10				A≠B, A≠C, B=C
PG 52-34	40%	0				A≠B, A≠C, B=C
PG 64-22	40%	-20				A=B=C
PG 64-22	40%	-10				A=B=C
PG 64-22	40%	0				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-12. Summary of Comparison of Means, Indirect Tensile Strength, Strength
RAP Source: Connecticut

Binder Type	**RAP Content**	**Test Temp.,°C**	**Mix Case**			**Significance**
			A	**B**	**C**	
PG 52-34	10%	-10				A=B=C
PG 64-22	10%	-10				A=B=C
PG 52-34	40%	-10				A≠B, A≠C, B=C
PG 64-22	40%	-10				A≠B≠C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

Table B-13. Summary of Comparison of Means, Indirect Tensile Strength, Strength
RAP Source: Arizona

Binder Type	RAP Content	Test Temp.,°C	Mix Case			Significance
			A	B	C	
PG 52-34	10%	-10				A=B=C
PG 64-22	10%	-10				A=B=C
PG 52-34	40%	-10				A≠B, B≠C, A=C
PG 64-22	40%	-10				A≠B, B≠C, A=C

*Cases with same symbol or shading are not significantly different at a 5% confidence level.
A = Black Rock, B = Actual Practice, C = Total Blending

APPENDIX C
FLOW CHARTS SHOWING DEVELOPMENT OF BLENDING CHARTS

Figure C1. Method A - Blending at a Known RAP Percentage (Virgin Binder Grade Unknown)

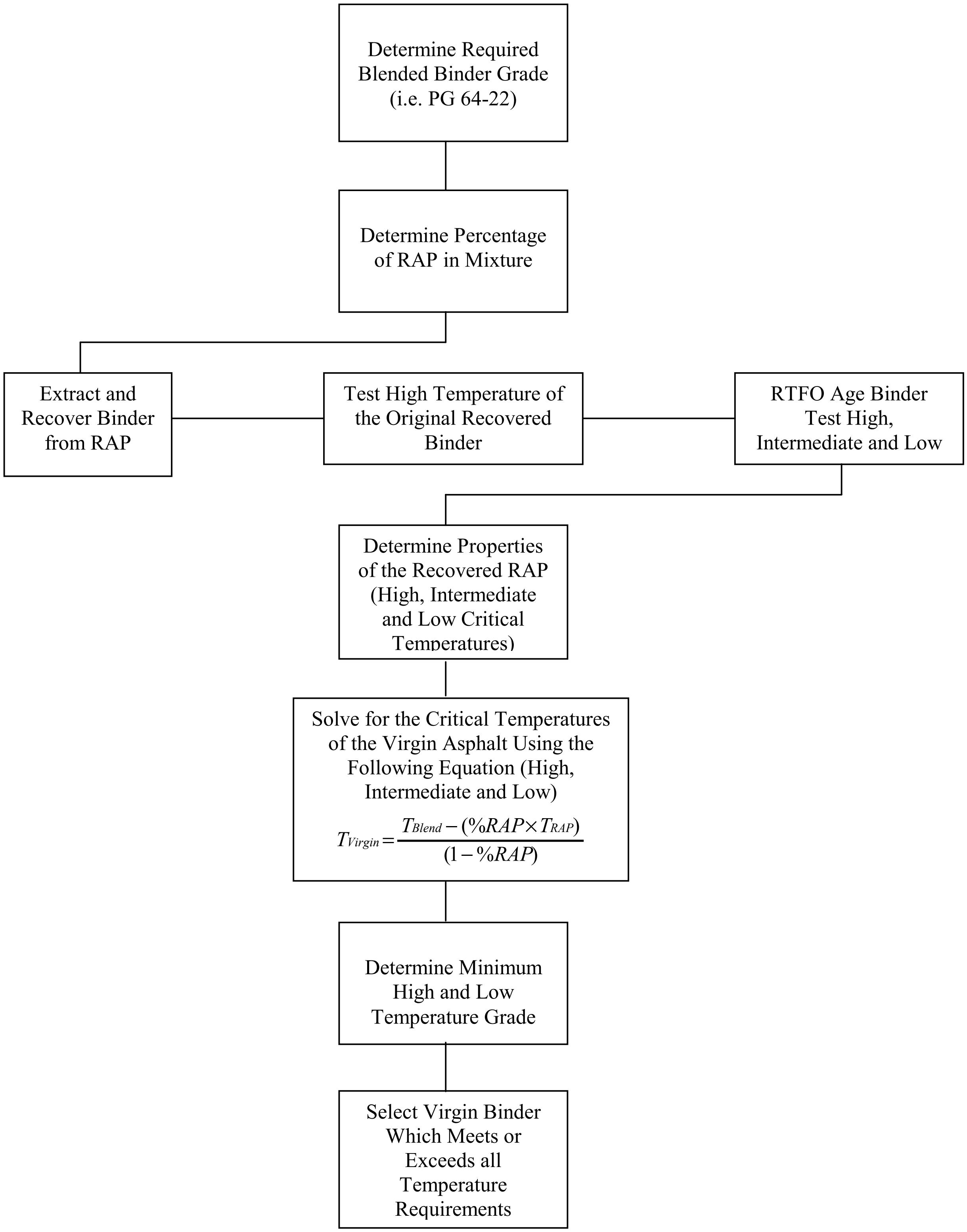
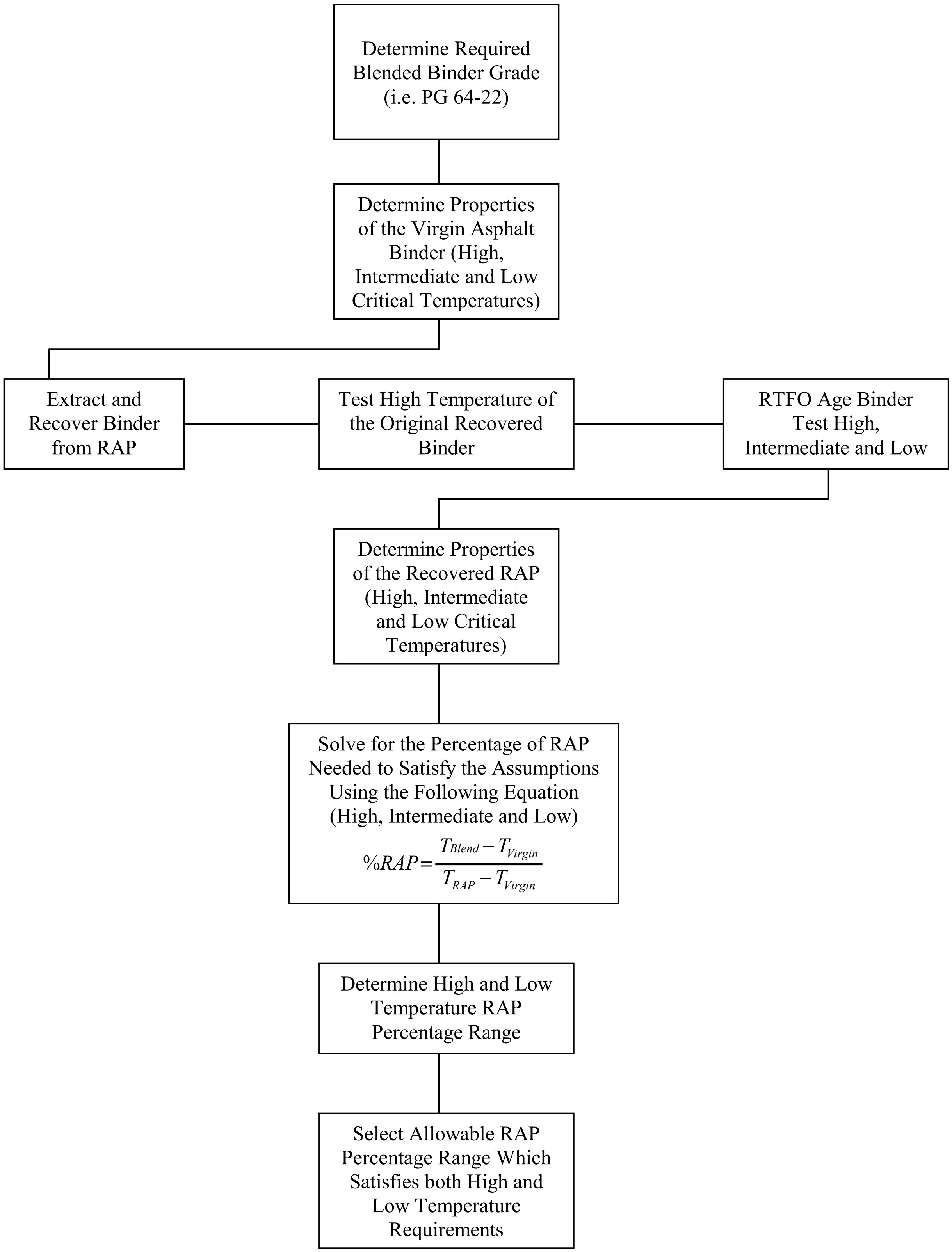


Figure C2. Method B – Blending with a Known Virgin Binder (RAP Percentage Unknown)



Appendix D is published as *NCHRP Research Results Digest 253,* "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Guidelines."

Appendix E is published as *NCHRP Report 452,* "Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual."

APPENDIX F

USE OF RAP IN SUPERPAVE: IMPLEMENTATION PLAN

Use of RAP in Superpave: Implementation Plan

Prepared for
National Cooperative Research Program
Transportation Research Board
National Research Council

North Central Superpave Center
West Lafayette, Indiana
and
Asphalt Institute
Lexington, Kentucky

May 2000

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INTRODUCTION

Reclaimed Asphalt Pavement (RAP) has been widely and successfully used in the past when producing new asphalt pavements. The findings of NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System*, should allow the beneficial use of RAP to be continued as states and other specifying agencies implement the Superpave system. The objectives of this research effort were to investigate the effects of RAP on binder grade and mixture properties and develop guidelines for incorporating RAP in the Superpave system. The products of the research include proposed revisions to applicable AASHTO standards, a manual for technicians and guidelines for specifying agencies.

Summary of Research Findings

Black Rock Study

The research effort was directed first at resolving the issue of whether RAP acts like a black rock or whether there is, in fact, some blending that occurs between the old, hardened RAP binder and the added virgin binder. This question was addressed by fabricating mixture specimens simulating actual practice, black rock and total blending. The so-called "black rock" and "total blending" cases represent the possible extremes. The "black rock" case was simulated by extracting the binder from a RAP mixture then blending the recovered RAP aggregate in the proper proportions with virgin aggregate and virgin binder. The "actual practice" samples were prepared as usual by adding the RAP with its coating intact to virgin aggregate and virgin binder. The "total blending" cases were fabricated by extracting and recovering the RAP binder and blending it into the virgin binder, then combining the blended binder with the RAP and virgin aggregates. All the samples were prepared on the basis of an equal volume of total binder.

Three different RAPs, two different virgin binders and two RAP contents (10 and 40%) were investigated in this phase of the project. The different cases of blending were evaluated through the use of various Superpave shear tests at high temperatures and indirect tensile creep and strength tests at low temperatures.

The results of this phase of the research indicated no significant difference between the three different blending cases at low RAP contents. At higher RAP contents, however, the differences became significant. In general, the "black rock" case demonstrated lower stiffnesses and higher deformations than the other two cases. The "actual practice" and "total blending" cases were not significantly different.

These results provide compelling evidence that RAP does not act like a black rock. It seems unreasonable to suggest that total blending of the RAP binder and virgin binder ever occurs, but partial blending apparently occurs to a significant extent.

This means that at high RAP contents, the hardened RAP binder must be accounted for in the virgin binder selection. The use of blending charts for determining the virgin binder grade or the maximum amount of RAP that can be used is a valid approach since blending does occur. Procedures for extracting and recovering the RAP binder with minimal changes in its properties and then developing blending charts are detailed in the final report and manual for technicians. The recommended extraction/recovery procedure uses either toluene and ethanol or an n-propyl bromide solvent.

The findings also support the concept of a tiered approach to RAP usage since the effects of the RAP binder are negligible at low RAP contents. This is very significant since it means that lower amounts of RAP, up to as high as 30% RAP depending on the recovered RAP binder grade, can be used without going to the effort of testing the RAP binder and developing a blending chart. The procedures for developing blending charts were perfected during the second portion of the project, the binder effects study.

Binder Effects Study

This phase of the research investigated the effects of the hardened RAP binder on the blended binder properties and lead to recommended procedures for testing the RAP binder for the development of blending charts.

The same three RAPs and two virgin binders were evaluated in this phase of the project at RAP binder contents of 0, 10, 20, 40 and 100%. The blended binders were tested according to the AASHTO MP1 binder tests.

The results show that the MP1 tests are applicable to RAP binders and linear blending equations are appropriate. The recovered RAP binder should be tested in the DSR to determine its critical high temperature as if it were unaged binder. The rest of the recovered binder should then be RTFO aged; linear blending equations are not appropriate without this additional aging. The remaining MP1 tests at high, intermediate and low temperatures should then be performed as if the RAP binder were RTFO and PAV aged. The RAP binder does not need to be PAV aged before testing for fatigue or low temperature cracking, as would be done for original binder. Conventional Superpave methods and equipment, then, can be used with the recovered RAP binder. (Above 40% RAP, or so, some non-linearity begins to appear.) Since PAV aging is not necessary, the testing process is shortened by approximately one day.

The binder effects study also supports the tiered usage concept. At low RAP contents, the effects of the binder are negligible. At intermediate levels, the effects of the RAP binder can be compensated for by using a virgin binder one grade softer on both the high and low temperature grades. The RAP binder stiffens the blended binder. At higher RAP contents, a blending chart should be used to either determine the appropriate virgin binder grade or to determine the maximum amount of RAP that can be used with a given virgin binder. The limits of the three tiers vary depending on the recovered binder stiffness. Higher RAP contents can be used if the recovered RAP binder stiffness is not too high.

These findings mean that, for the most part, conventional equipment and testing protocols can be used with RAP binders. The tiered approach allows for the use of up to 15 to 30% RAP without extensive testing. Higher RAP contents can also be used when additional testing is required.

Mixture Effects Study

The same three RAPs and two virgin binders were used in this portion of the research to investigate the effects of RAP on the resulting mixture properties. Shear tests and indirect tensile tests were conducted to assess the effects of RAP on mixture stiffness at high and low temperatures. Beam fatigue testing was also conducted at intermediate temperatures. RAP contents of 0, 10, 20 and 40% were evaluated.

All of the tests indicated a stiffening effect from the RAP at higher RAP contents. The shear tests indicated an increase in stiffness and decrease in shear deformation as the RAP content increased. This would indicate that higher RAP content mixtures (with no change in binder grade) would exhibit more resistance to rutting. The indirect tensile testing also showed increased stiffness for the higher RAP content mixtures, which could lead to increased low temperature cracking, if no adjustment is made in the virgin binder grade. Beam fatigue testing also supports this conclusion since beam fatigue life decreased for higher RAP contents.

The significance of these results is that the concept of using a softer virgin binder for higher RAP contents is again supported. The softer binder is needed to compensate for the increased mixture stiffness and help improve the fatigue and low temperature cracking resistance of the mixture. The results also support the tiered concept since low RAP contents, below 20%, yield mixture properties that are statistically the same as the virgin mixture properties.

Overall Conclusions

The findings of this research effort largely confirm current practice. The concept behind the use of blending charts is supported. The use of a tiered approach to the use of RAP is found to be appropriate. The advantage of this approach is that relatively low levels of RAP can be used without extensive testing of the RAP binder. If the use of higher RAP contents is desirable, conventional Superpave binder tests can be used to determine how much RAP can be used or which virgin binder to use.

The RAP aggregate properties may limit the amount of RAP that can be used. The RAP aggregate properties, with the exception of sand equivalent value, should be considered as if the RAP is another aggregate stockpile, which it in fact is. The mixtures being recycled presumably met specifications when constructed, so certain minimum aggregate properties and mixture properties were met. In the mix design, the RAP aggregates should be blended with virgin aggregates so that the final blend meets the consensus properties. Also in the mix design, the RAP binder should be taken into account and the amount of virgin binder added should be reduced accordingly.

Many specifying agencies will find that these recommendations largely agree with past practice. Dynamic shear rheometer and bending beam rheometer tests may replace the viscosity tests that were previously used, for example, but the concepts are still the same. These results should not be surprising, perhaps, since the asphalt binders and mixtures are largely the same as were previously used. This research effort, however, should give the agencies confidence in extending the use of RAP to Superpave mixtures.

The products of this research include suggested revisions to several AASHTO specifications; procedures for extracting and recovering the RAP binder, testing the RAP binder and developing blending charts, and designing a RAP mixture under the Superpave system; a manual for laboratory and field technicians; guidelines for the use of specifying agencies; and this implementation plan for moving these results into practice.

Applicability of Findings to Highway Practice

Many of the findings of NCHRP 9-12 largely confirm past practices. One example of this is the concept of a tiered approach to the use of RAP. Many states previously allowed the use of up to 15-20% RAP without a change in the binder grade. The findings of the black rock, binder effects and mixture effects studies all support the existence of a threshold level of RAP usage, in the range of 10 to 20% RAP, below which the RAP has a negligible effect on binder or mixture properties. Depending on typical RAP stiffnesses, agencies should be able to continue using RAP up to the threshold level without changing the binder grade.

Agencies also used to adjust the binder grade for higher RAP contents, either by using a softer grade of binder or by constructing blending charts to determine which binder or how much RAP to use. Both of these approaches are predicated on the assumption that blending occurs between the new binder and the hardened RAP binder. The findings of the black rock study demonstrate that blending does occur to an appreciable extent. So again, this approach to using RAP can be continued with Superpave mixtures.

There are, however, some changes that should be made in current practice as a result of this research project. An improved method for extracting and recovering the RAP binder, or any asphalt binder for that matter, was refined and validated in this project. Revisions have been proposed to AASHTO TP2, *Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures,* to reflect this improved technique.

The interim guidance on the use of RAP in Superpave mixtures, issued by the Superpave Mixtures Expert Task Group, has also been largely confirmed with slight revisions. The major revision is a more detailed chart for binder grade selection that takes into account the stiffness of the RAP binder.

The findings of the project are directly applicable to highway practice. Many of the findings, since they confirm current practice, are in essence already implemented. This project will lend support and increase the confidence level of the specifying agencies. Other findings can be easily implemented through revisions to existing AASHTO specifications. There should be no major barriers to implementation of these findings.

IMPLEMENTATION SUGGESTIONS

As mentioned earlier, implementation of many of the findings of this research will be greatly facilitated by the fact that current practice is largely confirmed. It is, nonetheless, important to communicate these findings widely so that they can be implemented through AASHTO and agency specifications. It is also prudent to monitor some projects including RAP to confirm the laboratory results in a field setting. The following suggestions should help to disseminate information about the findings of NCHRP 9-12 to help ensure wide implementation and secure the benefits of using RAP in Superpave mixtures.

Communication of Results

There are many avenues available to communicate the results of this research effort. In order to ensure that all interested parties get the necessary information, it is recommended to use every possible medium. There is also a high level of interest in this topic, which justifies a broad distribution of information.

Revisions of AASHTO Specifications

The most meaningful method to implement changes in highway practice is through official, approved changes to the AASHTO specifications. Most agencies adopt these standards, although some agencies make customized modifications to suit their particular circumstances.

Proposed revisions to the following standards have been developed as a result of this research effort:

- TP2, *Standard Test Method for the Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*
- MP2, *Standard Specification for Superpave™ Volumetric Mix Design*
- PP28, *Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*

These proposed revisions, as shown in Appendix A, will be presented to the appropriate Expert Task Group for their review and approval. The Superpave Binder Expert Task Group is expected to be primarily interested in the revisions to TP2, while the Mixture and Aggregates ETG is expected to be primarily interested in MP2 and PP28. The research team will attempt request time on the agenda for the next meetings of these two groups following the project panel's approval of the final report and associated documents. The Mixture and Aggregates Expert Task Group was briefed on the preliminary findings of the project at their meeting in March 2000.

Once the Expert Task Groups are satisfied with the proposed revisions, it is anticipated they will forward the revisions to AASHTO for balloting by the states and eventual inclusion in the specifications. At every step in the process, the supporting data will be reviewed and further revisions may be approved.

Revisions of Training Courses

There are currently a number of training programs in use around the country dealing with hot mix asphalt design. These courses should be modified to include the use of RAP in Superpave Mixtures. A set of slides that could be included is attached in Appendix B.

The courses that should be revised include the following:

- NHI 13150, *Asphalt Pavement Recycling for State and Local Governments*
- NHI 13151, *Superpave for Senior Managers*
- NHI 13153, *Superpave Fundamentals*
- FHWA, *Hot Mix Asphalt for the Undergraduate*
- NATC Superpave Mix Design course (used by most Superpave Centers, Asphalt Institute and others)

The suggested revisions will be communicated to NHI for possible inclusion in the first three courses, for which they are responsible. NHI is moving towards providing courses to instructors and others in electronic format, which may facilitate incorporation of the suggested changes. The two Superpave courses were recently revised. Additional revisions may be needed to add RAP. These changes may be accommodated in the course materials as additional handouts or addenda pending further revision of the course materials.

Changes to the FHWA and NATC courses can be implemented by distributing them through FHWA, the Superpave Centers and the Asphalt Institute. The FHWA course is posted on the Internet for free downloading. The additional information on RAP can also be posted on various sites as discussed below. The Superpave Centers are generally familiar with the states, universities and others doing Superpave training in their respective regions. The Centers can distribute the proposed course revisions within their regions.

Written and Electronic Communication

There are numerous outlets for written and electronic communication of the findings and implementation suggestions. The research team is directly involved in many of these and has routine contact with others. For example, most of the Superpave Centers have websites and newsletters. The newsletters are jointly produced and include both regional and national segments. The NCSC can ensure that summaries of the findings of this project are published in the national newsletter insert. Each regional segment could also include a discussion of the regional impacts of or reactions to the use of RAP in Superpave mixtures. For example, each region could survey their states and summarize the current extent of RAP usage in Superpave and/or other HMA mixtures. Detailed summaries and downloadable training presentations could be posted on each center's website (or linked to the NCSC site). The Asphalt Institute and FHWA also have websites that could post the information.

The South Central Superpave Center maintains a Superpave Newsgroup with a very wide and active audience. This group could be informed of the existence of web postings dealing with the use of RAP in Superpave. This is likely to promote a large number of hits and possibly discussion of the findings.

Other written means of communication include the *FHWA Superpave Implementation Update, FOCUS Newsletter* and trade publications. NAPA has included articles on RAP in *Focus on HMAT*. The Asphalt Institute publishes *Asphalt* magazine; their readers would be interested in RAP. The research team has already been contacted by ASCE for a possible article and is frequently contacted by local media. A news release could be prepared and distributed through the Purdue University News Service and/or Schools of Engineering publications office for wider, more general audiences.

Presentations

Due to the high level of interest in this project, several presentations of interim findings have already been made. (In each case, it has been noted that the presentations offered preliminary findings and conclusions that were not yet final or approved.) Presentations on various aspects of the project have been made at the following meetings:

- Superpave: Today and Tomorrow, April 1998
- Minnesota Asphalt Conference, November 1998.
- Transportation Research Board, January 1999.
- Rocky Mountain Asphalt Conference and Equipment Show, February 1999.
- MatCong 5, Fifth Materials Engineering Congress, May 1999.
- Asphalt Paving Association of Iowa Summer Meeting, July 1999.
- Missouri Asphalt Conference, November 1999.
- Asphalt Pavement Association of Indiana, December 1999.
- Transportation Research Board Annual Meeting, January 2000.
- North Central Asphalt User-Producer Group Meeting, January 2000.
- Association of Asphalt Paving Technologists, March 2000.
- Superpave Mixtures and Aggregate Expert Task Group, March 2000.
- International Center for Aggregate Research Meeting, April 2000.

The research team welcomes the opportunity to make presentations at other appropriate meetings. One abstract has been accepted by the Canadian Technical Asphalt Association for presentation at their next meeting. Other appropriate forums for similar presentations include the Mixture and Aggregates Expert Task Group and Binder Expert Task Group, TRB asphalt committees, state asphalt pavement association meetings, user-producer group meetings, etc.

Field Test Sections

Need and Benefits

Recycled mixtures have performed as well as virgin mixtures when using conventional penetration or viscosity graded asphalts in properly designed Marshall or Hveem mixtures. The research conducted under NCHRP 9-12 indicates that recycled mixtures designed under the Superpave system will also perform at least as well as virgin mixtures. Because of the long, successful history of RAP usage, the need for intensive field validation of the research findings is somewhat lessened. Nonetheless, field validation would be a prudent course of action. Implementation of RAP in Superpave mixtures can proceed without this field validation due to the long history of RAP usage. The field trials, however, would be useful for possible further refinement of the recommendations based on this research project.

The Superpave system itself is still evolving. It is reasonable to expect that the guidelines for RAP usage in the Superpave system will have to evolve accordingly. Field trials can provide the basis to support further refinements to the system.

Suggested Evaluation Criteria

Superpave mixtures incorporating RAP should be compared to virgin Superpave mixtures. The evaluation should focus on long term performance of the mixtures, including measurements of rutting, low temperature cracking, fatigue cracking, moisture damage and other distresses.

The findings of NCHRP 9-12 indicate that when high percentages of RAP are used with stiffer RAPs, the virgin binder grade needs to be adjusted to “soften” the resulting blend. The recommended tiers, then, vary depending on the RAP binder stiffness and the proposed RAP content. If no adjustment is made in the virgin binder grade, the resistance to rutting is likely to be improved (by a stiffer mixture), but the low temperature and fatigue cracking resistance will likely be decreased. When a softer virgin binder is used to compensate for the RAP binder stiffness, the rutting resistance may be decreased but the cracking resistance should be improved. Field trials that measure the performance of the recycled mixtures in terms of both rutting and cracking will help to ensure that a proper balance has been struck between rutting and cracking resistance.

The ideal field trial would include test sections with various RAP contents and virgin binders compared to a control section with no RAP. The traffic volume should be consistent throughout the test sections. A fairly high traffic volume is desirable in order to truly test the rutting performance.

Suggested Mechanism for Follow-Up

Pavement test sections included in the Long Term Pavement Performance studies will be assured of continued monitoring. Both Connecticut and Indiana have SPS-9 sections with RAP. The Connecticut project was the source of the medium stiffness RAP used in this research. The Indiana project provided RAP material that is currently being evaluated by the NCSC under a regional pooled fund project using techniques similar to those used in NCHRP 9-12.

Individual states will also likely construct their own test sections. Due to the high level of interest in this topic, sharing of field data should be encouraged. The regional user-producer groups and Superpave Centers may be able to facilitate this sharing. Both the user-producer groups and the Superpave Centers have interest in the continued evaluation and refinement of the Superpave system. Some user-producer groups, such as the Rocky Mountain group, have developed, or are trying to develop, regional databases to track the performance of Superpave pavements. These databases could be used to follow-up on applicable test sections.

Reporting of Long Term Performance

Reporting of long term performance of Superpave mixtures with and without RAP will likely be most effective on the regional level through the user-producer groups or the Superpave Centers. Through the coordination between the Superpave Centers, this regional information can be shared and disseminated nationally. There may also be a need in the future for a national review of Superpave RAP mixture performance similar to the review of SMA mixtures done by NCAT.

BENEFITS OF IMPLEMENTATION

Hot mix asphalt mixtures with RAP have performed well in the past in properly designed mixtures. The benefits of using RAP include the following:

- use of RAP is economical and can help to offset the increased initial costs sometimes associated with Superpave binders and mixtures,
- use of RAP conserves natural resources, and
- not reusing RAP could cause disposal problems and increased costs.

Historically these benefits have helped to make reclaimed asphalt pavement one the most widely recycled materials. An FHWA study [1] shows that 80% of the asphalt pavement removed every year is recycled. Only about 60% of aluminum cans, 37% of plastic soft drink bottles and 31% of glass beverage bottles are recycled. RAP would not be used to such a great extent if it did not perform well at an economical price.

This study will allow that high level of RAP reuse to continue as agencies move to the Superpave system for routine HMA mixture design.

REFERENCE

1. Federal Highway Administration, "A Study of the Use of Recycled Paving Material." Report No. FHWA-RD-93-147 (1993).