

Towards production of 100% recycled asphalt

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ABSTRACT

Re-use of old asphalt materials for production of new pavements is increasing every year. Because of reduced costs this is encouraged by public agencies. Re-use also reduces environmental footprint through lower emissions and avoiding extraction and processing of natural resources. But recycled contents are limited by current production technologies and mix design principles. To further increase recycling rate while ensuring quality pavement, a move towards fundamental, performance related specifications is necessary. This article presents a study aimed at developing procedures that enable up to 100% recycling of asphalt pavement in hot-mix asphalt. A mix design approach is presented based on performance related test methods both for binder and mixture. Validation of this method is based on laboratory performance of 100% reclaimed asphalt modified by six different rejuvenators. Rejuvenator dose optimization procedure is presented and the results demonstrate that the approach can be used to restore the desired performance grade (PG) of aged RAP bitumen. 100% recycled asphalt mixtures, modified with the same six rejuvenators, were tested for rutting and low temperature cracking and the results indicated that optimal design can provide performance equivalent to virgin mixture. Rutting requirements were satisfied for all six rejuvenated mixtures and five of them reduced the critical cracking temperature compared to the RAP mixture based on creep compliance and tensile strength results.

Keywords: Ageing, Mixture design, Reclaimed asphalt pavement (RAP) Recycling, Rejuvenators, Thermal Cracking

1. INTRODUCTION

Asphalt is one of the few materials that can be re-used directly in the same high value application. Use of reclaimed asphalt for production of new asphalt is the most advantageous application both economically and environmentally. Therefore, hot-mix recycling rates increase every year in most western nations [1]. However, there is still room for growth, especially in urban areas. Too often an excess of reclaimed asphalt accumulates in mill 2 pave 2 maintenance programs which is downgraded for use in lower value applications. There are multiple reasons for this that include physical limits on capacity of conventional plants to safely replace fresh materials with waste derived products. Modern drum plants can accommodate up to 50% RAP and a typical RAP range for batch plants where reclaimed asphalt is added into pugmill is 10 to 20%. Thus for a typical resurfacing job a large portion of the reclaimed asphalt has to be transferred to another application. The main limitation of the maximum amount of RAP is the heating principle. In a conventional production process superheated virgin materials indirectly heat the RAP aggregates thus imposing limitations on the amount of RAP that can be added. For an increased RAP content in mixture the reclaimed asphalt needs to be heated directly (not through superheating virgin aggregates) and to allow 100% recycling an entirely different production approach is necessary. RAP has to be heated without igniting and overly aging the already-hard binder. The blue smoke from volatilization of RAP binder must be filtered before releasing into the atmosphere. A thorough management system and careful quality control of RAP is also necessary.

During the previous four decades a few innovators have refined 100 % recycling technologies to a level where routine production of 100 % recycled hot mix asphalt is in clear sight. The production principles of multiple such plants are described by Zaumanis [2] and summarized in a video: <https://youtu.be/coj-e5mhHEQ>. For example “All RAP Process Plant” is located New York City and produces 100,000 tons of 100% recycled mixtures annually. The first 100% recycled asphalt jobsite was paved 14 years ago and is still serving (Figure 1).



Figure 1. 100% RAP pavement on 75th street in NYC, Woodhaven at construction (2001) and in 2012 [5]

2. DESIGN OF HIGH RAP MIXTURES

Quality of 100% recycled asphalt does not depend on the production process alone, mixture design is also critical. The current approach for high RAP pavement is to apply the same gradation and mixture volumetrics specified for virgin mixtures. However, when designing very high content RAP mixtures, the traditional mix design methodology may need to be altered to ensure satisfactory performance and longevity of asphalt pavement. There are at least three major reasons for this:

- Empirical specifications including gradation and volumetrics of high RAP mixtures do not have enough practical experience and data to demonstrate correlation with pavement field performance.
- The application of empirical specification is further complicated because of difficulty determining bulk specific gravity of RAP aggregates which can cause an error in the calculation of voids in mineral aggregates (VMA). Since this is the most important parameter to ensure mixture durability, errors can result in inadequate binder content that contribute to premature pavement deterioration. A study by West et al. [3] shows that even a small error caused by the extraction or burning process could cause the VMA to be off by 0.4% at 50% RAP content.
- For high RAP content mixtures application of rejuvenators is inevitable. These products are designed to alter the mechanical properties and chemical composition of aged RAP binder in order to ensure the required pavement performance for another service period. They must reduce RAP mixture stiffness and make RAP asphalt binder “available” for blending without overly softening the mix to cause rutting problem. However, currently enough experience has not been accumulated in the industry to control dose of rejuvenator during design and production. Excessive rutting, flushing, and fatigue cracking are some of the potential distresses when rejuvenator dose is incorrect [5].

For these reasons high RAP mix design must include fundamental, performance-based specifications. Such approach has been for long envisioned by the European Committee for Standardization (CEN) (EN 13108-1) and in the US. NCHRP

report 752 [3] evaluates suitability of numerous tests as performance specification criteria several states have already introduced performance-related specifications.

The authors of this article propose a general framework for designing of high RAP mixtures by including performance related tests as one of the steps in asphalt specification. The principles are summarized in Figure 2. First, the aggregates are tested for the required properties and the chosen RAP fractions are combined in an initial mixture composition. Binder is then extracted from the mixture to determine its properties and choose the necessary recycling agent type and dose. Binder content can be modified by changing RAP source, adjusting RAP fines content in the mixture, switching between rejuvenators and finally adding virgin binder. The asphalt is mixed and compacted in laboratory to determine the volumetric and performance-related properties. The chosen test performance-test methods should be based on the local climatic conditions, anticipated failure modes as well as the experience, confidence and availability of pass/fail criteria. These tests in some cases might have to supersede volumetric design principles. Steps are repeated after making appropriate modification if compliance with specification requirements is not achieved. Such approach can allow design of up to 100% recycled asphalt mixtures.

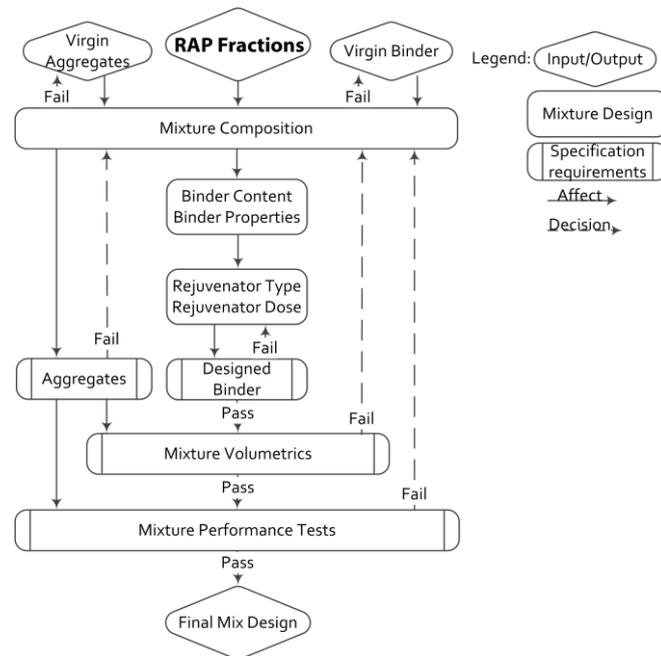


Figure 2. Design of high RAP mixtures

3. OBJECTIVE

Based on the above noted considerations, the objective of this research was to develop an approach to optimize rejuvenated recycled asphalt binders and verify the resulting performance of totally recycled asphalt mixtures.

4. BINDER REJUVENATION

The type and dose of rejuvenator should be selected to meet the target grade of the aged RAP binder, resulting in improved cracking resistance without adversely affecting rutting resistance. Six rejuvenators were used in the study: waste vegetable oil, waste vegetable grease, waste engine oil, organic oil (Hydrogreen S), distilled tall oil, and aromatic extract. RAP was acquired from New Jersey, US and the binder was extracted using toluene as a solvent and recovered using rotary evaporator. After blending with two doses of each rejuvenator the binder was tested for Performance Graded (PG) according to Superpave procedure. In PG system the physical properties required for the binder are the same for all grades, but the temperature at which those properties must be attained is determined by the specific climatic conditions at the paving location and the expected traffic load. The first number next to PG indicates the high-temperature grade while the second indicates the low-temperature grade. For example, a binder classified PG 64-22 would be suitable for applications with pavement temperatures ranging from -22°C to +64°C.

The Superpave grading confirmed that the RAP binder has severely aged. It graded as PG 94-12 (traditionally PG 64-22 binder is used in the region). Figure 3 demonstrates the effect of rejuvenator addition. Both the high and low PG were reduced almost linearly (R^2 values ranging from 0.925 to 1.0). The intermediate temperature PG parameter (indicator for fatigue) was tested at 25°C and it too was likely reduced linearly at least up to the Superpave requirement of $G^* \cdot \sin \delta$ of less than 5000 kPa.

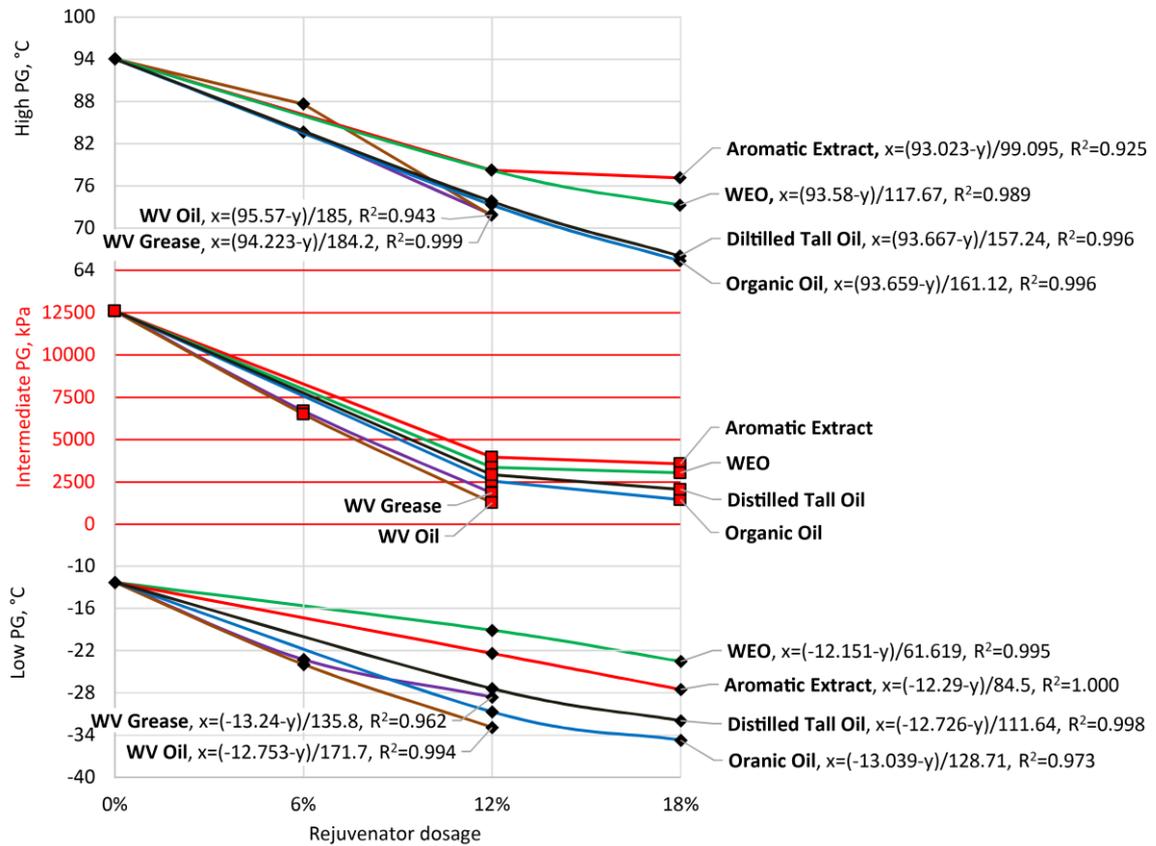


Figure 3. High and Low PG Temperature, and Intermediate PG Parameter of Extracted RAP Binder and After Modification with Two Doses of Each Rejuvenator

Based on these considerations the dose to reach target PG can be calculated. The calculation was performed as follows:

- The maximum rejuvenator dose was calculated to ensure sufficient rutting resistance (defined by high PG temperature). It was calculated according to Equation 1.
- The minimum rejuvenator dose was defined by the requirement to ensure low temperature cracking resistance (low PG) and fatigue resistance (intermediate PG) (equations 2 and 3). The higher of the two was defined as the minimum.

$$Max\ dose, \% = \frac{(high\ PG_{target} - high\ PG_{RAP}) \cdot (-\%_{trial})}{high\ PG_{RAP} - high\ PG_{trial}} \quad (1)$$

$$Min\ dose, \%_{low\ PG} = \frac{(low\ PG_{target} - low\ PG_{RAP}) \cdot (-\%_{trial})}{low\ PG_{RAP} - low\ PG_{trial}} \quad (2)$$

$$Min\ dose, \%_{intermed\ PG} = \frac{(5000 - intermed\ PG_{RAP}) \cdot (-\%_{trial})}{intermed\ PG_{RAP} - intermed\ PG_{trial}} \quad (3)$$

where,

Max dose, % - maximum rejuvenator dose to satisfy high PG_{target} requirement, % from binder mass

Min dose, %_{low PG} - minimum rejuvenator dose to satisfy low PG_{target} requirement, % from binder mass

Min dose, %_{intermediate PG} - minimum rejuvenator dose to satisfy intermediate PG parameter, % from binder mass

%_{trial} - rejuvenator dose for trial blend, %

high PG_{target} - specified high PG temperature, °C

high PG_{RAP} - RAP high PG temperature, °C

high PG_{trial} - high PG temperature for trial blend, °C

low PG_{target} - specified low PG temperature, °C

low PG_{RAP} - RAP low PG temperature, °C

low PG_{trial} - low PG temperature for trial blend, °C

intermed PG_{RAP} - RAP G*·sinδ at Superpave intermediate temperature, kPa

intermed PG_{trial} - G*·sinδ for trial blend at Superpave intermediate temperature, kPa

The calculation results are illustrated in Figure 4. In the area where RAP was obtained (New Jersey, US) PG 64-22 is mostly used and therefore this grade was set as the reference. The minimum dose to satisfy the low PG temperature (-22 °C) and intermediate PG parameter in all cases was much lower than the dose that would decrease the high PG

temperature below the required +64 °C temperature. Thus any dose in the gray shaded area would ensure correspondence to PG 64-22. The figure also shows that the organic products require lower dose compared to the petroleum products to deliver the same effect on PG. Thus switching between the different rejuvenators can be advantageous for modifying the mixture binder content. Products of higher effectiveness will reduce the total mixture binder content and vice versa.

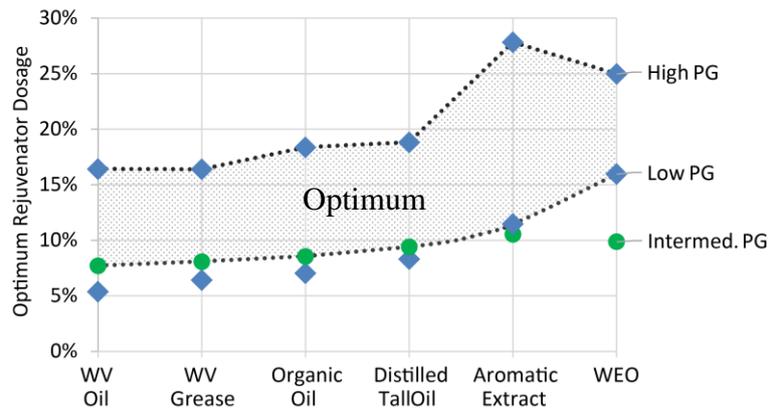


Figure 4. Minimum Rejuvenator Dose to Reach Performance Grade of PG 64-22 Binder

Interestingly, aging and consecutive rejuvenation tends to increase the PG sum (extend PG range). Such effect occurs because the high PG temperature increases (becomes warmer) relatively more compared to low PG as a result of aging. This was demonstrated by comparing the PG of extracted RAP binder from 14 locations [4] with a conclusion that the average grade sum of RAP binder is about 10% higher compared to grade sum of corresponding virgin binder. According to the results of this study rejuvenation reduces the RAP binder grade by 3.7% thus the final grade is higher compared to original binder by 6% as demonstrated in Figure 5. This is an important finding because most RAP stockpiles exhibit variability and a larger grade sum compared to targeted binder grade sum provides a higher confidence of reaching the desired PG with using just one rejuvenator dose (like demonstrated before in Figure 4). It also allows to reduce the number of required mixture design formulas since changing the rejuvenator dose would change the volumetric properties of the mixture.

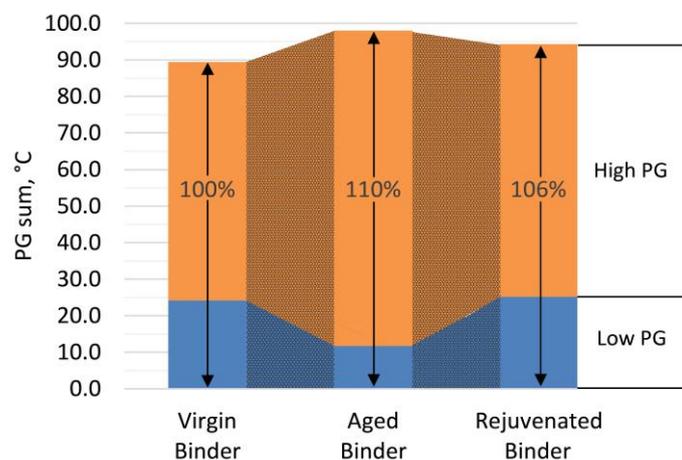


Figure 5. Changes in High and Low PG Due to Aging and Rejuvenation [6]

5. PERFORMANCE TEST RESULTS

The distresses in high RAP mixtures are mostly associated with the aged binder. The stiff, less elastic binder in RAP typically increases mixture stiffness and can cause fatigue damage and low temperature brittleness thus reducing lifetime of pavement. While the optimization of rejuvenator dose can ensure the desired binder properties, not always this guarantees the expected performance of asphalt mixture. This is because of the unknown amount of actual blending that occurs in the system of virgin binder, RAP binder, and rejuvenator. The unknown effective contribution of the RAP binder towards the total binder content of the mix (often referred to as “black rock”) [5] is one of the main reasons for reluctance for government agencies to allow high RAP content since this can lead to fatigue and cracking damage. Rutting, although seldom, has also been reported a problem. This is a result of rejuvenator overdose or insufficient diffusion into RAP binder thus creating a layered binder system with a soft outer layer. For these reasons rutting and low temperature cracking were evaluated in the study. The rutting tests can demonstrate whether rejuvenator is overdosed, while the low temperature tests allow the evaluation of the rejuvenator effectiveness in reducing formation of stress due to thermal loads.

5.1. Materials

The same six rejuvenators were used as described in the previous section. In this case, however, to provide equal binder content for all mixtures they were used at a constant 12% dose from binder mass. This allows direct comparison of the test results. At this dose all the rejuvenators, except WEO, ensured the required PG (see Figure 4). RAP sample was obtained in the state of NJ and re-graded to correspond to 9.5mm Superpave design gradation requirement (Figure 6). The 100% RAP mixture test results were compared to a virgin sample that was prepared by burning off the RAP binder in an ignition oven and replacing with virgin PG 64-22 binder at the same 5.9% as all the other mixes had. Another reference mixture entitled “RAP mix” was designed by adding virgin binder to the RAP at 12% dose, again, to provide equal binder content to the other mixes. This can be considered as un-rejuvenated mixture. The samples were blended with rejuvenator at 145°C. Before compaction with gyratory compactor, the mixtures were also short term conditioned for 4h at the same temperature. The air voids for all mix samples were kept to $7\pm 0.5\%$.

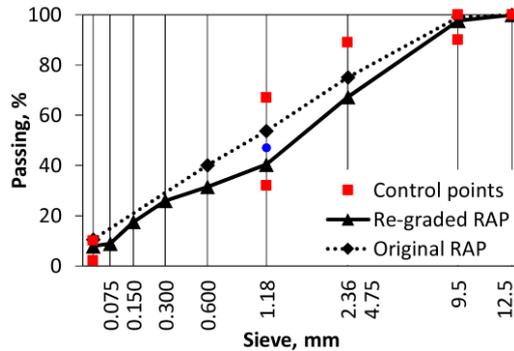


Figure 6. Mixture gradation

5.2. Rutting

Rutting resistance was tested using Hamburg Wheel Tracking Test (WTT). The samples were prepared by gyratory compactor using 150 mm molds to 60.5 mm height and placed in WTT testing molds in pairs. Two pairs of each mixture type were tested for rutting in water at 50 °C.

The rutting results are illustrated in Figure 7 along with the Texas DOT requirement for maximum rut depth (12.5mm at 10,000 wheel passes for PG 64-22 binder). As expected due to presence of aged binder, RAP mixture has the highest rutting resistance. Rejuvenators have slightly increased the rut depth but all of the samples pass the specification requirement. The only sample that fails the limit is the virgin mixture. As noted, this sample was prepared by burning off binder from the 100 % RAP mixtures and replacing it with virgin PG 64-22 binder at a dose that is equal to that of the rejuvenated samples (5.9 %). The poor performance of this mix in comparison to the other mixes might be caused by (1) lower binder viscosity, (2) loss of fines during the burning process and therefore excessive binder content and low filler to binder ratio, (3) moisture damage.

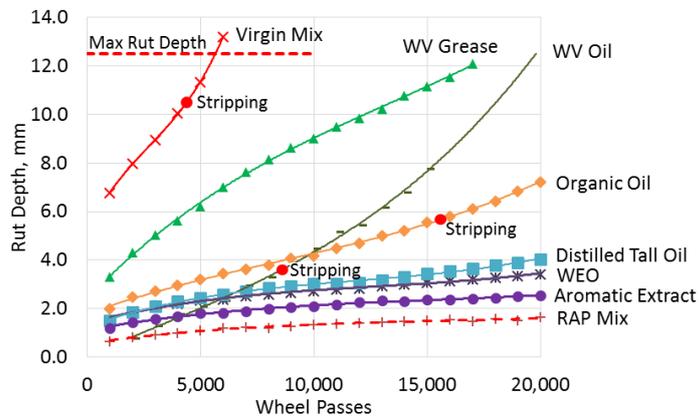


Figure 7. Hamburg WTT rutting results [8]

5.3. Low temperature cracking

Neither stiffness nor strength alone determines when a mixture will crack. A stiff mixture will not crack if its strength is high enough; and a weaker mixture will not crack if it is sufficiently flexible [6]. Strength of rejuvenated mixtures was tested by indirect tensile strength test, while creep compliance at low temperature shows the pavement's potential to creep under thermal load stress. The tests were performed on samples of 46.5mm height and 150 mm diameter. Creep compliance was measured by applying static load to initiate asphalt deformation in the viscoelastic range (0.00125 to 0.0190 mm horizontal deformation at 1000 s). The deformation was measured with horizontal and vertical displacement transducers glued on both sides of saw-cut sample and three replicates at three temperatures (0, -10, -20 °C) were tested for each rejuvenator type. These tests were followed by tensile strength test at -10 °C by applying 12.5 mm/min vertical loading rate.

Creep compliance up to 100 seconds and tensile strength were used to determine the master relaxation function curve and fracture parameters in order to calculate the critical cracking temperature of the pavement. LTSTRESS MS Excel™ spreadsheet (version from April 2012), developed by Christensen [7], was used for this calculation. The spreadsheet is based on mechanistic prediction model developed under the Strategic Highway Research Program (SHRP). The critical pavement cracking temperature (T_{crit}) is estimated as the temperature at which the surface thermal stress reaches the fracture resistance of the mixture as illustrated in Figure 8.

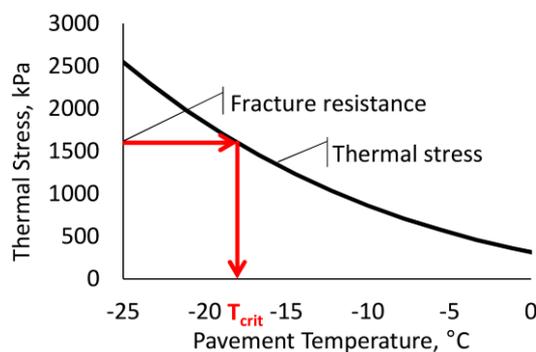


Figure 8. Critical Cracking Temperature Calculation Example

Figure 9 shows the critical mixture low cracking temperature as calculated using LTSTRESS. The tensile strength at -10 °C is plotted using rhombs on a reverse scale relative to source RAP mixture to provide visual comparison with cracking temperature. The figure shows that most of the rejuvenators have improved the cracking resistance compared to the source RAP mixture. The Aromatic Extract and WV Oil even provide temperature similar to the virgin mixture. Note that, as shown by the rutting test, this mix would require reduction of binder content or increase of viscosity thus likely the cracking temperature would increase (become warmer).

Most of the rejuvenated mixes have very similar tensile strength (rhombs in Figure 9) compared to the source RAP Mix, hence lowering in cracking temperature is generally caused by reduction of stiffness. The relatively poor performance of Distilled Tall Oil sample is caused by insignificant change in mixture stiffness. Only the Aromatic Extract has provided statistically higher tensile strength compared to the un-rejuvenated RAP Mix, which is the main cause of improved cracking resistance.

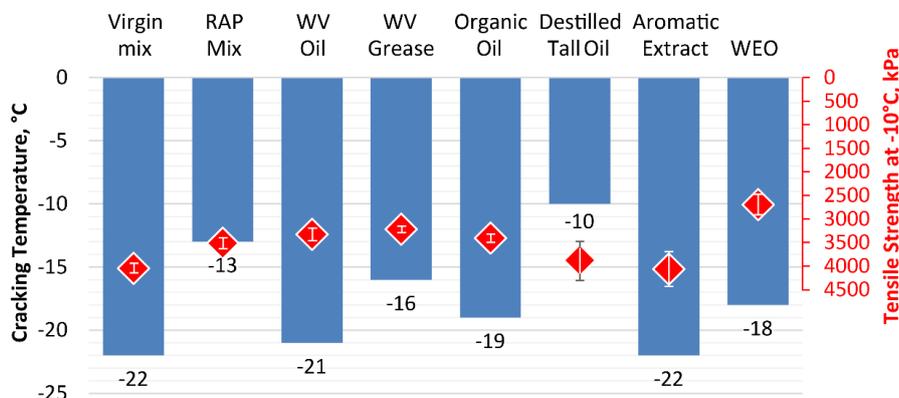


Figure 9. Mixture critical cracking temperature and tensile strength at -10 °C as calculated using LTSTRESS

6. COSTS

A calculation was performed to assess the materials related costs for production of mixtures with increased RAP content, considering average material prices in the city of New Jersey in the middle of 2014. The calculation includes all major positions that are expected to change with increased RAP use. These expenses may vary depending on the technology in use and the location of the contractor but the trends are expected to be similar. The operational expenses that are likely to remain constant (e.g. staff wages, rent) were not included in the calculation. The material related costs must be paired with a mix design to perform a calculation of savings per unit of produced mixture. In this case aggregate content of 94.3% and binder content of 5.7% (RAP binder 5.1% + rejuvenator 0.6%) was used for calculations.

Figure 10 summarizes the calculation results of material related costs per ton of produced asphalt ranging from 0% to 100% RAP content. Depending on the market situation with the availability of RAP, the costs of per ton of 100% RAP mixture would be reduced between 50 to 70% compared to virgin mix. Clearly, the major expense cut is caused by reducing expenses for purchasing binder. If the price of oil continues to rise, the cost effectiveness of using high RAP mixtures will only increase. These savings of course must be quantified to account for additional expenses related to installing the new technology.

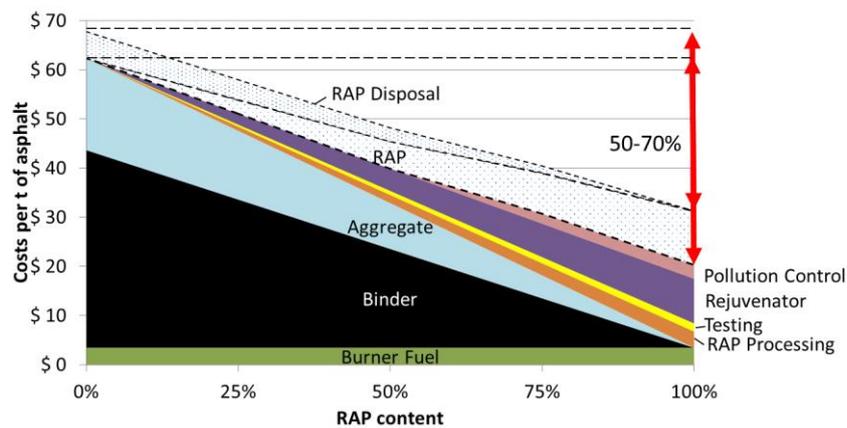


Figure 10. Material related costs of hot mix recycling [5]

7. SUMMARY AND CONCLUSIONS

In recent years the industry focus has been placed on increasing the amount of RAP in asphalt production. This is a result of tripled binder costs during the last decade that come at a time of extremely strained funding for road construction and maintenance. Most of the research has been aimed at development of practices for up to 40% RAP in hot mix design, but the current state-of-the-art technologies and the know-how might allow to leapfrog the intermediate steps and take advantage of total RAP hot-mix recycling as summarized in video: <http://youtu.be/coj-e5mhHEQ>. This is especially beneficial for locations with surplus of RAP (frequently large urbanized areas) where currently this valuable material is often degraded for use in lower value applications like unbound base layers, road shoulders, rural roads, and in-place recycling. Economically use of reclaimed asphalt in production of new hot mix asphalt is the most effective application. Switching to 100% RAP production would enable material related cost savings of 50 to 70% compared to virgin mixture, mostly due to replacement of virgin binder with the less expensive RAP binder.

High RAP recycling can only be viable alternative to conventional asphalt pavements if the properties and longevity are equivalent. To ensure this a mix design method relying mostly on fundamental, performance-related properties of asphalt mixtures has to be developed. This article presents a potential mix design framework and demonstrates the methods to choose appropriate rejuvenator content according to US performance grade (PG) specifications as well as performance-related test results of 100% recycled mixtures. The most significant findings of the study are as follows:

- The dose of all six selected rejuvenators was optimized to ensure the required PG of aged binder and a general procedure for optimization of rejuvenator dose according to PG specifications was presented.
- High and low PG temperatures decrease linearly with an increase in the rejuvenator dose. Intermediate PG parameter decreases linearly up to the $G^* \cdot \sin \delta$ requirement of maximum 5,000 kPa.
- Organic rejuvenators require smaller dose compared to petroleum rejuvenators to cause similar softening effect on aged RAP binder.
- PG sum of RAP binder is likely to be higher than that of source virgin binder. Rejuvenators typically decrease it slightly compared to that of the RAP binder but it remains higher than that of virgin binder.
- An approach for performance-based evaluation of mix design including high RAP content was described. Mixture performance tests were conducted to illustrate potential approach for mixture design optimization.
- All rejuvenated mixtures had high rutting resistance as demonstrated by Hamburg wheel tracking test.

- Low temperature mixture cracking test results showed that five of the six rejuvenators have decreased cracking susceptibility compared to RAP mixture. WV Oil and Aromatic Extract performed similar to virgin mixture while others had slightly warmer cracking temperature.

8. REFERENCES

- [1] EAPA Asphalt in Figures 2013. European Asphalt Pavement Association, 2014
- [2] 100% Recycled Hot Mix Asphalt: A Review and Analysis. Zaumanis, M., Mallick, R.B., Frank, B. Res Cons Rec. 92: 230-245, 2014. DOI: 10.1016/j.resconrec.2014.07.007
- [3] NCHRP Report 752 Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content. West, R., Willis, J.R, Marasteanu, M. January, 2013.
- [4] Determining Optimum Rejuvenator Dose for Asphalt Recycling Based on Superpave Performance Grade Specifications. Zaumanis, M., Mallick, R.B., Frank, B. Constr Build Mater. 69:159-166, 2014. DOI: 10.1016/j.conbuildmat.2014.07.035
- [5] Review of Very High Content Reclaimed Asphalt Use in Plant Produced Pavements: State-of-the-Art. Zaumanis, M., Mallick, R.B., Int. J. of Pavement Eng., 16(1): 39-55, 2014. DOI: 10.1080/10298436.2014.893331
- [6] Investigation of Low and High-Temperature Properties of Plant-Produced RAP Mixtures. R. S. McDaniel, A. Shah and G. Huber,, North Central Superpave Center, West Lafayette, IN, 2012.
- [7] Analysis of Creep Data from Indirect Tension Test on Asphalt Concrete. D. Christensen, Journal of the Association of Asphalt Paving Technologists. 67: 458-492, 1998.