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RECLAIMED ASPHALT PAVEMENT – A LITERATURE REVIEW

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16. Abstract

While the state of Illinois has been recycling Reclaimed Asphalt Pavement (RAP) material into hot-mix asphalt (HMA) since 1980, there continues to be questions regarding the correct approach to design HMA with RAP. The Illinois Department of Transportation's current method of RAP HMA design provides 100% contribution for the residual asphalt binder from the RAP based on solvent extractions. This means that the amount of virgin asphalt binder is reduced by the full amount of asphalt binder in the RAP for the percentage specified. This has recently been reported to be inaccurate and could result in an erroneous HMA job mix formula and may cause dry HMA. Hence, the HMA may become vulnerable to durability cracking and premature failure. The objective of this research project is to develop an understanding of the interaction between aged and virgin asphalt binders in RAP. Based on this understanding, this study will determine the appropriate level of contribution that should be given to the residual asphalt binder in RAP. The level of interaction between aged and virgin binders will then be used to investigate the influence on the performance and the durability of the mixtures as compared to virgin HMA. As a first step in this research project, an in-depth review of the literature related to RAP was conducted. This report presents the findings of the literature review and its implication on this research project. Availability of this report will also serve future research projects dealing with RAP materials

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EXECUTIVE SUMMARY

While the state of Illinois has been recycling Reclaimed Asphalt Pavement (RAP) material into hot-mix asphalt (HMA) since 1980, there continues to be questions regarding the correct approach to design HMA with RAP. The Illinois Department of Transportation's current method of RAP HMA design provides 100% contribution for the residual asphalt binder from the RAP based on solvent extractions. This means that the amount of virgin asphalt binder is reduced by the full amount of asphalt binder in the RAP for the percentage specified. This has recently been reported to be inaccurate and could result in an erroneous HMA job mix formula and may cause dry HMA. Hence, the HMA may become vulnerable to durability cracking and premature failure. The objective of this research project is to develop an understanding of the interaction between aged and virgin asphalt binders in RAP. Based on this understanding, this study will determine the appropriate level of contribution that should be given to the residual asphalt binder in RAP. The level of interaction between aged and virgin binders will then be used to investigate the influence on the performance and the durability of the mixtures as compared to virgin HMA. As a first step in this research project, an in-depth review of the literature related to RAP was conducted. This report presents the findings of the literature review and its implication on this research project. Availability of this report will also serve future research projects dealing with RAP materials.

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RECLAIMED ASPHALT PAVEMENT – A LITERATURE REVIEW

1. INTRODUCTION

Recycling hot mix asphalt (HMA) material results in a reusable mixture of aggregate and asphalt binder known as reclaimed asphalt pavement (RAP). Recycling of asphalt pavements is a valuable approach for technical, economical, and environmental reasons (Kennedy et al. 1998). Using RAP has been favored over virgin materials in the light of the increasing cost of asphalt, the scarcity of quality aggregates, and the pressuring need to preserve the environment. Many state agencies have also reported significant savings when RAP is used (Page and Murphy 1987). Considering material and construction costs, it was estimated that using reclaimed HMA pavement provides a saving ranging from 14 to 34% for a RAP content varying between 20 to 50% (Kandhal and Mallick 1997). This analysis considered the cost of HMA at $11.90 per ton, which can only be considered as an indicator of the true savings when RAP is used at the present time.

The use of RAP also decreases the amount of waste produced and helps to resolve the disposal problems of highway construction materials, especially in large cities such as Chicago. In 1996, it was estimated that about 33% of all asphalt pavement in the United States was recycled into HMA (Sullivan 1996). In 2001, the Illinois Department of Transportation (IDOT) used 623,000 tons of RAP in highway construction and anticipates increasing its use in the near future (Griffiths and Krstulovich 2002). After more than 30 years since its first trial in Nevada and Texas, it appears that the use of RAP will not only be a beneficial alternative in the future but will also become a necessity to ensure economic competitiveness of flexible pavement construction.

To facilitate incorporating RAP in the design of HMA, many states have relied on blending charts developed by the Asphalt Institute in the late 1980s (Asphalt Institute 1989). Most states have also established limits on the maximum percentage of RAP that can be used, ranging typically between 10 to 50%. However, high percentages of RAP are not commonly used in practice. With the introduction of the SuperPave™ HMA design procedure, many questions were raised about the proper method of incorporating RAP in the SuperPave™ HMA. Despite the fact that the original SuperPave™ HMA design procedure did not incorporate the use of RAP, many states have continued its use. In 1997, the Federal Highway Administration's RAP expert task force developed guidelines for the design of SuperPave™ HMA containing RAP (Bukowski 1997). The developed methodology was based on a tiered approach to determine the level of testing required in the design of HMA containing RAP. These guidelines have been supported by the findings of the NCHRP research report 9-12 (McDaniel et al. 2000).

Despite recent advancements in the design of HMA containing RAP, many states including Illinois insert restrictions in their regulations to avoid durability problems related to the recycled materials. In 2000, the Illinois Department of Transportation allowed the use of RAP in SuperPave™ HMA with a percentage varying between 0 to 30%; a maximum RAP percentage of 50% is allowed in HMA shoulders and stabilized sub-bases. Based on expert opinions, future specifications are expected to allow the use of RAP in highest-class HMA. On the other hand, many state agencies are taking a more aggressive approach by considering increasing the allowable percentages of RAP in HMA to take full advantage of this promising technology. For instance, up to 80% RAP has been used in some HMA with an acceptable level of performance (FHWA 1993). However, ensuring confidence in the design procedure and the success of using RAP would require addressing many durability concerns related to the interaction between virgin and recycled materials.

One major factor that is still unclear is the level of interaction between aged and virgin asphalt binders. If RAP acts like a black rock, the aged and virgin binders will not interact. Hence, it would be assumed that RAP does not significantly change the virgin binder properties. In that case, the use of blending charts may be invalid. However, it is usually assumed that RAP does not act as a black rock and that the aged asphalt blends with the virgin binder during mixing. In fact, many design procedures including the IDOT design method assumes that all the aged binder is fully available in the mixture and would effectively contribute to the blend. This means that the amount of virgin asphalt binder can be reduced by the full amount of asphalt binder in the RAP for the percentage specified.

2. RECLAIMED ASPHALT PAVEMENT CHARACTERISTICS

When HMA reaches the end of its service life, milled materials still maintain considerable value. The milled materials, RAP, can be reused in virgin HMA to reduce the amount of new material that needs to be used. However, it is necessary to account for old materials in the HMA design process. During service, the blend of aggregates and binders undergoes various physical and rheological changes that have to be considered in the design process to ensure that HMA mixtures with RAP perform as well as HMA produced with virgin materials. This section discusses some of the most important characteristics of RAP materials.

2.1 RAP BINDER PROPERTIES

In general, asphalt binder demonstrates two stages of aging: short-term and long-term. During construction (short-term), asphalt binder is exposed to hot air at temperatures ranging from 135 to 163°C, resulting in a significant increase in viscosity and changes in the associated rheological and physiochemical properties such as complex shear modulus and adhesion. During service (long-term), asphalt binder also progressively ages and hardens through various mechanisms. Age hardening during construction and service has been associated with six major mechanisms (Roberts et al. 1996; Tyrion 2000; Karlsson and Isacsson 2006):

- Oxidation through diffusive reaction between the binder and oxygen in the air;
- Volatilization through evaporation of the lighter components especially during construction;
- Polymerization through chemical reaction of molecular components;
- Thixotropy due to the formation of a structure within the asphalt binder over a long period of time;
- Syneresis due to the exudation of thin oily components; and
- Separation through the removal of oily constituents, resins, and asphaltenes by absorptive aggregates.

The level of aging that asphalt binder experiences during production and service also depends on the void content of the HMA. Recovered binder from porous HMA has shown significantly greater stiffness than regular HMA (Kemp and Predoehl 1981). In addition, properties of aged binder depend on the level of damage to the recycled pavement (Smiljanic et al. 1993). The greater the damage to the pavement prior to recycling, the greater the changes are in the properties of the binder. This is illustrated by the reduced oxidation susceptibility in pavements that are better preserved. Stockpiling also accelerates binder aging as the material is more prone to air exposure and oxidation (McMillan and Palsat 1985).

As asphalt binder reacts and loses some of its components during the aging process, its rheological behavior will naturally differ from virgin materials. This suggests the importance of controlling the blending process between recycled and virgin binders. If the old binder is too stiff, the blend of old and virgin binders may not perform as expected. At small percentages (up to 20%), an aged binder does not significantly affect the properties of the blend of virgin and RAP binder (Kennedy et al. 1998). However, when used at intermediate to higher percentages, an aged binder can significantly influence the properties of the blend and may affect the resultant binder grade. Recent modifications have been introduced to conventional asphalt plants in order to reduce aging of the old binder during mix production. This includes counterflow drum mixer and microwave heaters (NAPA 1996).

Whereas microwave heat is more easily absorbed by the aggregates, it is not absorbed as easily by the binder, thus reducing its susceptibility to aging during production.

The properties of aged binder are also affected by the level of moisture damage on the existing pavement prior to recycling. In principle, stripped HMA should not be recycled due to the probability of reoccurrence of this distress in the new HMA (Karlsson and Isacsson 2006). However, when a small percentage of RAP is used (15 to 20%) together with an anti-strip agent, samples with moisture-damaged HMA provided a comparable strength and moisture resistance to samples made with virgin materials (Amirkhanian and Williams 1993). Other researchers have reported that RAP materials might in fact provide stronger moisture resistance than virgin HMA since the aggregates are already covered and protected with binder (Karlsson and Isacsson 2006).

2.1.1 Rejuvenation of Recycled Binder

To address the properties of hardened, recycled binder, it must be mixed with a recycling agent or soft asphalt binder in order to restore its rheological properties (Sondag et al. 2002). In addition to soft binder, softening agents and rejuvenating agents are commonly used. Softening agents lower the viscosity of the aged binder while rejuvenating agents restore the physical and chemical properties of the old binder (Roberts et al. 1996). Examples of softening agents include asphalt flux oil, lube stock, and slurry oil. Rejuvenating agents consist of lubricating and extender oils, which contain a high proportion of maltene constituents (Terrel and Epps 1989). As noted above, asphalt binder loses many of its oil components during construction and service resulting in a high proportion of asphaltenes in the blend, which leads to increased stiffness and viscosity of the binder and decreased ductility. An important consideration in the selection of the rejuvenating agent is that it must be compatible with the aged binder. Rejuvenating agents with low saturate content and high aromatic content are usually compatible with aged binder (Dunning and Mendenhall 1978).

Carpenter and Wolosick (1980) studied the rejuvenation process by using a two-staged extraction method, which consisted of extracting the inner and outer layers of the recycled binder film separately. The process of rejuvenation starts with a low viscosity layer forming around the aggregates coated with the aged binder. The rejuvenator then penetrates the aged binder layer and slowly softens the old asphalt binder. After some time, all the rejuvenator has penetrated the aged binder and the diffusion process continues until equilibrium is reached. Carpenter and Wolosick (1980) have also shown that the blending process between aged binder and the rejuvenating agent does not solely occur during mixing and construction. Based on the results of their study, the authors concluded that the diffusion process of the rejuvenating agent into the recycled materials takes place over a period of time and exerts a large influence on the HMA properties. Another method to soften the aged binder is to blend it with a virgin binder. In this case, the virgin binder grade needs to be selected to account for the hardening properties of the RAP binder. The required binder grade is determined in conjunction with the desired final grade of the blended binder and the RAP percentage, using a blending chart and a tiered approach as presented in the following sections.

2.1.2 Blending of Aged and Virgin Binders

A serious concern that directly affects the performance of HMA that incorporates RAP relates to the level of blending that occurs between the residual and virgin asphalt binders. The level of blending affects both the performance of the produced HMA and the economic competitiveness of the recycling process. If the designer assumes that the materials blend totally when it is actually behaving as a black rock, the binder will not be stiff enough and insufficient asphalt binder is used. In contrast, if it is assumed that RAP does not blend with the virgin asphalt binder when it is actually blending, then the binder will be stiffer than expected and rich mix will result. The problem can be further complicated if one considers that the blending process may take some time to occur and is influenced by the rejuvenating agent as reported by Carpenter and Wolosick (1980).

A limited number of studies have investigated the blending process between aged and virgin asphalt binders (McDaniel et al. 2000; Oliver 2001; Stephens et al. 2001; Huang et al. 2005). In NCHRP 9-12, three possible levels of interaction between aged and virgin binders were compared experimentally: black rock (no blending), total blending (100% blending), and actual practice (blending as it usually occurs in practice). In all cases, the overall gradation and total asphalt binder content were kept constant. Two RAP contents (10 and 40%) were used as the minimum and maximum percentages of RAP normally used in practice. Reclaimed asphalt pavement was obtained from sources in Arizona, Connecticut, and Florida. Produced mixtures were compared using SuperPave™ performance parameters obtained from the Frequency Sweep (FS) test, the Simple Shear (SS) test, and the Repeated Shear at Constant Height (RSCH) test. The Indirect Tensile Creep (ITC) and Strength (ITS) tests were also used to evaluate the HMA performance at low temperature.

Based on the results of the NCHRP 9-12 study, it was concluded that at a RAP content of 10%, no significant difference existed between various blends. On the other hand, at a RAP content of 40%, the black rock case was statistically different from the actual practice and total blending cases. These results indicate that no change in binder grade is required at low RAP content; however, total blending can be assumed at a higher RAP content. One should emphasize that the results of the NCHRP 9-12 study only partially supported these findings. Figure 1 illustrates the results of the statistical analysis conducted in that study. Out of 66 possible comparisons, 11 and 16 cases were inconclusive at a RAP content of 10% and 40%, respectively. At a RAP content of 10%, a majority of the cases (70%) supported the conclusion that all cases were similar. However, at a RAP content of 40%, only 42% of the comparisons supported the conclusion that the total blending (TB) cases are similar to the actual practice (AP) cases. In fact, the authors acknowledged that other factors influenced the results including the stiffness of the virgin binder. It was also suggested by the authors that it was not likely that total blending occurs in all cases even at high RAP contents.

Oliver (2001) investigated the blending process between aged and virgin asphalt binders using mechanical testing. A virgin HMA was aged, compacted, and broken up, after which it was blended with a new HMA and compacted again. A second HMA containing the same aggregate was produced using another binder grade. Asphalt binders from both mixtures were extracted and recovered for testing. Both mixtures had the same binder and void contents. In addition, both mixtures were tested for laboratory fatigue and rutting performance. Results of laboratory testing showed that the recycled HMA exhibited better fatigue and rutting performance than the virgin HMA. Based on these results, Oliver (2001) postulated that aged and virgin binders might not fully blend in HMA containing RAP materials due to the formation of agglomerates of aggregate and filler, making it harder for the fresh binder to penetrate. Therefore, incomplete mixing between virgin and aged binder was expected to result in areas with soft binder. This results in an overall softer binder than regular HMA.

Stephens et al. (2001) conducted an experimental program to evaluate the effects of blending between RAP and virgin binders on the resulting SuperPaveTM grade. To validate that RAP does not act as a black rock and has an effect on the overall blend, 11 mixes were prepared with the same gradation, RAP percentage (15%), and binder. The difference between the prepared samples was the RAP preheating time before being added to virgin aggregates and binder. A 12th mix was also prepared with virgin aggregates and binder with no RAP binder (reclaimed RAP aggregates were recovered by the ignition oven). The RAP preheating time was varied from zero to 540 minutes. If RAP acts as a black rock, preheating time should not have any effect on the mix properties. In contrast, if long heating times facilitate the blending between aged and virgin binders, an increase in the mix strength should be detected. Figure 2 presents the variation of the indirect tensile and unconfined compression strengths with RAP preheating time. As shown in this figure, preheating time had a profound effect on the mix strength, indicating that blending does occur between aged and virgin binders. In addition, when comparing the mix with no preheating to the mix made with virgin materials, an increase in strength is immediately observed upon adding the RAP to the virgin materials even without any preheating.

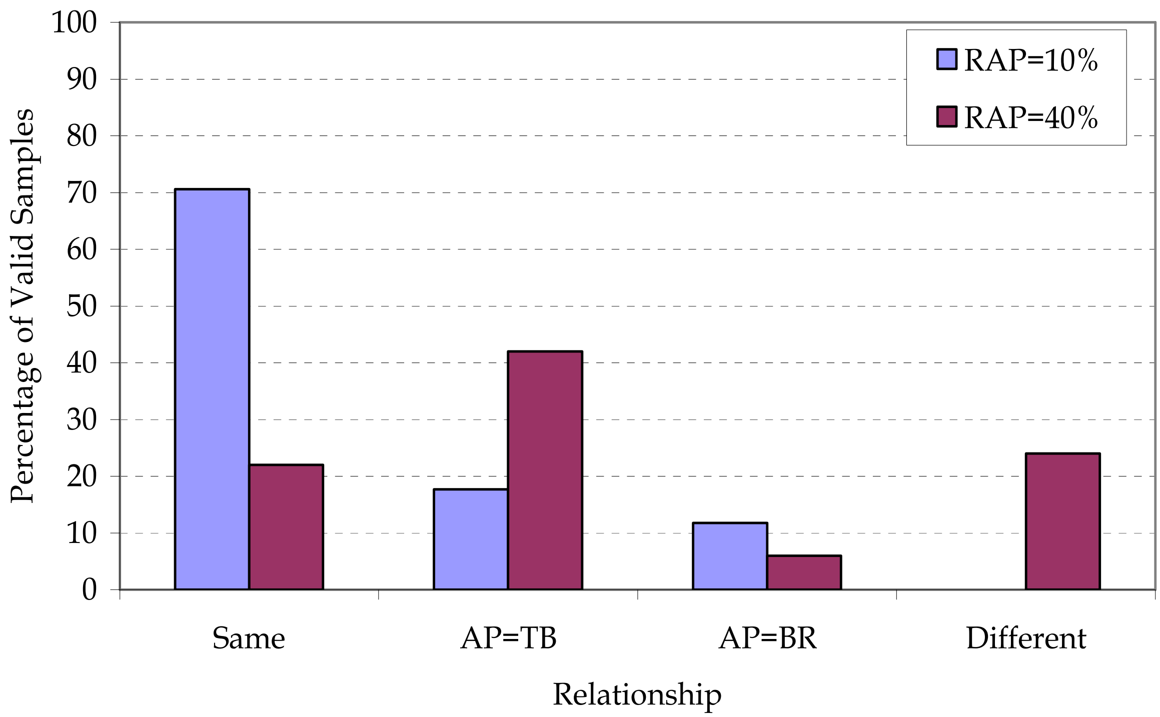

Figure 1. Statistical results of interaction between aged and virgin binders evaluated in NCHRP 9-12 study.

Same: Actual Practice = Total Blending = Black Rock
AP = TB: Actual Practice = Total Blending ≠ Black Rock
AP = BR: Actual Practice = Black Rock ≠ Total Blending
Different: Actual Practice ≠ Black Rock ≠ Total Blending

Stephens at al. (2001) also investigated the concept that asphalt films on coarse aggregates would be more prone to blending with virgin aggregates than asphalt film around fine aggregates. After being lightly heated and spread in a flat plan at one stone layer thick, an HMA containing RAP materials was placed in a drum mixer with steel ball bearings and agitated for four minutes. Binder was then recovered from the coarse aggregate pieces and compared to binder recovered from fine aggregates using a Dynamic Shear Rheometer (DSR). Results indicated that variation in the binder stiffness did not relate to the asphalt coating of coarse or fine aggregates. In fact, for a virgin HMA, large differences in asphalt binder stiffness were detected between recovered fractions. The stiffness of the thin layer of binder around coated aggregates is mainly controlled by its exposure to heat and air during production, which is a random process and does not relate to whether the aggregate is coarse or fine. Laboratory testing conducted in this study also indicated that the use of RAP substantially affects the binder blend grade.

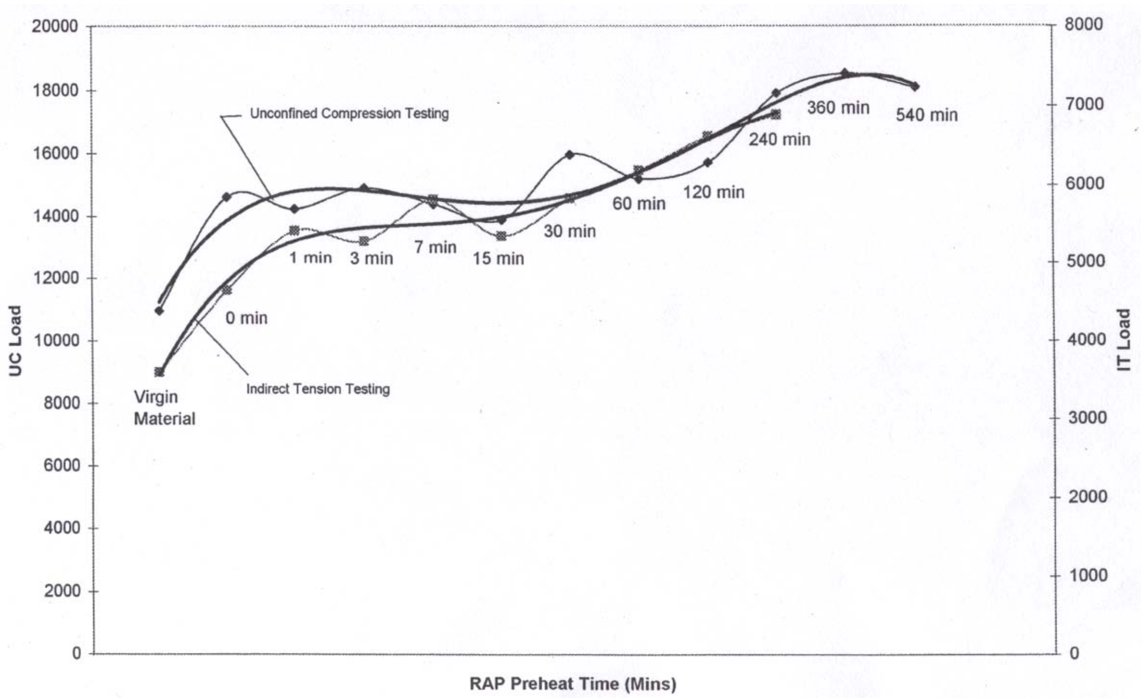

Figure 2. Effect of RAP preheating time on unconfined compression and indirect tensile strength (after Stephens et al. 2001).

Huang et al. (2005) conducted a study to investigate the blending between aged and virgin binders in HMA containing RAP. In this study, only one virgin binder type was considered (PG 64-22). In addition, the RAP material was limestone, which was fractionalized so that only material passing through a No. 4 sieve was used. Virgin aggregates were fractionalized so that only the particles retained on a No. 4 sieve were used. To assess the blending due to pure mechanical mixing, RAP materials were blended with virgin aggregates only (i.e., no virgin binder was added). After mixing, it was determined that the asphalt binder content in RAP materials was reduced by about 11% due to pure mechanical mixing.

However, one should note that pure mechanical mixing as conducted by Huang et al. (2005) is not sufficient to determine the percentage of aged binder that can be removed from the RAP and that can be available for use as effective asphalt binder for coating both virgin aggregates and recoating the RAP particles. This is due to the diffusion of virgin asphalt in the RAP mixtures and the intermixing between aged and virgin binders. This process allows rejuvenating the aged binder and may facilitate its separation from the RAP materials and its effective contribution to the coating of virgin and RAP aggregates (Roberts et al. 1996). One may consider also the fact that only minus #4 RAP was used in this study, which would result in more asphalt binder available in the fine fraction of the mixture. This is coupled with a longer mechanical mixing time than what is used in typical laboratory situations or at the plant and at a higher temperature.

Actual mixing between RAP materials and virgin asphalt binder and aggregates can be demonstrated by the level of blending between aged and virgin asphalt binders around RAP aggregates. In this case, Huang et al. (2005) conducted staged extractions to obtain asphalt binders from various layers coating the RAP aggregates. Results indicated that after blending, outside layers of asphalt binder around RAP aggregates were much softer than the inside layers of binder. In terms of percentages, about 60% of the aged binder did not blend with the virgin binder while 40% of the outside binder was a blend between aged and virgin binders. Although the authors cautioned that the mixtures used in that study do not reflect common HMA normally used in practice, it was evident that the level of contribution of the residual asphalt binder should be something substantially lower than the usually assumed 100%. Hence, it is clear that the appropriate amount of the RAP aged binder that effectively contributes to HMA (containing RAP) needs to be further investigated.

3. DESIGN OF MIXTURE WITH RAP

Under the guidelines developed by the SuperPaveTM Mixtures Expert Task Group, the design of HMA with RAP is based on a three-tier system (Bukowski 1997). Up to 15% of RAP can be used without changing the virgin binder grade from that selected for the project location and conditions. When RAP content is between 15 and 25%, the high and low temperature grades of the virgin binder are both reduced by one grade to account for the stiffening effect of the aged binder (i.e. a PG 58-28 would be used instead of a PG 64-22). If over 25% RAP is to be used in the HMA, blending charts are used to determine the percentage of RAP that can be used with a given virgin binder (McDaniel and Anderson 2001).

When a blending chart is used, it is necessary to extract, recover, and test the RAP binder. The test uses the dynamic shear rheometer (DSR) at high temperature to determine the critical temperature T_c (High) at which $G^*/\sin\delta$ is equal to 1.00kPa:

$$T_c(\mathrm{High}) = \left(\frac{\log 1 - \log G_1}{a}\right) + T_1 \tag{1}$$

where,
$G_1 = G^*/\sin\delta$ at temperature T_1; and
a = slope of the stiffness-temperature curve as $\Delta\log(G^*/\sin\delta)/\Delta T$.

The RAP binder is also aged using the rolling thin film oven (RTFO) and is tested in the DSR and in the bending beam rheometer (BBR). Binder aged in the RTFO is used to determine the critical temperature Tc (High) at which $G^*/\sin\delta$ is equal to 2.2kPa:

$$T_c(\mathrm{High}) = \left(\frac{\log 2.2 - \log G_1}{a}\right) + T_1 \tag{2}$$

Based on this testing, the high-temperature performance grade may be determined. A portion of the RTFO-aged binder is then aged using the pressure aging vessel (PAV). The PAV-residue is then tested using DSR to determine the critical intermediate temperature Tc (Int) at which $G^*\sin\delta$ is equal to 5000kPa:

$$T_c(\mathrm{Int}) = \left(\frac{\log 5000 - \log G_1}{a}\right) + T_1 \tag{3}$$

where,
$G_1 = G^*\sin\delta$ at temperature T_1; and
a = slope of the stiffness-temperature curve as $\Delta\log(G^*\sin\delta)/\Delta T$.

Binder aged in the RTFO is also tested in the BBR to determine the critical low temperatures Tc (S) and Tc (m), at which the stiffness is equal to 300MPa and the m-value is equal to 0.30 [Tc (low) is the higher of the two values], respectively:

$$T_c(S) = \left(\frac{\log 300 - \log S_1}{a}\right) + T_1 \tag{4}$$

$$T_c(m) = \left(\frac{0.3 - m_1}{a}\right) + T_1 \quad (5)$$

where,
S_1 = S-value at temperature T_1;
m_1 = m-value at temperature T_1; and
a = slope of the stiffness-temperature curve as $\Delta\log(S)/\Delta T$.

Upon characterizing the rheological properties of the RAP binder, two blending approaches may be used, depending on whether the RAP percentage or the virgin binder grade is fixed.

3.1 BLENDING AT A KNOWN RAP PERCENTAGE

In this scenario, the RAP percentage is preset based on availability or specification limits while the virgin binder grade is adjusted to obtain a desired final grade for the blend of old and new binder. The following equation relates the critical temperature of the blended asphalt binder to its two components:

$$T_{blend} = T_{virgin}(1 - \%RAP) + T_{RAP} \text{ x } \%RAP \quad (6)$$

where,
T_{virgin} = critical temperature of the virgin asphalt binder;
T_{blend} = critical temperature of the blended asphalt binder;
%RAP = preset percentage of RAP to be used in the HMA expressed in decimal; and
T_{RAP} = critical temperature of the recovered RAP binder.

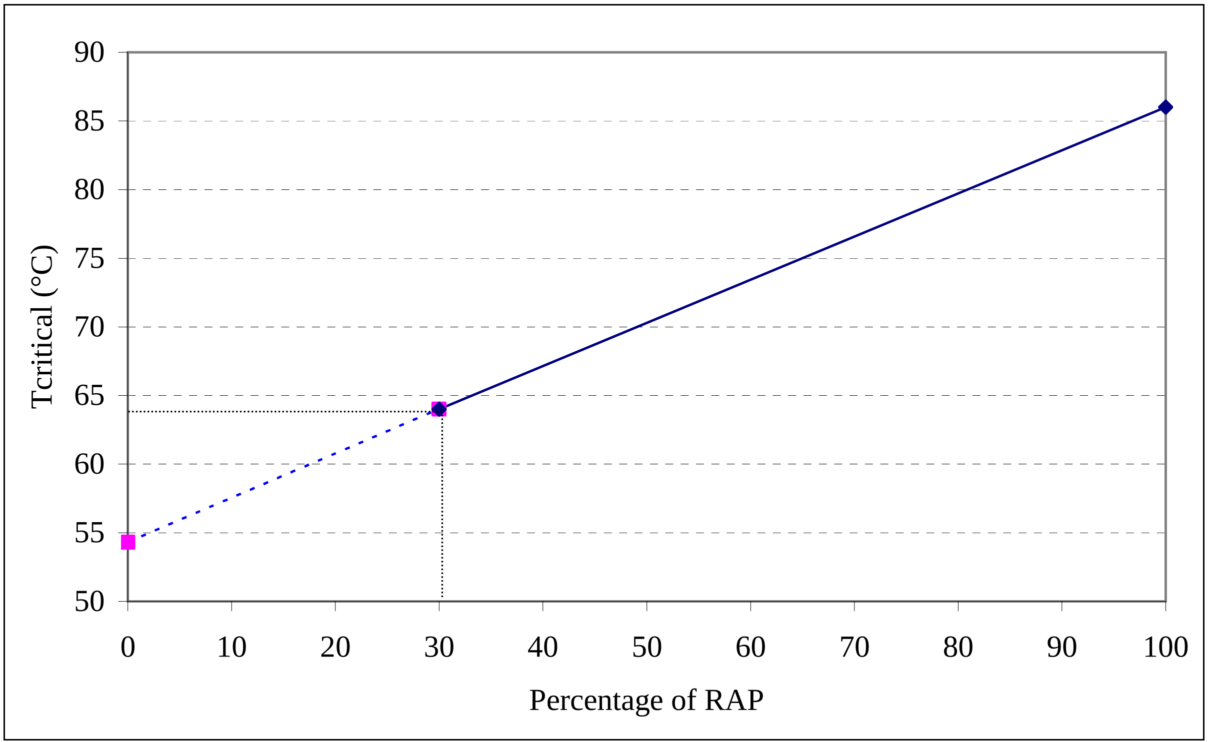

Figure 3. Example of a high temperature blending chart, where RAP percentage is known.

While Tblend is specified by the agency depending on the project location and conditions, TRAP has been characterized through extraction and testing. Therefore, the unknown parameter in Equation 6 is the virgin binder grade. Thus, Equation 6 can be rearranged as follows:

$$T_{virgin} = \frac{T_{blend} - (\%RAP \, x \, T_{RAP})}{(1 - \%RAP)} \tag{7}$$

Equation 7 is used to satisfy the SuperPaveTM requirements at low, intermediate, and high temperatures. Results of this equation may also be presented using a blending chart as shown in Figure 3. In this figure, it is assumed that the desired blended binder grade is PG 64-22 and that 30% of RAP will be used. Based on the high temperature requirements, the minimum virgin binder grade would be PG 58. The same process is repeated at intermediate and low temperatures.

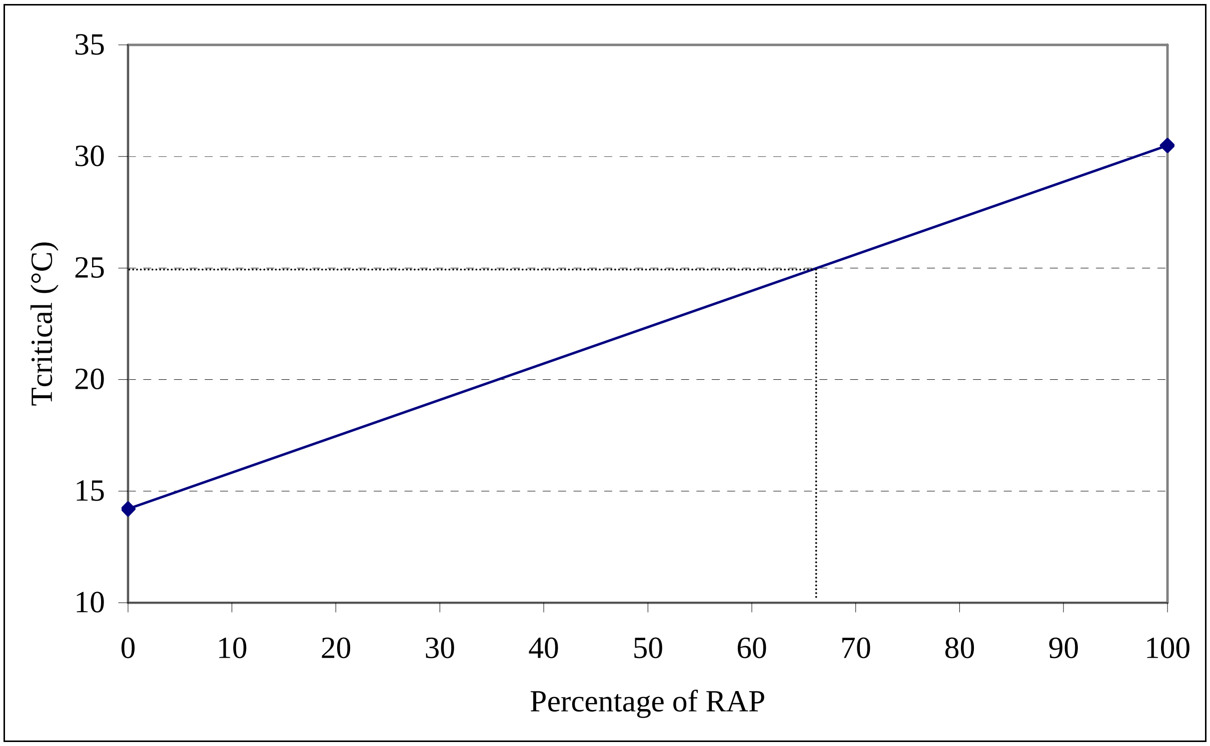

Figure 4. Example of an intermediate temperature blending chart, where the virgin binder grade is known.

3.2 BLENDING AT A KNOWN VIRGIN BINDER GRADE

In this blending scenario, the RAP percentage is determined to allow the use of a preset virgin asphalt binder grade. Equation 6 can be re-written as follows:

$$\%RAP = \frac{T_{blend} - T_{virgin}}{T_{RAP} - T_{virgin}} \tag{8}$$

where all terms are as previously defined. Figure 4 presents the intermediate-temperature blending chart for the aforementioned example, assuming that the virgin binder grade is PG 58-28 and that the RAP percentage is unknown. In this example, the intermediate critical temperature for the RAP binder was 30.5 as determined from testing the recovered binder and 14.2 for the virgin binder, also determined from testing. In this case and to satisfy the intermediate-temperature grade of PG 64-22, the maximum RAP percentage is 66%. To satisfy low, intermediate, and high temperature requirements, the minimum RAP percentage of the various tests should be used.

3.3 MIXTURE DESIGN PROCEDURE

Other factors should be considered in determining the amount of RAP to satisfy the SuperPaveTM requirements of the selected binder grade, including plant capacity for heating RAP aggregates and satisfying volumetric specifications in SuperPaveTM. The design procedure for HMA incorporating RAP materials is similar to regular mixtures by treating RAP aggregate as another stockpile. To account for the presence of binder in the RAP material, the weight of RAP aggregate is calculated as follows:

$$M_{dryRAP} = \frac{M_{RAPAgg}}{(100 - P_b)} x100 \qquad (9)$$

where,
M_{dryRAP} = mass of dry RAP;
M_{RAPAgg} = mass of RAP aggregate and binder; and
P_b = RAP binder content.

To satisfy gradation requirements, the selected blend must pass between the control points and avoid the restricted zone. Mixture volumetric requirements consist of voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), dust proportion, and densification properties at 4% air void. Coarse aggregate angularity is also verified based on the weighted average of the individual stockpile data, and the fine aggregate angularity is verified for the final blend.

Of critical importance, however, in the mixture design procedure of HMA incorporating RAP materials is that the required amount of asphalt binder at 4% air voids is reduced by the amount of binder in the RAP stockpile based on solvent extraction or ignition. For instance, if the design binder content is 4.5% and the asphalt binder in the RAP materials is estimated at 0.3%, the virgin binder to be added is 4.2%. This has recently been reported to be inaccurate and could result in an erroneous HMA job mix formula and dry HMA. In the previous example, if only 50% of the RAP binder is available for blending with the virgin binder in HMA, the actual binder content in the produced mixture would be 4.35% instead of the desired 4.5%. In this case, 0.15% of the RAP is inherent and does not effectively contribute to the active binder in the mixture. Since many volumetric calculations are based on the asphalt content, the values of VMA, VFA, and effective asphalt content may also be erroneous. Hence, the HMA may be vulnerable to durability cracking and premature failure.

4. PERFORMANCE OF RAP MIXTURES

Various researchers have investigated the proper methods of utilizing RAP and the associated performance of HMA incorporating recycled materials. Results have been widely mixed and no clear conclusion can be drawn from past research projects. While some researchers have found that HMA incorporating RAP provide inferior fatigue and thermal performance when compared with virgin mixes (Tam et al. 1992, McDaniel et al. 2000), others have reported that the use of RAP improves the rutting performance of HMA (Sargious and Mushule 1991, Huang et al. 2004).

4.1 FIELD EVALUATION

Kandhal et al. (1995) compared the performance of recycled to virgin HMA pavements in the state of Georgia. Five test sections, which incorporated both a recycled and a virgin wearing course on the same project, were evaluated. In each of these projects, the virgin and recycled mixtures used the same aggregates (type and gradation), were produced by the same plant, were placed by the same contractor, and were subjected to the same traffic and environmental conditions during service. A RAP percentage between 10 to 25% was used. In addition to visual survey of the performance of the sections, laboratory tests were also conducted on field cores. Laboratory tests included resilient modulus, indirect tensile strength, and dynamic creep. After one to two-and-a- half years in service, no significant rutting, raveling and fatigue cracking had occurred in any of the test sections, indicating that both recycled and virgin mixtures performed equally well. However, one should note that one to two years in service is not sufficient to evaluate the long-term performance of the installed mixtures. Laboratory tests indicated comparable results for virgin and recycled sections with the exception of the indirect tensile strength test, which showed that the control mixes had slightly higher values than the recycled mixtures.

In a subsequent analysis, performance of 15 projects involving virgin mixtures was compared to 18 projects involving recycled mixtures. The age of the selected pavements varied from one to three-and-a-half years and the percentage of RAP used ranged from 10 to 40%. Based on visual surveys, there was no significant overall difference in the performance of virgin and recycled pavements. Similarly, a monitoring period ranging from one to three-and-a-half years is not sufficient to determine the long-term effects of RAP on pavement performance.

Paul (1996) compared the field performance of recycled pavements (six to nine years old) to conventional pavements in Louisiana in terms of pavement condition, serviceability, and structural analysis. A RAP percentage between 20 to 50% had been used. With the exception of one case, the compared sections were not on the same project but had similar mix design, traffic, and were preferably constructed by the same contractor. In general, no significant difference was found between recycled and conventional pavements in terms of pavement condition and serviceability ratings.

4.2 LABORATORY EVALUATION

Abdulshafi et al. (2002) conducted an experimental program to recommend a simple laboratory test that could determine the optimum RAP percentage based on mix durability. Four RAP percentages varying between 0 to 30% and six sources of RAP materials were used. One of the assumptions of this study was that the RAP binder completely blends with virgin binder in the mixture produced. To quantify durability of HMA, AASHTO T283 “Resistance of Compacted Bituminous Mixture to Moisture Induced Damage” was used to calculate the absorbed energy at failure for unconditioned and conditioned samples based on the indirect tensile strength test:

$$E = \frac{0.5Pd}{t} \tag{10}$$

where,
E = energy (lb.in/in);
P = ultimate load at failure;
d = specimen vertical deformation at the ultimate load (in); and
t = specimen thickness (in).

Conditioning of the samples consisted of moisture exposure at constant saturation, followed by a freeze cycle, and hot water soaking. After conditioning, dry and conditioned samples were tested for indirect tensile strength. Using Equation 10, the percentage of absorbed energy was then calculated, as follows:

$$PER = \frac{E_{conditioned}}{E_{control}} \tag{11}$$

where,
PER = percent of absorbed energy;
$E_{conditioned}$ = average level of absorbed energy for conditioned specimens; and
$E_{control}$ = average level of absorbed energy for control specimens.

The authors recommended that the optimum RAP percentage be selected at the maximum percentage of absorbed energy level. Minimum thresholds for the absorbed energy at failure were also recommended for unaged and aged HMA samples. For a mixture containing limestone aggregates, the maximum percentage of absorbed energy was obtained at a RAP percentage of 30%. For another mixture produced with gravel aggregate, the absorbed energy data did not show a specific trend but the percentage of absorbed energy was the highest at a RAP percentage of 10%.

McDaniel and Shah (2003) conducted a laboratory study to determine if the tiered approach of the Federal Highway Administration and SuperPave RAP specifications are applicable to Midwestern materials obtained from Indiana, Michigan, and Missouri. The experimental program consisted of first comparing laboratory mixtures to plant-produced mixes containing the same RAP content and source, virgin aggregates, and binder. Additional samples were prepared in the laboratory with a RAP content of up to 50% to determine the effect of recyled materials on the mix performance. Prepared mixes were tested using the SuperPave^{TM} shear tester.

Results of this study indicated that plant-produced mixes were similar in stiffness to laboratory mixtures at the same RAP content for the Michigan and the Missouri samples. The plant-produced mixes from Indiana were significantly stiffer than the lab mixes. Analysis of the shear tester data also demonstrated the stiffening effect of RAP materials on the mixture properties as compared to virgin mixtures. The increased stiffness may improve the rutting resistance of the mixture but it can also increase the potential for fatigue and thermal cracking. Testing conducted for the NCHRP 9-12 study confirmed that recycled mixtures with a RAP content greater than 20% have a lower fatigue life than virgin mixtures (McDaniel et al. 2000). Decreasing the virgin binder grade may be an option to improve the mixture fatigue performance, especially at high RAP content. The authors also highlighted that designing mixtures that conform to the SuperPave™ specifications may not be feasible at a RAP content greater than 40 to 50% due to the high fine content in RAP materials.

Mohammad et al. (2003) investigated the recycling of polymer-modified asphalt using laboratory testing. An eight-year-old polymer-modified mix was recovered and characterized using binder tests (thermal analysis, Fourrier Transform Infrared [FTIR], gel permeation chromatograph [GPC], force ductility, dynamic shear rheometer [DSR], and bending beam rheometer [BBR]). In addition, a polymer-modified mixture with a RAP content varying from 0 to 60% was prepared and tested using indirect tensile strength, indirect tensile creep, repeated shear test, asphalt pavement analyzer, and beam fatigue. Results of binder testing indicated that significant binder aging had occured during service. More specifically, no residual polymer was detected in the aged binder, indicating possible degradation and disappearance of the modifier. Aging properties of the recycled binder were related to extensive oxidation during service, which resulted in a much stiffer behavior than anticipated. Mixture testing indicated that as the RAP content increased, the rutting resistance of the mix increased while its fatigue resistance decreased. In addition, binder testing for rutting and fatigue performance correlated fairly well with the results from mixture performance tests.

Huang et al. (2004) conducted a laboratory study to investigate the effect of using RAP on the fatigue performance of HMA at a percentage varying between 0 to 30%. According to the authors, fatigue performance is the main concern when using RAP materials since the resulting blend tends to be stiffer, and therefore more rut-resistant than conventional mixtures. The experimental program was designed to ensure that samples had the same aggregate structures and the same asphalt content; using Marshall Design procedure. However, no indication is given of how the residual binder was dealt with in the mix process. Performance testing for this study included the indirect tensile strength test, the semi-circular bending test, and the four-point beam fatigue test. Results of this study indicated that with the increase in RAP materials, the tensile strength of the mixture also increased. In addition, the inclusion of RAP materials improved the fatigue life of HMA.

5. SUMMARY

Attaining the goal of recycling, namely to achieve good performance in fatigue, rutting, thermal resistance, and overall durability while optimizing the amount of RAP utilized, poses problems for the mixtures engineer. Considerable research into the effects of mixture characterizations, aggregate properties and gradation, and the binder properties of the RAP has given inconsistent results at times. This is especially true at high RAP blending percentages. The three tier system of FHWA provides good recycled mixtures at low to moderate blend percentages. Aggregate gradation concerns become significant at higher blend percentages, principally due to high fines content; and binder properties become uncertain.

While rutting performance has typically been improved by the use of RAP, the fatigue and thermal performance has been inconsistent. Typically fatigue resistance is improved due to the stiffer nature of a recycled mixture, but this is only found in constant strain testing, and no consistent level of improvement has been reported. At higher blending percentages, the results are unpredictable. Thermal resistance is typically lowered because of the stiffer nature of the recycled mixtures.

The stiffness of a mixture can be impacted by the aggregate and gradation, but the most significant factor is the stiffness of the binder in the recycled mixture. Research has shown that typical recycling projects have achieved blending of the RAP binder and the virgin binder, but have not been able to predict a-priori what the percentage of the RAP binder that effectively combines with the new binder will be. The blending is somewhere between 0 (black rock) and 100% (complete combining of the two binders). Because the final mixture properties are so highly dependent on the binder stiffness which cannot be predicted before construction, an excessive amount of laboratory testing is necessary to determine the mechanistic design properties of a recycled mixture with high RAP content.

The construction process further complicates the investigation into RAP binder utilization. Given the different temperatures and times the recycled mixtures are held at elevated temperatures compared to laboratory conditions, the degree of blending of the two binders will be decidedly different in the two situations. This makes utilization of laboratory characterization uncertain at present.

This inability to accurately characterize binder properties has kept the percent of RAP in the recycled mixtures to relatively low values. Before higher percentages can be utilized, a method for determining blending potential of a RAP that takes into account the relative effectiveness of the RAP binder must be developed.

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