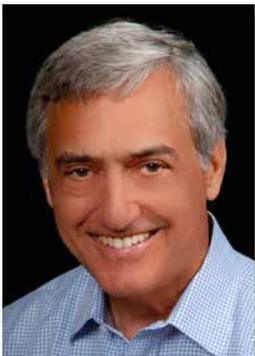


100% Hot-Mix Asphalt Recycling



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Conventional hot-mix asphalt recycling provides many benefits: reduces the asphalt costs and price variability caused by oil cost fluctuations, saves natural resources, and reduces emissions. 100% hot-mix recycling ensures these same benefits but magnified to the maximum. In the doctorate research (with supervision of Prof. Mallick) a holistic evaluation of 100% recycled hot-mix asphalt was performed, including surveying of the available production technologies, calculation of the economic and environmental effects, development of mixture design procedures, testing of multiple rejuvenators, and verification of performance of the designed mixes using binder and mixture performance related test methods as well as chemical analysis. The research is summarized in a six minute video: youtu.be/y-rYvdGiEbY

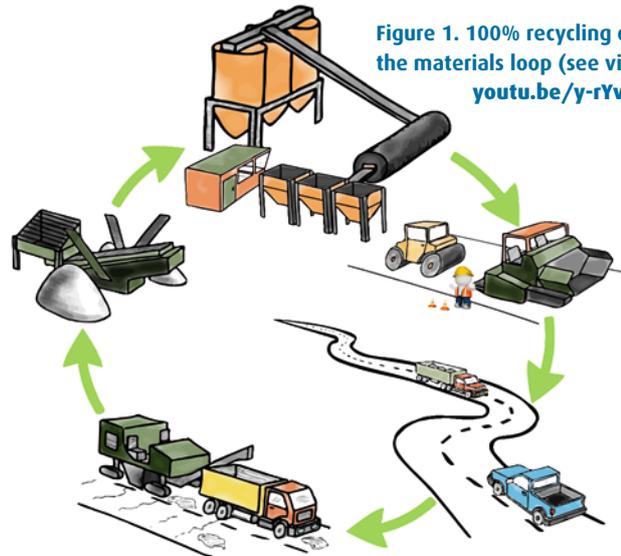


Figure 1. 100% recycling can close the materials loop (see video: youtu.be/y-rYvdGiEbY)

1. Can it be done?

In a conventional recycling process superheated virgin materials indirectly heat the RAP aggregates thus imposing limitations on the amount of RAP that can be added. Modern drum plants can accommodate up to 50% RAP and a typical RAP range of batch plants is 10 to 20%. Total RAP recycling requires a different approach to asphalt production. 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. There are many companies that have tackled these tasks and provide production units for 100% recycling, including:

- ‘All-RAP process’ process uses conventional hot mix asphalt plant components and a patented multi-stage filtration system to capture blue smoke.
- ‘Ammann RAH 100’ is a counter flow dryer with two phase drum where the RAP is heated with hot air and

dispatched before contact with direct flame.

- ‘Rapmaster’ processor heats the RAP indirectly using combustion gases that are generated in a dedicated combustion chamber and channeled inside heat exchange tubes that pass through the length of the drum in counter flow direction.
- ‘Astec RAP King’ is a hot-oil tube type rotary drum where RAP flows across internal hot-oil filled tubes as the drum rotates.
- ‘HyRAP’ is a direct heating system that uses a parallel flow drum with four point material entry collars for different fractions of RAP.
- ‘Alex-Sin Manufacturing’ uses a double shell drier where the RAP is passed through the inner shell and heated from the outer shell using seven perpendicularly located burners.
- ‘RATech’ uses indirect heating from a separate hot air generator to heat RAP

in an originally designed triangle profile drier.

- ‘HERA System’ is an indirect heating process in which hot gasses heat the outside of satellite tubes in drum, inside which the asphalt is heated and dried while rotating.
- ‘Bagela’ recycler is an ultra-portable (towable) drum with up to 10t/hour production capacity. Flame in a separate combustion chamber heats RAP mainly through the hot wall of mixing drum.
- ‘RSL’ is another company producing towable recycling units with up to 25t/h capacity. In the process heat is directed into the top of the mixing drum, inside which the asphalt is heated and dried while rotating.

Of course the quality of 100% recycled asphalt does not depend on the production process alone. Application of rejuvenators is critical. These are products 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 should reduce the RAP mixture stiffness and make the RAP asphalt binder effectively 'available' for blending without overly softening the mix to cause rutting problem.

The management and quality control operations of reclaimed asphalt are another important issue. Vertical integration of the entire material supply chain, including the milling, processing, storage, and quality control operations would help to ensure the required performance of the final product. For example road constructions where the different layers have aggregates or binder of various quality or grade should be removed by partial milling. This would later allow the use of RAP in higher value layers. Special attention should be given to minimize fines content since they can significantly restrict the RAP mixture design by not allowing to meet the mixture aggregate size distribution requirements, dust to binder ratio, air voids, and VMA [1, 2, 3]. Fast forward speed and slow drum rotation of milling apparatus, and avoiding fractionation of RAP will all limit fines content. Moisture content in RAP is another important factor that can restrict the maximum RAP content. It will cause higher drying and heating costs, reduce the plant production rate, and increase emissions by 10% for every 1% moisture increase [4]. Moisture content can be reduced by covering stockpiles, using of paved, sloped storage area with conical stockpiles, and processing RAP in small portions at the day of use.

2. Does it make economic sense?

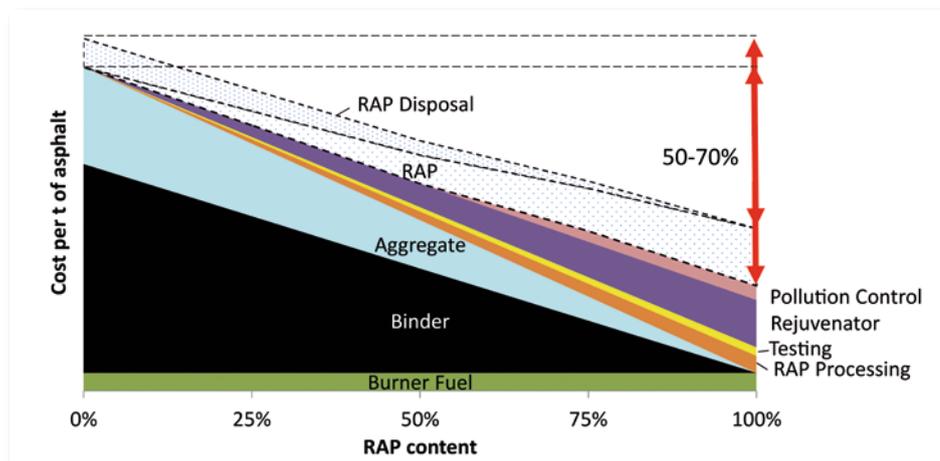
A simple calculation was performed to assess the materials related costs for production of mixtures with increased RAP content. The calculation includes all major positions that are expected to change with increased RAP use. These expenses may vary depending on the technology in use and the location 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 2 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. As the price of oil continues to rise, the cost effectiveness of using high RAP mixtures will only increase. These savings must be quantified to account for additional expenses related to installing the new technology.

3. Mix Design

The basic principle for ensuring well performing high RAP pavement is to apply the same requirements to the RAP aggregates and mixture volumetrics as those that are specified when using virgin materials. When designing 100% RAP mix same holds true, however, the traditional mix design methodology has to be altered in respect to optimization of binder content and ensuring the required binder properties. The binder content can be modified by changing RAP source, adjusting fines content in the mixture, switching between rejuvenators or modifying their dose and finally adding virgin binder. The binder properties can be altered by carefully choosing rejuvenator and its dose. Finally, performance-related tests of mixture are beneficial to verify the critical mixture properties. The chosen 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 replace the volumetric design principles for 100% recycled mixtures.

Figure 2. Material related costs of hot mix recycling



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3.1. 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. A research study was undertaken with a goal to develop a simple method for choosing rejuvenator and optimizing its dose to account for the inevitable variability in RAP binder properties while minimizing the required binder extraction. The results of the study are described in full by Zaumanis et al. [5]. 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 and the binder was extracted using toluene as a solvent and recovered with rotary evaporator. After blending with two doses of each rejuvenator the binder was tested for penetration at 25°C and 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 PG64-22 would be suitable for applications with pavement temperatures ranging from -22°C to +64°C.

Penetration. All rejuvenators reduced the penetration of extracted binder (19 ×0.1mm) to the target level of virgin binder (78 ×0.1mm in this case) but organic oils required lower dose to provide the same effect as petroleum products (Figure 3). The penetration grew exponentially with increased rejuvenator dose meaning that the required rejuvenator dose to reach the target penetration can be calculated using only two data points (e.g. extracted binder and one rejuvenator dose) as demonstrated in Equation 1.

$$Dose = \log_e PENAB \quad (1)$$

where

Dose – dose of the rejuvenator, %

PEN – penetration of rejuvenated binder, ×0.1 mm

A – penetration at 0 % dose (y-intercept of the exponential function), ×0.1 mm

B – constant calculated by least squares fit through data points

(intermediate PG). The higher of the two should be defined as the minimum.

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

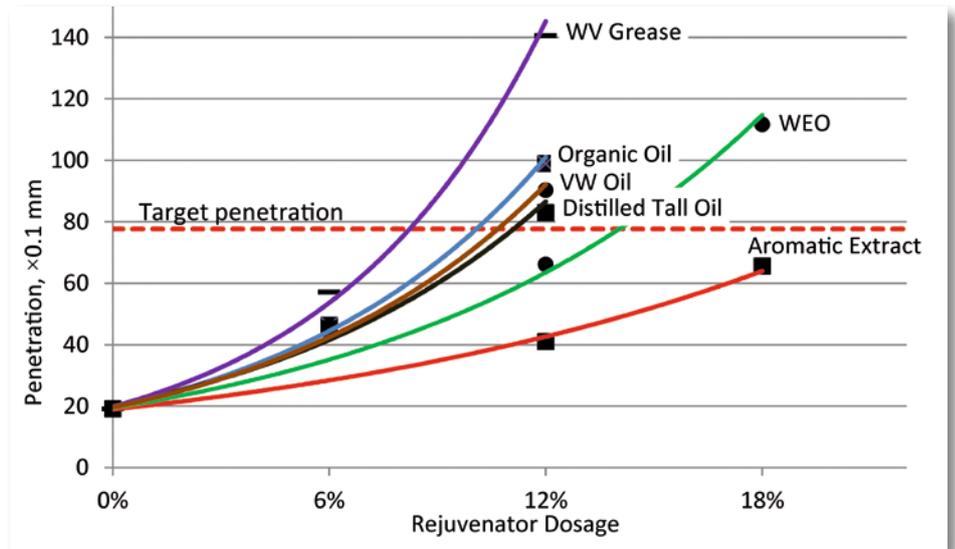


Figure 3. Changes in RAP binder penetration after adding rejuvenators

Performance grade. The Superpave grading confirmed that the RAP binder has severely aged and graded as PG 94-12. The addition of rejuvenators reduced both the high and low PG almost linearly (R² 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^{*}·sinδ of less than 5000 kPa. Based on these considerations the dose to reach target PG can be calculated. The calculation was performed as follows:

- The maximum rejuvenator dose should be calculated to ensure sufficient rutting resistance (defined by high PG temperature).
- The minimum rejuvenator dose should be defined by the requirement to ensure low temperature cracking resistance (low PG) and fatigue resistance

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. Of course this zone of favorable rejuvenator content would depend both on the RAP binder PG and the target PG but, as demonstrated in the full article [5], it is likely that dose of rejuvenators can be optimized for any aged binder to restore the PG equal to that of the original source binder. The figure also shows that, similarly to penetration results, 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. The dose to reach penetration of the reference binder (78 ×0.1mm), calculated

according to Equation 1, is also plotted in Figure 4. It is always in between the allowed maximum and minimum PG dose. Hence adding the rejuvenators at a dose calculated to reach the penetration of virgin binder would also ensure the required performance grade in all cases. Because penetration test is inexpensive and simple to perform, such dose calculation would provide a practical tool to select the initial dose before conducting further testing, if any. Such tool can also be helpful for quality control purposes when the source or age of the millings changes.

not to over soften the binder. Second, sufficient rejuvenator diffusion in the binder film must have occurred before opening to traffic (no "black rock" situation).

The tests reported here are rutting resistance and low temperature brittleness. The rutting tests can demonstrate whether rejuvenator is overdosed while the low temperature tests allow to evaluate rejuvenator effectiveness in reducing formation of stress due to thermal loads. The full study is reported by Zaumanis et al. [7, 8], and also include test results on

entire "RAP mix" was designed by adding virgin binder to the RAP at 12% dose, again, to provide equal binder content to the other mixes. 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±0.5%. Interestingly, the required compaction energy to reach equal air void level varied significantly among the samples. While addition of rejuvenators improved the workability compared to RAP mix, it remained lower than that of virgin mix.

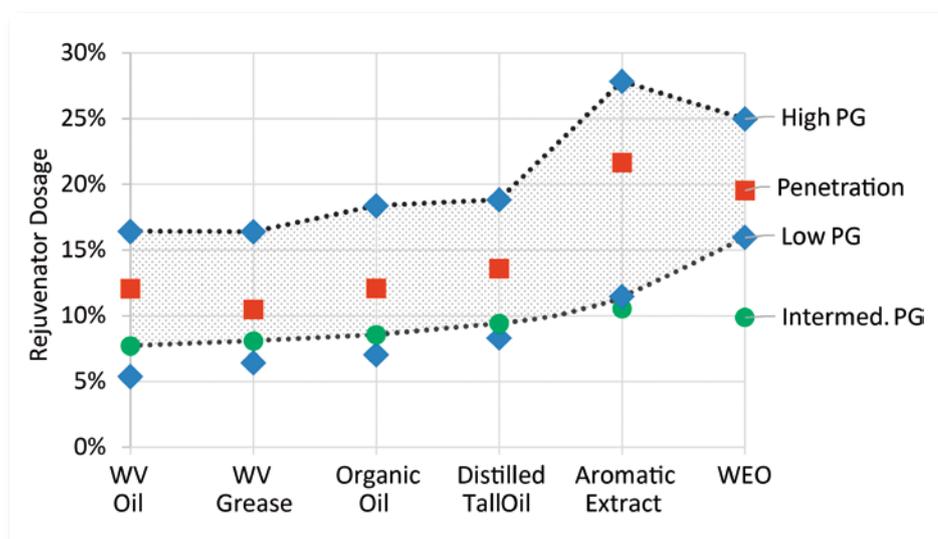


Figure 4. Minimum Rejuvenator Dose to Reach Performance Grade and Penetration of PG 64-22 Binder

4. 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. Other potential problems are associated with the unknown amount of actual blending that occurs between virgin and RAP asphalt binders and the effective contribution of the RAP binder towards the total binder content of the mix (often referred to as "black rock") [6]. These are some of the main reasons for reluctance for government agencies to allow high RAP content. Rutting, although seldom, has also been reported a problem. This can occur if rejuvenators are inappropriately applied but can be avoided by two steps. First, rejuvenator dose must be carefully chosen

mixture fatigue, moisture susceptibility, workability as well empirical and performance test results of binder. 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). The 100% RAP sample was obtained in the state of NJ and re-graded to correspond to 9.5mm Superpave design gradation requirement. The 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

4.1. 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 50°C water.

The rutting results are illustrated in Figure 5 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, the 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, (3) moisture damage.

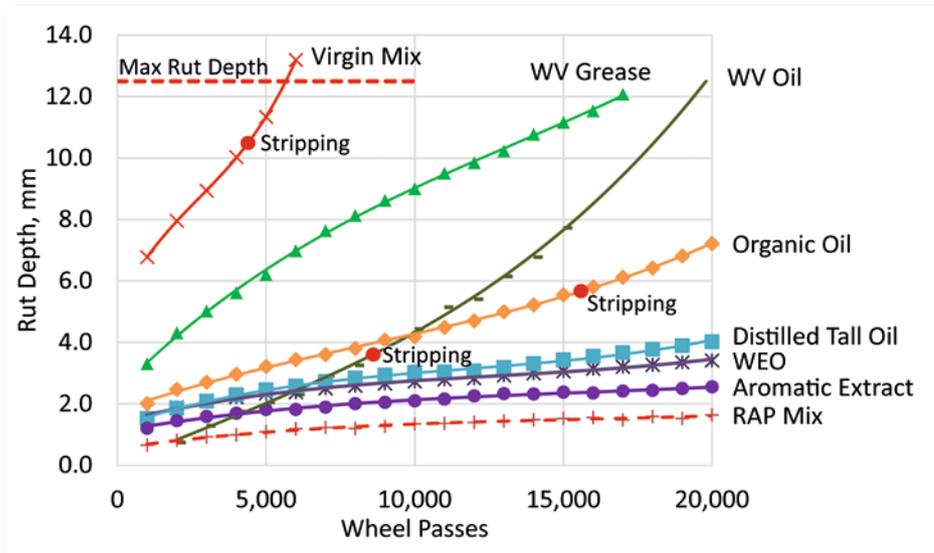


Figure 5. Hamburg WTT rutting results

4.2. Low temperature properties

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 [9]. 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 in 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 1,000 s). The deformation was measured with horizontal and vertical displacement transducers glued on both sides of saw-cut sample (cutting improves the repeatability of results) 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 [10], 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 (Tcrit) is estimated as the temperature at which the surface thermal stress reaches the fracture resistance of the mixture.

Figure 6 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 6) compared to the source RAP Mix, hence the lowering in cracking temperature is generally caused by reduced 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. The good performance

of WV Oil rejuvenated mixture, conversely, is caused primarily by the reduction in mixture stiffness (increase in compliance). WEO also provides relatively large reduction in stiffness, but due to lowered strength demonstrates only average Tcrit. On the other hand, the relatively poor performance of Distilled Tall Oil sample is caused by insignificant change in mixture stiffness.

5. Summary

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: 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.

Vertical integration of the materials supply chain control would greatly benefit the quality of final product. Starting from the milling process of old pavement the goals should be to minimize fines content, separate materials of different values, limit contamination, minimize moisture content and ensure RAP homogeneity. Before production RAP should be processed in the necessary fractions to allow design of mixture gradation, while minimizing excess material. A quality control procedure should be implemented to verify the properties and variability of RAP stockpiles.

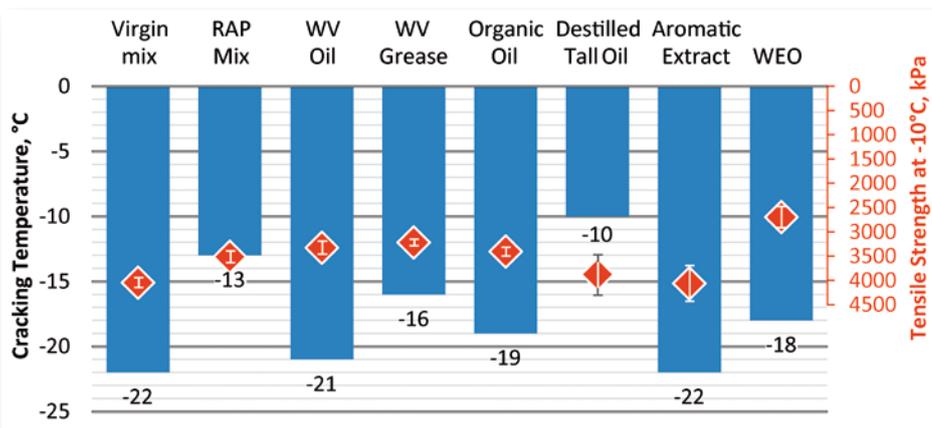


Figure 6. Mixture critical cracking temperature and tensile strength at -10 °C as calculated using LTSTRESS

The production technologies are already there and, as shown by the test results, so can be the performance of 100% recycled asphalt. The laboratory test results demonstrated that careful choice of rejuvenator and its dose can ensure low temperature crack resistant pavement with high rutting resistance. See video for detailed information of the results: youtu.be/y-rYvdGiEbY. The long-term field performance of 100% recycled mixtures has also been demonstrated by the 100% RAP mixtures routinely paved in New York City (see the first 100% RAP section in Figure 7).

6. References

- [1] D. E. Newcomb, E. R. Brown and J. A. Epps, *Designing HMA Mixtures with High RAP content: A Practical Guide*, Lunham, MD: National Asphalt Pavement Association, 2007.
- [2] R. McDaniel, H. Soleymani and A. Shah, "Use of Reclaimed Asphalt Pavement (RAP) Under Superpave Specifications: A Regional Pooled Fund Study," Joint Transportation Research Program, 2002.
- [3] A. Copeland, "Reclaimed asphalt pavement in asphalt mixtures: state of the practise," Federal Highway Administration, Washington, DC, 2011.
- [4] B. D. Prowell, G. C. Hurley and B. Frank, *Warm -Mix Asphalt: Best practices*. 3rd Edition, Lunham, MD: National Asphalt Pavement Association, 2012.
- [5] M. Zaumanis, R. Mallick and R. Frank, "Determining Optimum Rejuvenator Dose for Asphalt Recycling Based on Superpave Performance Grade Specifications," *Construction and Building Materials*, vol. 69, pp. 159-166, 2014, DOI: 10.1016/j.conbuildmat.2014.07.035
- [6] M. Zaumanis and R. Mallick, "Review of Very High Content Reclaimed Asphalt Use in Plant Produced Pavements: State-of-the-Art," *International Journal of Pavement Engineering*, 2014, DOI: 10.1080/10298436.2014.893331
- [7] M. Zaumanis, R. B. Mallick and R. Frank, "Influence of Six Rejuvenators on the Performance Properties of Reclaimed Asphalt Pavement (RAP) Binder and 100 % Recycled Asphalt Mixtures," *Construction and Building Materials*, vol. 71, pp. 538-550, 2014, DOI: 10.1016/j.conbuildmat.2014.08.073
- [8] M. Zaumanis, R. B. Mallick and R. Frank, "Evaluation of Different Recycling Agents for Restoring Aged Asphalt Binder and Performance of 100 % Recycled Asphalt," *Materials and Structures*, 2014, DOI: 10.1617/s11527-014-0332-5
- [9] R. S. McDaniel, A. Shah and G. Huber, "Investigation of Low and High-Temperature Properties of Plant-Produced RAP Mixtures," North Central Superpave Center, West Lafayette, IN, 2012.
- [10] D. Christensen, "Analysis of Creep Data from Indirect Tension Test on Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologists*, vol. 67, pp. 458-492, 1998.

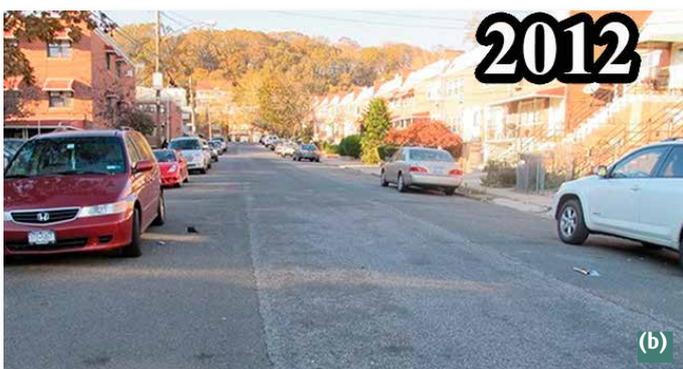


Figure 7. 100% RAP pavement on 75th street in NYC, Woodhaven at construction (2001) and in 2012.

The long-term field performance of 100% recycled mixtures has also been demonstrated by the 100% RAP mixtures routinely paved in New York City