100% recycled hot mix asphalt: A review and analysis

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100% recycled hot mix asphalt: A review and analysis

Martins Zaumanis a, *, Rajib B. Mallick b, Robert Frank b

a Worcester Polytechnic Institute (WPI), 100 Institute Road, Kaven Hall, Worcester, MA 01609, United States
b RAP Technologies, 217 Belhaven Avenue, Linwood, NJ 08221, United States

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A B S T R A C T

A holistic evaluation of the feasibility of producing 100% recycled mixtures is presented. Eleven technologies readily available for producing 100% Reclaimed Asphalt Pavement (RAP) hot asphalt mixtures are described in the article and the complementary video (http://youtu.be/coj-e5mhHEQ). The recorded performance of 100% RAP mixtures is analyzed along with identification of typical high RAP distresses. Recommended mix design procedures and the best RAP management strategies are described. A cradle-to-gate analysis of environmental effects indicated 18 kg or 35% CO2eq savings per t of produced 100% RAP asphalt mixture compared to virgin mix, while cost analysis showed at least 50% savings in material related expenses.

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* Corresponding author. Tel.: +1 8572648722.
E-mail addresses: jeckabs@gmail.com (M. Zaumanis), rajib@wpi.edu (R.B. Mallick), info@raptech.us (R. Frank).
URL: http://zaumanis.com (M. Zaumanis).

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1. Introduction

Currently in many construction projects asphalt is recycled in unbound base layers; for road shoulders and rural roads; cold or hot in-place recycling; and adding a relatively small percentage added to new hot mix asphalt. Asphalt recycling is not truly sustainable when it is degraded and used in these lower value applications. 100% hot mix recycling closes the materials cycle by fully utilizing the valuable materials found in reclaimed asphalt in high quality applications.

There are many questions and confusion among researchers and industry regarding the feasibility and necessity for production of total Reclaimed Asphalt Pavement (RAP) recycling. This paper and the complementary video (http://youtu.be/coj-e5mhHEQ) presents a holistic study to evaluate the technology, benefits, constraints, costs, and viability of 100% RAP hot mix asphalt as well as summarizes the recorded performance of such mixes.

1.1. RAP use and availability

In Europe, the data from 19 countries that provided European Asphalt Pavement Association (EAPA) with RAP use statistics shows that 47% of the available RAP was used in hot or warm mix asphalt applications, while 22 million tonnes were used in other applications or stockpiled (EAPA, 2012). In the US, a survey by National Asphalt Pavement Association (NAPA) (Hansen and Copeland, 2013) estimates a total of 71.8 million tonnes of RAP accepted in 2011, 84% of which were used in asphalt applications. Although nationally this is a high re-use rate, in urbanized areas the restrictions on the maximum allowed RAP content in mix design and technical capabilities of asphalt plants have created high surplus of RAP. Estimation by New Jersey Asphalt Pavement Association (data provided by K. Monaco and J. Purcell) for the last six years shows only 41% RAP use in asphalt pavements which has caused excess RAP of 4.1 million tonnes (Table 1).

In developed countries, road maintenance overwhelm new construction creating great amounts of readily available material that can potentially be re-used for resurfacing of the same road pavements. These statistics demonstrate that there is enough RAP available for higher RAP use in HMA applications, especially in urbanized areas. Establishing 100% RAP recycling asphalt plants can significantly increase the recycling capacity and help reduce the amount of RAP that is wasted in low value applications.

2. 100% RAP production

The maximum amount of reclaimed asphalt is mainly limited by the available production technology. 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. Most drum plants can accommodate up to 50% RAP (Bonaquist, 2007) and a typical RAP range of batch plants is 10–20% (Kandhal and Mallick, 1997). Producing mixtures of higher RAP content using conventional plants would require an unrealistically high superheating temperature of virgin aggregates, causing blue smoke from volatilization of RAP binder, and risk dryer fires if RAP feed is interrupted.

There are multiple technologies readily available for production of 100% recycled hot mix asphalt. The authors contacted owners/producers of five of these plants and visited two of these facilities. Basic information about these facilities is summarized in Table 2 and the main principles of each technology are summarized later in this section as well as illustrated in the video (http://youtu.be/coj-e5mhHEQ). All contacted producers pointed out that conventional techniques and equipment can be used for placement and compaction of 100% RAP mixes. None of them revealed any serious issues with mixture workability or performance.

Other technologies that are designed for 100% RAP recycling, but are not described in detail, include:

- “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 (Volker Wessels, 2013).
- “Bagela” recycler is an ultra-portable (towable) drum with up to 10t/h production capacity. Flame in a separate combustion chamber heats RAP mainly through the hot wall of mixing drum (Bagela, 2013).
- 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 (RSL, 2014).

Table 1
Estimated amount of excess RAP in New Jersey.

<table>
<thead>
<tr>
<th>Year</th>
<th>RAP milled, t</th>
<th>RAP used</th>
<th>Excess RAP, t</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>1,593,017</td>
<td>42%</td>
<td>675,853</td>
</tr>
<tr>
<td>2008</td>
<td>1,391,622</td>
<td>26%</td>
<td>359,245</td>
</tr>
<tr>
<td>2009</td>
<td>1,552,194</td>
<td>41%</td>
<td>636,844</td>
</tr>
<tr>
<td>2010</td>
<td>1,687,364</td>
<td>42%</td>
<td>703,976</td>
</tr>
<tr>
<td>2011</td>
<td>1,893,295</td>
<td>50%</td>
<td>939,844</td>
</tr>
<tr>
<td>2012</td>
<td>1,925,047</td>
<td>43%</td>
<td>833,703</td>
</tr>
<tr>
<td>Total</td>
<td>10,042,538</td>
<td>41%</td>
<td>4,149,464</td>
</tr>
</tbody>
</table>
Table 2
Summary of the described processes.

<table>
<thead>
<tr>
<th>Technology name</th>
<th>All-RAP process</th>
<th>Ammann RAH 100</th>
<th>Alex-Sin Manufacturing, Inc</th>
<th>Rapmaster</th>
<th>RAtech</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant producer</td>
<td>RAP-Technologies, Inc (modification of generic plant)</td>
<td>Ammann</td>
<td>Alex-Sin Manufacturing, Inc</td>
<td>RAP Process Machinery, LLC</td>
<td>E-MAK</td>
</tr>
<tr>
<td>Owner of visited plant</td>
<td>Green Asphalt</td>
<td>BAB Belag AG</td>
<td>Pavement Recycling Systems &amp; Alex Sin Manufacturing</td>
<td>Evergreen Sustainable Pavements</td>
<td>–</td>
</tr>
<tr>
<td>Plant location</td>
<td>Long Island City, New York City, USA</td>
<td>Birmenson, Canton Aargau, Switzerland</td>
<td>Riverside, California, USA</td>
<td>Not in operation</td>
<td>Plant manufacturer located in Turkey</td>
</tr>
<tr>
<td>Plant type</td>
<td>Drum plant</td>
<td>Batch plant</td>
<td>Drum plant</td>
<td>Drum plant Indirect rotary tube dryer</td>
<td></td>
</tr>
<tr>
<td>Dryer type</td>
<td>Conventional counter flow shell dryer</td>
<td>Counter flow with two phase drum</td>
<td>Counter flow with extreme oxidized conductor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximal plant output</td>
<td>200 t/h</td>
<td>240 t/h</td>
<td>300 t/h</td>
<td>100 t/h</td>
<td></td>
</tr>
<tr>
<td>Current status</td>
<td>Commercial production</td>
<td>Commercial production</td>
<td>Idle, technology development</td>
<td>Idle</td>
<td>Commercial production</td>
</tr>
<tr>
<td>Amount of 100% RAP mixtures produced to date</td>
<td>~300,000 t</td>
<td>~1000 t</td>
<td>~4100 t</td>
<td>~100,000 t</td>
<td></td>
</tr>
<tr>
<td>Asphalt layers produced</td>
<td>Base, binder, wearing and specialty mixes</td>
<td>Base and binder coarse</td>
<td>Base and binder coarse</td>
<td>Base</td>
<td>Base</td>
</tr>
<tr>
<td>Main 100% RAP mixture applications</td>
<td>Commercial sites, temporary, and secondary streets.</td>
<td>Industrial areas</td>
<td>Currently not in operation</td>
<td>Commercial sites, local area roads</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- “Benninghoven” has developed a uniflow large volume drum with a burner that precludes direct contact between the flame and recycled material (Benninghoven, 2013).
- “RapSaver” is a preheating system comprised of a continuously fed sealed conductive heating system that allows RAP to be heated and dried using a slow moving hollow screw heating auger (Augering, 2013).
- “HyRAP” is a direct heating system that uses a parallel flow drum with four point material entry collars for different fractions of RAP (Brooks Construction Company, 2013).
- “Cyclean” is a microwave heating technology that was utilized at the end of 1980s and beginning of 1990s. Due to the high energy requirements of microwaves and thermal oxidizer compared to conventional systems the process has only seen limited use (Techapplication, 1992; Federal Highway Administration, 2008).

2.1. All-RAP Plant

All-RAP Plant (RAP Technologies, 2013) process uses conventional hot mix asphalt plant components and a special blue smoke filtration system (Frank, 2004)(Fig. 1a). Since most of the fine dust is encapsulated by RAP binder there is little need for dust collection. Instead, blue smoke generated by the direct contact of RAP with flame has to be removed prior to releasing combustion gases to the atmosphere. RAP Technologies employs a multiple stage filtration system (Fig. 1) to comply with local air quality rules as follows (the recorded emissions are summarized in Table 3):

- Inertial separator drops out small quantity of coarse fines that are then manually removed a few times per year.
- Dispersible fiberglass pocket filters remove micron size particles with up to 99% control efficiency.
- Recirculated water spray cools air stream and condenses hydrocarbons stripped from RAP during drying to form aerosol mist.
- Fiberbed filters remove aerosol mist by Brownian capture and release zero opacity gases to atmosphere.
- Exhaust gases comply with 0.04 g per SCF (Standard Cubic Foot) and 10% opacity limits for conventional asphalt plants established by US federal “Standards of Performance for New Stationary Sources” described in 40 CFR Part 60.
- Air flow is approximately 30,000 ACFM (Actual Cubic Feet per Minute) at 30% moisture.
- The dryer is maintained at slight negative pressure to vent combustion gases and fugitive emissions to the air pollution control device.

Separate cold feed bins for fine and coarse RAP fractions volumetrically meter design blends onto inclined conveyers that deliver them to the heating drum. Due to differences in ratio of thermal mass and surface area, the fine RAP fractions require less time to reach mix temperature than coarse aggregates. Therefore, coarse
RAP is introduced in the drum at the beginning of it, while the fine RAP is introduced at dryer midpoint via a conventional “center entry” RAP collar. The mix discharge temperature is around 150 °C.

The recycling agent type and dose is chosen based on extracted binder penetration test results. It is sprayed on the hot RAP at the dryer discharge chute as demonstrated in Fig. 1b. It mechanically mixes with the RAP binder during transportation by drag slat conveyor. The diffusion continues during storage, transportation, and laying of the asphalt.

2.1.1. Current operation, RAP processing and mix design

The RAP is run through a screening plant and separated into fractions using 6.4 mm, 12.5 mm and 19.0 mm sieves. A combination of these fractions is used to produce 4.75, 12.5 or 19 mm Nominal Maximum Aggregates Size (NMAS) Superpave mixes. Oversize clumps of pavement are crushed to liberate sand from stone in a manner that avoids generation of excess 70 μm material. Additional 19 mm material is trucked in from conventional plants to keep up with demand for base mixes. RAP fines are used immediately after processing to avoid high moisture content due to precipitation.

100% RAP is used to pave utility trenches, commercial parking lots, and industrial areas. A study that evaluated one site is reported in Section 3.3. In 2013 a demonstration project of 100% RAP along with conventional asphalt was paved by New York City Department of Transportation (NYC DOT) at Jewel Avenue & 147th Street in Kew Garden Hills, Queens (New York City, 2013). 85th Road and 75th street was paved in 2001 along with numerous other streets that are still in service providing record of the durability of 100% RAP mixes on public streets.

2.2. Ammann RAH 100 plant

The indirect heating system “RAH 100” is paired with Ammann “Uniglobe 200” plant at the visited location in Birmensdorf, Switzerland. The plant has three cold storage bins for storing different RAP fractions. The bunkers are located underground, thus RAP is not exposed to weathering. The material is metered and transported via conveyor belt to bucket elevators that deliver the cold RAP to heating drum.

The drum is installed on top of the tower to ensure gravity-driven handling of the hot RAP as illustrated in Fig. 2a. A counter flow dryer with two phase drum is used. The material heating and drying phase of the drum rotates, while the combustion chamber is static as demonstrated in Fig. 2b. The RAP is heated with hot air and is discharged before getting in contact with the flame thus reducing emissions and limiting RAP binder aging. Usual RAP discharge temperature is 165–180 °C. The air recirculation system improves drying efficiency in comparison to conventional systems by 10%, ensures low oxygen content to further reduce aging and reduces emissions (Ammann, 2011). After discharge gravity drives the material into hot storage silo which has a capacity of 28t. The RAP is further released to the weight hopper and asphalt pugmill of 3t capacity. The rejuvenator and virgin binder, if any, is added in the pugmill and mixed together with RAP for 30–40 s.

2.2.1. Current operation, RAP processing, and mix design

RAP is crushed and screened to NMAS of 22 mm. On average the material has around 10% fines and binder penetration of 30–40 by 0.1 mm. Rejuvenator can be added to the heated RAP in the asphalt pugmill. However, currently the plant operates without addition of any recycling agent.

2.3. Alex-Sin manufacturing plant

A drum dryer without direct exposure of RAP to flame is used in the “Alex-Sin Manufacturing” plant that is capable of 100% RAP production (Alexander and Sindelar, 1994). Seven burners are located in a heating chamber and perpendicularly heat rotating drum dryer shell from exterior as demonstrated in Fig. 3. Radiation shields (46 cm wide) are located on the drum perpendicular to flames to prevent drum from heating unevenly. Heat is transferred from drum to RAP by conduction through the metal shell. The front third of the drum (cold end) is constructed of aluminum while the rear two-thirds are made of stainless steel. Hot combustion gases flow through the heating chamber and enter the drum at 680 °C to move in counter-flow direction. In addition, breech ports are placed inside the drum to introduce hot air at drum center. Fins are welded on the exterior of the drum at 45° angles to aid at churning of air and work as secondary thermal mass conductors. The burner output is controlled by three infrared readers that are set to maintain the inner drum surface temperature between 480 and 540 °C. The burners operate between 850 and 900 °C and, based on temperature readings, are typically set to three different output levels ranging from 100% at the entrance of materials to 50% (or less) of maximum output at the exit of the drum. Fuel use of 3.4–5.21 t per t of mixture produced has been recorded at ambient temperatures ranging from 10 to 30 °C. The final mixture temperature can be adjusted as required and the maximum stack temperature is 80 °C.

Virgin binder or recycling agent can be added at the mixing zone at the end of the drum though a pipe that penetrates the rear wall.

2.4. Rapmaster™ plant

In the Rapmaster™ processor (Anderson et al., 2010) RAP is indirectly heated through convection, conduction, and radiation within the rotating drum from stainless steel heat exchange tubes and heated drum wall surface. Hot combustion gases 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 to the materials (Fig. 4). The drum has a double shell whereby the spent exhaust gases from heat exchange tubes are
running back the length of the drum, and after blending with fresh air are directed to combustion gas exhaust. Since there is no air velocity within the drum and all exhaust gases are isolated from the material, the main exhaust fan collects gases directly from the plant without a baghouse. A second fan draws blue smoke created during heating process to a combustion chamber for incineration. After the hot RAP at around 160 °C is discharged from the drum, it enters post mixer pugmill where it is blended with a recycling agent and, if necessary, virgin binder. The asphalt from pugmill is transported by a drag slat conveyor to heated silos.

2.4.1. Current operation, RAP processing and mix design

The plant is currently idle. When in operation, the RAP was typically screened to two or three fractions using a high frequency screening system (i.e. using screens of 12.7 mm and 6.4 mm). Oversized material was crushed into the necessary fraction. The Rapmaster™ producers note that RAP uniformity and consistency after processing was often better than that of virgin aggregates. “Cyclogen L” recycling agent was typically added at around 0.6% by weight of mixture to provide the desired performance grade.

In a demonstration project on Tinkham Street, Springfield, MA in 2003, a 100% RAP mixture, the pavement was placed along with a virgin mix. Visual observations of the site show equal or less cracking of 100% RAP compared to control sections.

2.5. RAtech plant

RAtech™ heating unit can be integrated in existing batch asphalt plant to provide partial or total RAP recycling. It uses indirect heating from a separate hot air generator to heat RAP in an originally designed triangle profile drier (Gencer, 2010) using vertical elevator. RAP is indirectly heated by hot air of 200–400 °C and directly exposed to 120–200 °C as illustrated in Fig. 5a. This reduced temperature compared to conventional plants helps limit the aging of RAP binder and lowers the emissions. A controllable speed spiral conveyor spreads the RAP slowly between the drier’s plates where it is heated through hot surfaces of channels and driving plate surfaces to the desired temperature. The driving plates are designed to limit sticking of RAP and reduce segregation. After heating RAP is released to RAtech mixer via weighing unit. Any recycling
additives or virgin bitumen are added in at this stage and 45 s mixing time is suggested. The hot RAP is kept in a heated silo until ready for discharge. The production capacity of the plant significantly varies based on the RAP moisture content. It will drop from 180 t/h for 1% moisture to around 80 t/h for 5% moisture content.

The hot air that is used to bring RAP to the desired process temperature is obtained from heat generator, which consists of combustion space and burner (Fig. 5b). The released hot air from the burner is mixed with controlled amount of cold air and fed into circulation channels of triange driller at the required temperature. The temperature, flow rate, speed, and pressure of the circulating air is controlled automatically. The temperature of air when it reaches air filter has dropped to 90–95 °C.

3. 100% RAP performance

3.1. Typical distresses associated with high RAP use

Before describing the few studies that have evaluated 100% recycled asphalt, typical distresses of traditional very high RAP content mixtures are reviewed. Although the findings of such studies cannot be directly attributed to 100% RAP mixtures, the trends in most cases are likely to remain similar.

3.1.1. Cracking

The distresses in high RAP mixtures are mostly associated with the aged binder. The stiff, less elastic binder in RAP typically increases mixture stiffness (Al-Qadi et al., 2012; West et al., 2013) and therefore can cause fatigue damage (Daniel et al., 2010; Shah et al., 2007; West et al., 2011) and low temperature brittleness (West et al., 2011; Terrel et al., 1992). For example, National Cooperative Highway Research Program (NCHRP) study 9–46 (West et al., 2013) evaluated the use of 55% RAP mixes and showed that stiffness, as measured by dynamic modulus at different temperatures and frequencies, increased by 25–60% compared to virgin mixes. These are some of the main reasons for reluctance for government agencies to allow very high RAP content (Mogawer et al., 2012; Willis et al., 2012).

Contrary to general perception, the studies by Al-Qadi et al. (2012), Huang et al. (2004, 2005), Shu et al. (2008), McDaniel et al. (2012), as well as Sargious and Mushule (1991) have all indicated increased fatigue life of mixtures containing at least 40% RAP compared to conventional mixes. These results may be partially explained by reduced tensile strains in the mixture due to increased stiffness and improved bond between binder and aggregates. In addition, Huang et al. (2005) concluded that the hardened binder forms a stiff micro layer at the interface of RAP which reduces the stress and strain concentration within the HMA and could improve fatigue resistance. Yet, the authors predict that finalization of recycling agent diffusion would likely neglect this effect over time. Therefore, laboratory evaluation of mixtures where diffusion has not finalized can create “false positive” results.

3.1.2. Rutting

Multiple studies have shown that the resistance to rutting resistance is likely to be very good for high RAP mixes because of the presence of aged binder (McDaniel et al., 2000; Silva et al., 2012; Karlsson and Isacsson, 2006). However, the recycling agents are aimed at reduction of the mix stiffness and may cause increased rutting if inappropriately used. Two main factors must be taken into account to avoid forming of plastic deformations:

– The recycling agent dose must be carefully chosen not to over soften the binder.

– Sufficient recycling agent diffusion into the binder film must have occurred before opening to traffic. Insufficient diffusion will form soft outer layer of binder film (Shah et al., 2007; Mogawer et al., 2012) which may lead to increased dynamics of developing permanent deformations in early stages of pavement life until equilibrium is reached (Potter and Mercer, 1997).

3.1.3. Water susceptibility

Since the RAP aggregates are already covered with asphalt, there is less chance of water penetration in the particles. Therefore, generally high recycled asphalt mixtures are expected to have similar or better moisture susceptibility compared to conventional asphalt (Mogawer et al., 2012; Karlsson and Isacsson, 2006; Tran et al., 2012). If the milled pavement had stripping problems, adhesion additive should be used (DeKold and Amirkanian, 1992).

3.1.4. Flushing

In field studies with the use of incompatible products or excessive dose of recycling agents, a migration of oils toward the surface of the asphalt layer has been noticed, resulting in reduction of the friction of wearing course and compromised pavement performance. This has been described as unstable rejuvenation resulting in bleeding or flushing (Kandhal and Mallick, 1997; Karlsson and Isacsson, 2006).

3.2. Laboratory research results of 100% RAP mixtures

A doctorate research by Zaumanis (2014) compared recycling agents for 100% RAP HMA mixes. Both conventional petroleum and novel organic recycling agents were tested, including organic oil, aromatic extract, waste engine oil (WEO), distilled tall oil, waste vegetable oil (WVO) and waste vegetable grease. The tests of extracted binder showed that the products at 12% dose, except WEO, reduced the aged binder performance grade (PG) temperature from −12 °C of RAP binder to the required −22 °C. Most recycling agents also reduced critical mixture cracking temperature, calculated from creep compliance and tensile strength test results, and two products (WVO and aromatic extract) ensured
cracking temperature similar to virgin mixture. The high temperature rutting potential was in all cases within the required specification limits for Hamburg wheel tracking test (Zaumanis et al., 2014a). The authors also concluded that workability of virgin mix cannot be reached with any of the products. Overall at 12% dose waste vegetable products outperformed other recycling agents in most of the tests.

A laboratory study by Silva et al. (2012) evaluated the potential of 100% RAP hot mix recycling with the use of recycling agents. Instead of extracting binder from RAP, the researchers chose a hard binder grade to replicate aged binder and performed testing using two rejuvenating agents: “ACF Iterlene 1000” and used motor oil. The aim was to reduce viscosity of the binder, which had penetration of 14 × 0.1 mm and softening point of 68 °C to penetration grade of 20/30 and respective required softening point of 55–63 °C. Through addition of three doses of recycling agents, it was found that both of them satisfied this requirement at 5% dose from binder mass. All mixtures had high resistance of water damage, measured as indirect tensile strength ratio (ITSR). The wheel tracking test results of the unmodified mixture, as expected due to aged RAP binder, showed superior performance, while the rejuvenated mixes demonstrated similar result to conventional mixture having the same binder grade. As measured by a four point bending test, the stiffness of mixture has been reduced, phase angle increased and fatigue resistance improved with the addition of recycling agents. The authors concluded that mixture performance results were even better than those of conventional HMA with using either of the recycling agents.

A study by Zaumanis et al. (2013) evaluated the use of nine recycling agents for softening extracted RAP binder and improving 100% RAP mixture low temperature properties. Doses of 9% and 18% from binder mass were used. The extracted RAP binder was severely aged having penetration of 16 × 0.1 mm at 25 °C and kinematic viscosity of 2054 mm²/s at 135 °C while the virgin binder had 85 × 0.1 mm and 474 mm²/s respectively. The effectiveness of reducing the RAP binder consistency to the target of virgin binder varied by a factor of twelve between the different recycling agents. Two of the products were not able to ensure binder softening to the required level at a reasonable dosage rate. Creep compliance and tensile strength of mixtures were tested at −10 °C with the different recycling agents. All products provided similar or reduced stiffness compared to unmodified RAP mixture, but only five of them ensured equal or higher strength. The authors concluded that four of the tested products (organic blend, refined tallow, aromatic extract, and distilled tall oil) reduced low temperature brittleness and at the same time provided binder consistency similar to that of target virgin binder.

A study by Mallick et al. (2010) evaluated 100% RAP hot mix asphalt produced with addition of 0.9% Reclamite recycling agent (from mixture mass). The RAP was re-graded to meet 12.5 mm Superpave gradation specification for use in base course. Compared to RAP mix without a recycling agent a decrease in dynamic modulus value (reduced stiffness) was noted in most temperatures and frequencies, except the highest temperature (54.4 °C) and the lowest loading frequencies (0.1 and 1 Hz). The authors compared these results with reports from multiple other studies to conclude that the stiffness of 100% RAP rejuvenated mixes is very similar or lower than that of conventional HMA. Low temperature cracking potential was evaluated through the use of creep compliance and indirect tensile strength test to conclude that reduced embrittlement was obtained after introduction of Reclamite.

3.3. Full Scale Trials of 100% RAP mixtures

The study by Mallick et al. (2010) presents results of full scale application of 100% RAP wearing coarse in New York City (NYC). The 12.5 mm NMAS dense-graded mixture was produced using the asphalt plant described in Section 2.1. “Renoil” recycling agent was used to restore the RAP binder grade to PG 70-28. The quality control results demonstrated good consistency of air voids, Marshall stability and flow. Samples were also cored from 7 year old 100% RAP pavement where Renoil was used as recycling agent. The air void content at four of six core locations was similar to control section while at the others two it was high (9.6 and 11.2%). Stiffness of the rejuvenated 100% RAP mixture, measured by resilient modulus test, was lower than that of concurrently paved 15% RAP mixture that was used as control. Creep compliance at −10 °C, which is an indicator of low temperature stiffness, showed similar results for both 15% and 100% RAP mixtures.

Due to scarce availability of research reports, in summer of 2012 the authors performed a visual inspection tour of the 100% RAP sites in NYC DOT demonstration projects at Woodhaven 85th Road and 75th Street. These wearing coarses were paved in 2001 using Marshall mix design with 12.5 mm NMAS aggregate design (6F mix designation by NYC DOT). No differences in pavement performance compared to control sections of virgin mixtures were noted (Fig. 6). Tinkham Street in Springfield, MA was paved in 2003 using 100% RAP mixture along with control virgin mixture and both sections are performing well.

Historically, due to oil crisis in the 1970s and consecutive increase in binder cost, a significant effort was placed on research of high use of RAP. FHWA demonstration project No. 39 in the 1970s and beginning of the 1980s was aimed at reducing energy use and asphalt costs by maximizing the recycling. Due to the available technology at the time, RAP content in most projects was limited to around 30–70% (Helinegel, 1980; Howard et al., 2009; Henley, 1980; Zywiak, 1982; Federal Highway Administration, 1995). The few 100% RAP field research projects that could be found in the literature are listed in Table 4. The observed problems of pavement performance, consistency, production and emissions at the

![Fig. 6](https://example.com/figure6) 100% RAP pavement on 75th street in NYC, Woodhaven at construction (2001) and in 2012.
Table 4
Historic 100% RAP plant-produced hot mix asphalt projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>Construction year</th>
<th>Layer</th>
<th>Additive dose and type</th>
<th>Plant type</th>
<th>Performance</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate 8, Sentinel, Arizona</td>
<td>1978</td>
<td>Base and surface</td>
<td>2.5% Cyclogen</td>
<td>Central, drum dryer</td>
<td>Likely due to overdose of rejuvenator, in-place density showed low air voids (0–2.3%) although the mixture was designed with 4.1% air voids Section required heavy maintenance and was removed in 1986</td>
<td>(Federal Highway Administration, 1995; Little and Epps, 1980)</td>
</tr>
<tr>
<td>Interstate 15, Henderson, Nevada</td>
<td>1974</td>
<td>Surface</td>
<td>1.5% AR-8000 0.75% Paxole</td>
<td>Central, drum dryer</td>
<td>–</td>
<td>(Federal Highway Administration, 1995; Little and Epps, 1980)</td>
</tr>
<tr>
<td>U.S. 84, Snyder, Texas</td>
<td>1976</td>
<td>Base</td>
<td>4.0% AC-10</td>
<td>Central, hot pug mix dryer</td>
<td>–</td>
<td>(Little and Epps, 1980)</td>
</tr>
<tr>
<td>Loop 374, Mission, Texas</td>
<td>1975</td>
<td>Surface</td>
<td>1.6% Reclamite 3.0% AC-5 2.0% flux oil</td>
<td>Central, drum dryer</td>
<td>–</td>
<td>(Little and Epps, 1980)</td>
</tr>
<tr>
<td>U.S. 50, Holden, Utah</td>
<td>1975</td>
<td>Surface</td>
<td>1.5% AC-10</td>
<td>Central, drum dryer</td>
<td>“Cyclean” Good performance after 17 months of service</td>
<td>(Bloomquist et al., 1993)</td>
</tr>
<tr>
<td>Georgia</td>
<td>1991</td>
<td>Unspecified</td>
<td>0% and 4% unspecified recycling agent</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

very high RAP projects significantly reduced the research and trust in high RAP content mixtures (Howard et al., 2009; Bloomquist et al., 1993). A comfortable approach of using low RAP content (10–25%) has been adopted since then and is reality even nowadays. Bonaquist has noted that many of the isolated failures with high RAP contents have occurred when unprocessed RAP was produced in asphalt plants that were not designed to handle such mixtures (Bonaquist, 2007).

4. Mix design

The traditional mix design methodology, especially with respect to design of optimal binder content, has to be modified for very high content RAP mixtures. The mix designer will have to make compromises when choosing how to process the reclaimed asphalt and what size fractions best satisfy the mixture gradation, binder content, mixture volumetric and performance-property requirements while efficiently utilizing the available material. Choice of recycling agent and its dose is another significant aspect.

The authors’ proposed mix design principles for dense-graded 100% RAP mixtures are summarized in Fig. 7. First, the aggregates are tested for required properties and the chosen RAP fractions are combined in an initial mixture composition. The binder is then extracted from the mixture to determine its properties and choose the necessary recycling agent type and dose. The asphalt is mixed and compacted in laboratory to determine the required volumetric and performance-related properties. The steps are repeated by taking appropriate modification if correspondence to the specification requirements is not ensured at any stage. If due to properties of milled RAP (especially fines and binder content) the design of mixture with 100% RAP is not possible (Gencer et al., 2012; Arnold et al., 2012), virgin binder and aggregates can be added. However, care should be given to ensure sufficient blending of RAP and virgin binder as well as homogeneous coating of virgin and RAP aggregates.

4.1. RAP gradation and aggregate characterization

The basic principle for ensuring good performing asphalt pavement is to apply the same requirements to the RAP aggregates as those that are specified for virgin mineral aggregates (Willis et al., 2012). A study by NCAT and University of Nevada Reno (West et al., 2013; Kvasnak et al., 2010) suggests that either ignition oven test or solvent extraction can be used for extraction before determining aggregate fractured faces, fine aggregate sand equivalent, LA abrasion, and bulk specific gravity (except aggregates that undergo significant changes in ignition oven). For soundness testing and aggregate gradation, solvent extraction is preferred.

4.2. Binder content

Several parameters will impact the binder content in 100% RAP mixtures and optimization can be performed by changing them alone or together. For example, binder content can be increased by either of the following actions (lower content can be achieved by opposite steps):

- Choose source RAP with higher binder content.
- Increase fines content in the mixture, since they usually contain higher binder content (Khedaywi and White, 1995; Brock and Richmond, 2007).
- Choose less effective recycling agent. Organic products tend to be more effective at a select dose compared to petroleum products (Zaumanis et al. 2013, 2014b; Dony et al., 2013).

\[ \text{Fig. 7. 100% RAP mixture design.} \]
– Increase recycling agent dose. Care should be given to comply with the performance specification requirements, especially rutting.
– Add virgin binder.

### 4.3. Recycling agents

A successful use of recycling agents should reverse the RAP binder aging process, restore the properties of asphalt binder for another service period, and make the RAP binder effectively “available” to the mixture. It is necessary to carefully select the recycling agent to provide the necessary short and long term properties, as follows:

**Short term.** Recycling agents should allow the production of high RAP content mixture by rapidly diffusing into the RAP binder and mobilizing the aged asphalt in order to produce uniformly coated mixtures. Recycling agent should soften the binder in order to produce a workable mixture that can be easily paved and compacted to the required density without the hazard of producing harmful emissions. Major part of diffusion process should be completed before the traffic is allowed to avoid reduction of friction and increased susceptibility to rutting.

**Long term.** Recycling agents should reconstitute chemical and physical properties of the aged binder and maintain stability for another service period. The binder rheology has to be altered to reduce fatigue and low temperature cracking potential without over softening the binder to cause rutting problems. Sufficient adhesion and cohesion have to be provided in the mix to prevent moisture damage and raveling.

#### 4.3.1. Dose selection

The dose of recycling agents should be selected to meet the target grade of the aged RAP binder, resulting in improved cracking resistance without adversely affecting rutting resistance (Tran et al., 2012). Mixing of the recovered RAP binder with recycling agent to determine the rejuvenated binder grade is considered the best approach at this time for selection of appropriate recycling agent dose. Such method is used in majority of the research studies (West et al., 2013; Silva et al., 2012; Tran et al., 2012; Zaumanis et al., 2013). A report by NCAT (West et al., 2011) suggests using centrifuge extraction over other methods for recovery of the RAP binder from high RAP mixtures.

The research by Zaumanis et al. (2014b), Tran et al. (2012), Lei et al. (2014), and Ma et al. (2010) have all shown that the change in Superpave performance grade (both high and low) is almost linear at different doses of the same recycling agent. Research by Zaumanis et al. (2014b) and Dony et al. (2013) showed that penetration increases exponentially with higher recycling agent content and softening efficiency of organic products is generally much higher than that of petroleum recycling agents. The research by Asli et al. (2012) and Lin et al. (2011), however, showed linear penetration increase. The viscosity for any dose can be predicted using Refutas equation (Zaumanis et al., 2014a). Research by Zaumanis et al. (2014b) demonstrated with six different recycling agents that the dose calculated to reach the penetration of virgin binder also ensures conformity to the performance grade of the same binder. In this research, a method for rejuvenator dose optimization was developed to account for the RAP binder variability due to source and age of the material.

There are several drawbacks of determining recycling agent dose based on binder performance alone, as follows:

– The entire RAP binder is extracted and blended with recycling agent thus assuming full activation of RAP binder in the mixture.

However, it has been reported by multiple studies (Huang et al., 2005; Al-Qadi et al., 2007; Bennett and Dongre, 2010) that part of RAP binder stays inherent and does not actively contribute to mix properties (often referred to as “black rock”).

– Softening of binder to reach the desired viscosity, penetration or softening point can be achieved by various oils, but does not ensure binder rejuvenation.

– Many recycling agents will also allow aged binder to reach the desired performance grade (PG). While this provides better characterization of binder properties than viscosity alone, research by Burke and Hesp (2011) and Hesp and Shurvell (2010) has shown that conformity to PG did not prevent pavement premature excessive thermal cracking when WEO bottoms (residue) was used as recycling agent.

– Incompatible recycling agent or overdose can cause lack of binder cohesion and reduce adhesion with the aggregate thus leading to premature pavement deterioration, especially susceptibility to water damage.

For these reasons, determination of relevant mixture performance-related properties should be considered and is discussed in Section 4.4.

#### 4.3.2. Diffusion of recycling agents

Diffusion speed of the recycling agent into the hard RAP binder depends on binder and recycling agent properties and occurs most rapidly at elevated temperatures during mixing, storage, transportation, and compaction (Kuang et al., 2011; Zaumanis and Mallick, 2013; Karlsson and Isacsson, 2003). It can continue during the service life until equilibrium is reached (Huang et al., 2005; Tran et al., 2012; Carpenter and Wolosick, 1980). Part of the RAP binder in fact may not be activated and stays as “black rock” (Huang et al., 2005; Shirodkar et al., 2011; Zaumanis and Mallick, 2014). Karlsson and Isacsson (2003) argued that the diffusion rate is governed by the viscosity of the meltane phase instead of the entire recycled binder. The recycling agent diffusion process in RAP binder film is illustrated in Fig. 8 as described by Carpenter and Wolosick (1980):

– The modifier forms a very low-viscosity layer that surrounds the aggregate, which is coated with a very high viscosity aged asphalt cement. Due to weathering the outer micro-layer of RAP binder is typically harder compared to the inner layers (Carpenter and Wolosick, 1980; Nureldin and Wood, 1987).

– The modifier starts to penetrate into the aged binder, decreasing the amount of raw modifier on the binder.

– The penetration continues and the viscosity of the inner layer is lowered and gradually the viscosity of the outer layer is increased.

– Equilibrium is approached over the majority of the aged binder film.

The recycling agent diffusion can significantly affect performance of the asphalt mixture as follows:

– In mix design assumption of full binder activation while the binder is actually behaving as partial “black rock”, the mixture will be soft and under asphalted (Al-Qadi et al., 2007; Shirodkar et al., 2011), which can lead to cracking and raveling failures of the pavement.

– Alternatively, assumption of “black rock” situation when the RAP binder actually contributes to the mixture performance will lead to soft mixture because of high bitumen content (Howard et al., 2009; Al-Qadi et al., 2007). This can cause plastic deformations of the pavement.

– If traffic is allowed on pavement where recycling agent diffusion is not complete, its concentration in the outer layer of binder film
4.3.3. Other

Bailey – stability with venating content – including aromatic precipitation asphaltenes in oils, and applications.

Increase of petroleum products has been most widely reported for rejuvenation. “Reclamite” has been reported as a recycling agent that provides good performance in multiple sites (Mallick et al., 2010; Boyer, 2000) and it has been used for more than 50 years (Brownridge, 2010). “Cyclogen” has been used for production of 100% RAP pavements in Arizona (Jimenez and Meier, 1986) and research by Tran et al. (2012) has shown that this product can be used for improving the low temperature cracking resistance of RAP binder to a level of virgin binder. The fatigue resistance of 50% RAP binder mixture plus 12% of recycling agent, measured with the LAS test described by Hintz et al. (2011), was also improved but not to the level of virgin binder.

Different types of organic oils have also been tested as recycling. Bailey et al. has performed laboratory and field trials of vegetable oils (both virgin and waste) as recycling agents (Bailey and Zoorob, 2012b; Artamendi et al., 2011) and concluded that the use of such oils can reduce the viscosity to reach the target grade, ensure

![Fig. 8. Recycling agent diffusion into binder film and binder layer viscosities.](image)

![Fig. 9. Binder chemical composition at different states (Brownridge, 2010).](image)
similar rheology to virgin binder as measured with DSR, reduce the mixture stiffness to a level of virgin sample and improve the resistance to aging compared to virgin binder by 20%. The mixture workability, however, was not affected with the addition of these oils. Gordon et al. (2009) concluded that recycled cooking oil is a good candidate for improving the low-temperature grade. Zaumanis et al. (2013) showed based on low temperature mixture tests and binder softening efficiency that organic blend, refined tallow, and distilled tall oil are efficient in improving RAP cracking resistance. In a later study (Zaumanis et al., 2014a) the authors concluded that waste vegetable products, “Hydrogreen”, distilled tall oil and petroleum product aromatic extract are likely to improve the overall performance of 100% RAP mix. All tested products were able to reduce the binder penetration to level of virgin binder and passed the mixture rut resistance requirement at the selected dose of 12%. Waste vegetable products provided the most reduction in mixture stiffness, likely because of most binder softening at the tested dose. Dony et al. (2013) similarly concluded that vegetable oil and aromatic oil can be successfully used to soften the binder to the required consistency grade (penetration, softening point). The authors also concluded that binder that was modified with vegetable oil exhibited the highest hardening during short term aging (RTFO). This was explained by slow oxidation of fatty acid unsaturations present in the vegetable oil (siccative phenomenon).

4.4. Mixture volumetric and performance-related tests

Ensuring the required voids in mineral aggregate (VMA) is the most important volumetric parameter to ensure mix durability (West et al., 2013). Calculation of VMA requires the use of Gsb (bulk specific gravity) of the RAP aggregates and NCHRP Report 752 (West et al., 2013) results show that even a small error caused by the RAP extraction or burning process could cause the VMA to be off by ±0.4% at a 50% RAP content. This error would magnify at 100% recycling.

Because of the possible uncertainty in calculation of volumetric properties and the small experience of high RAP and recycling agent use, performance related tests are recommended to further assess the mix design. The tests should be chosen based on the climatic conditions, anticipated failure modes as well as the experience, confidence and availability of criteria on the use of specific methods. A summary of most advanced performance-related test methods and pass/fail criteria (for select tests) for high RAP mixes is available in NCHRP Report 752 (West et al., 2013). Before testing of performance-related properties, it is important to provide enough time for diffusion of the recycling agent, since that might significantly affect the test results. If failures that typically occur later in pavement life need to be evaluated (e.g. cracking), long term laboratory aging is also necessary (McDaniel et al., 2000).

To obtain dry RAP without further aging the material, it can be placed in an oven at 110 ℃ for up to 6 h (West et al., 2013). Alternatively fan can be used for drying at room temperature. Before mixing samples, the RAP should be pre-heated at the design temperature between 1.5 and 3 h in order to ensure homogeneous temperature while having the least effect on the properties of RAP binder (West et al., 2013).

5. Best practices for RAP management

Vertical integration of the materials RAP supply chain, including the milling, processing, storage, and quality control operations, would greatly benefit the quality of final product. The best practices of RAP management are discussed below.

5.1. RAP milling and processing

Asphalt pavement can be milled in partial or full depth. Road constructions where the different layers have aggregates or binder of various quality or grade should be removed by partial milling, in order to later allow the use of RAP in higher value layers (Arnold et al., 2012; Kerkhof, 2012). Choice of the milling apparatus, depth and speed will all influence the quality of RAP (Kerkhof, 2012). Special attention should be given to minimize fines content. For example, slow forward speed or fast drum rotation will generate more undesirable fines. “SmartPave System” designers indicate that generally the RAP milled with upward cut milling heads stay within 10% of original gradation (RAP Process Machinery, 2013).

In most cases, production of 100% RAP mixture will require processing of RAP in order to provide several fractions. Screening of the material provides flexibility to the mix designer for ensuring the necessary particle size distribution and give control over the binder and fines content (Hansen and Copeland, 2013; Al-Qadi et al., 2012; West et al., 2013; Brock and Richmond, 2007). Crushing, however, should be avoided in order to reduce generation of excessive fines content that is usually already present from milling operation (West, 2011). Too high fines content can significantly restrict the RAP mixture design by not meeting the mixture aggregate size distribution requirements, dust to binder ratio, air voids, and VMA (Newcomb et al., 2007; McDaniel et al., 2002; Copeland, 2011).

5.2. Storage of RAP

RAP stockpiles should be treated just like any virgin aggregate stockpiles to avoid contamination and separation of different materials (Brock and Richmond, 2007). The startup waste should not be mixed together with RAP material (Brock and Richmond, 2007). If RAP from different sources is stored in the same stockpile it can be blended to increase homogeneity before processing or feeding into the cold feeder (West, 2011).

Moisture content in RAP is an important factor that can limit the maximum RAP content. It will cause higher drying and heating costs, reduce the plant production rate (E-MAK, 2013), and increase emissions by 10% for every 1% moisture increase (Prowell et al., 2012). Moisture content can be reduced by the following actions, in the order of most to least effective (Zaumanis and Mallick, 2014; Zhou et al., 2010):

- Covered stockpiles under a roof.
- Use of paved, sloped storage area.
- Use of tall conical stockpiles.
- Crushing and screening of RAP in small portions at the day of use (West et al., 2013; Brock and Richmond, 2007).

5.3. RAP quality control and variability analysis

The studies in 1980s and 1990s have concluded that RAP exhibits variability in composition (Kallas, 1984; Solaimanian and Tahmoressi, 1996). However, recent findings show that consistency of RAP from a single project (and with adequate handling from multiple projects) is mostly uniform even without fractionation and RAP is generally more consistent than virgin aggregates (West, 2008; Estakhri et al., 1999).

RAP should be well characterized for mix design and quality control purposes. The material should be sampled from multiple locations around RAP stockpile by using back-dragging technique to determine its properties and variability (West et al., 2013). While for small contents of RAP it may be enough to determine the binder content and aggregate gradation, for high RAP content mixtures the required aggregate and binder properties should be determined as well (Newcomb et al., 2007).
6. Environmental analysis

Most life cycle studies clearly indicate that use of high content RAP reduce the emissions and energy use (Lee et al., 2012; Aurangzeb et al., 2014). For hot mix pavements, the main two major processes that are responsible for GHG emissions and energy use are binder and asphalt production (Chappat and Bilal, 2003; Huang et al., 2009). RAP use reduces the binder consumption and thus proportionally decreases the environmental effect. For example, the European Commission sponsored project Re-Road (Waymen et al., 2012) and Vidal et al. (2013) demonstrated that even at a relatively low RAP rate of 15% the environmental benefits from recycling are higher than those achieved by application of WMA technologies resulting in temperature decrease of 30–35 °C compared to HMA.

A comprehensive view of 100% RAP pavement is necessary to cover the environmental effects during entire life cycle of asphalt, including production of constituent materials, asphalt production phase, construction, maintenance and end of life solutions. Pavement durability is the largest unknown in such estimations and can have a large impact on the conclusions of life cycle effects compared to conventional pavement (Aurangzeb et al., 2014). Research by Waymen et al. (2012) suggests that reduction of durability of pavement from 20 to 14 years would increase the global warming potential by 13%. Lee et al. (2012) concludes that at 30% RAP rate the pavement service life has to be 80–90% from that of virgin mix to ensure environmental benefits. Unfortunately, the existing state of practice for 100% recycling does not allow for conclusive evidence on the long-term performance of such pavements. Thus the analysis is currently limited to unit inventory or cradle-to-gate analysis, which at the same time is the most reliable part of any life cycle calculation.

According to “Re-Road” project (Waymen et al., 2012) and the practical experience reported by 100% RAP mixture producers, the energy use at asphalt production and paving operations can be assumed independent of recycled asphalt content rate. The developers of the different technologies also claim that emissions are similar to traditional asphalt plants (RAP Technologies, 2013; RAP Process Machinery, 2013; Volker Wessels, 2013). Therefore the energy use and emissions from different processes that are summarized in Table 5 were considered applicable to both virgin and 100% RAP mixtures. Milling of old pavement was not considered as part of process since it is an integral part of reconstruction and would be done irrespective of the type of mixture paved. A mixture containing 25% sand, 70% crushed stone and 5% bitumen was used in the calculations as a representation of a typical virgin mix. 100% RAP mixture is considered having 12% recycling agent added from binder mass. It is also assumed that 100% RAP mix does not require any virgin binder addition. In practice this is often the case, since any lost binder is replaced by the addition of recycling agent.

The emission data from Table 5 was used to estimate the cradle-to-gate emissions and energy use of virgin mix versus 100% RAP mixture, including raw material production, RAP processing, asphalt production, hauling and paving. For simplicity, the transport distance was considered equal and consists of 50 km distance from quarry/RAP site to asphalt plant plus 50 km asphalt plant to paving site. The only variables in the process are energy use for production of constituent materials. The calculation results in Fig. 10 demonstrate that 18 kg of CO2 equivalent and 20% energy per t of paved mixture can be saved by producing asphalt from 100% reclaimed material.

7. Economic analysis

The cost of binder has tripled during the last decade as illustrated in Fig. 11. The RAP price compared to that is very low ranging from USD 15 to USD 30 (Howard et al., 2009) and in urban areas the RAP can often be obtained free of charge due to excess of the material. Hence major savings can be realized through replacement of virgin by the RAP binder. These savings must be quantified to account for additional expenses related to RAP processing, testing, and use of recycling agent. Switching to 100% recycling would also require significant investments for modification of production technology that must be put into the equation.
7.1. Cost analysis

A simple calculation was performed to assess the materials related costs for production of mixtures with increased RAP content. The assumptions for costs that were used for calculation are listed in Table 6 and include 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. For example, large metropolitan areas often have surplus of RAP from city streets and the contractors will often pay for disposing it, thus the “RAP disposal” position in Table 6. Rural areas, on the other hand may have shortage of RAP and asphalt producers will need to purchase it. Testing is another additional expense. According to guidelines from NCHRP Report 735 (West et al., 2013) RAP binder content and gradation should be tested once per 900t and specific gravity once per 2700t. Mixture performance-related test frequency was assumed equal to RAP binder performance grading (once per 4500t). The testing expenses, including rutting, low temperature and top down cracking, from commercial testing facility were obtained and the calculation based on the proposed frequencies shows 1.48 USD expenses per t of produced asphalt. 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. Aggregate content of 94.3% and binder content of 5.7% (RAP binder 5.1% + recycling agent 0.6%) was used for calculations.

Fig. 12 summarizes the calculation results of material related costs per t of produced asphalt ranging from 0% to 100% RAP content. Depending on the market situation with availability of RAP, the costs of per t of 100% RAP mixture would be reduced between 32 and 48 USD or 50 and 70% compared to virgin mix. Clearly, the major part of the costs comes from binder expenses and as the cost of oil continues to rise, the benefit of using high RAP mixtures will only increase.

These calculation results are consistent with the estimates of 100% RAP producers:

- Ammann demonstrates more than 40% savings in material related expenses for 100% RAP mixture production compared to 0% RAP mixture (Ammann, 2013).
- L. Otero, a representative from “BAB Belag”, who owns Ammann 100% RAP capable plant in Switzerland, indicates savings of approximately USD 11 for every 10% increase in RAP content.
- Smart PAVE system (RAP Process Machinery, 2013) claims 30% or higher savings in production related costs compared to HMA produced with primarily virgin aggregates.

7.2. Break even time

Switching to production of 100% RAP mixture would require investment in plant technology, such as asphalt production
related equipment, RAP processing units, and possible RAP storage upgrade. These expenses will vary greatly depending on the chosen technology and readily available equipment.

Three assumptions have to be made to perform a simple calculation on time to break even:

- The investment amount.
- Production rate.
- Profit margin per t of mix.

The average annual production rate of a plant located in the US in 2011 was 95,000 t (EAPA, 2012). Reaching country average might be a high target for a new technology and therefore a calculation at 30,000 t per year rate was performed as well. Three different investment levels (1, 2, and 5 million USD) and profit margins ranging from USD 0 to 40 per t of mix were used for calculation of time to break even and the results are illustrated in Fig. 13. The profit per t of mix will likely not be directly related to the savings calculated earlier; at least until proved that the quality and longevity of 100% RAP pavement is equal to that of conventional asphalt. However, even a reduction of asphalt price by as much as USD 20 compared to low RAP mix would still promise the contractor at least USD 12 profit per t of produced mixture (see Fig. 12). At such margin, for example, time to reach break-even point would be less than three years for 1 million USD investment and 30,000 t/year production rate.

8. Summary and discussion

In recent years the industry focus has been placed on increasing the amount of RAP in mix asphalt production. This is a result of tripled binder costs during the last decade that came 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 recycling. This article demonstrates the availability of the necessary tools and know-how for production of such mixtures. Switching to 100% RAP production would enable material related cost savings of 50–70% compared to virgin mixture. Thus price reduction of as much as USD 20 per t of asphalt would still provide the contractor a profit of at least USD 12 per t of processed asphalt. Such margin, for example, would allow the contractor to break even in just one year at the US average yearly production rate of 90,000 t and initial investment in plant technology of 1 million USD. The material related expenses would be stabilized at constant level by removing the dependence on the increasing binder price.

Eleven plant technologies readily available for 100% hot mix recycling were identified and five of them are described in detail as well as demonstrated in the complementary video (http://youtu.be/coj-e5mhHEQ). These technologies allow production of mixture at the conventional production temperatures and paving can be performed using existing equipment and techniques. Modification is required to the existing asphalt plants. Ten of the technologies require installation of a new drying/heating system and one is designed to retrofit existing drum plants with a different filtration system. Both drum and batch production systems have been used to produce 100% RAP mixtures.

The conventional mix design methodology will have to be modified for designing 100% RAP mixtures, most notably in respect to binder content and use of recycling agents. The binder has to be extracted from RAP to verify its properties and determine the necessary recycling agent type and dose to ensure correspondence to the specification requirements. The binder content can be modified by switching between RAP sources, using recycling agents of different efficiency, modifying the RAP fines content, or adding virgin binder. The designed mixture should be tested for conventional volumetric properties and performance-related specification requirements may be added. Care should be given to allow finalization of recycling agent diffusion before performing testing to avoid false results. Advances in performance related test methods, especially cracking tests, will greatly benefit the confidence in use of 100% RAP mixtures and allow performance-based specification.

An important challenge for production of 100% recycled mixture is ensuring high quality input material. The specification criteria for RAP aggregates should be equal to virgin materials. 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, including aggregate gradation and specific gravity as well as binder content and properties.

The literature survey confirmed the general wisdom that the stiffness of high RAP mixtures is higher than for virgin. While typically undesirable, this might be beneficial for structural design purposes of specialty applications, including perpetual pavements and high modulus asphalt concrete (HMAC). For production of conventional asphalt the stiffness has to be reduced to avoid fatigue and thermal cracking. Various recycling agents have shown to be able to modify the aged binder to a level that corresponds to the required Superpave or empirical binder grade, but the workability in most cases remained lower than that of virgin binder. Both petroleum and organic products have been successfully used. Laboratory research studies of 100% RAP mixtures have shown that appropriate choice of recycling agent type and dose can reduce the stiffness of aged RAP mixture to the level of virgin mixture while providing high rutting resistance. Most of the reluctance for the use of recycling agents stems from isolated unsuccessful projects in 1970s and 1980s which showed rutting and raveling problems. These failures have been associated with the recycling agent diffusion and effect on adhesion, but are equality likely caused by immature production technology and use of unprocessed RAP. The newly developed production technologies, adequate RAP management, improved mix design in conjunction with modern performance-related testing methods are likely to neglect such problems. However, the durability performance of 100% RAP pavements remains the major question. This asks for further research to evaluate the performance in laboratory and most importantly in full scale demonstration projects. Successful cases should allow for legislation of such mixtures by road shareholders for paving on public roads. Until then the application is limited mainly to lower level roads and privately owned construction sites where the asphalt costs are driving demand.

100% recycling can provide true sustainability by closing the materials cycle and allowing to use the reclaimed asphalt in the same high value application as conventional asphalt. A reduction in emissions of 18 kg CO2eq per t of paved mixture can be achieved by switching to 100% RAP asphalt, mostly due to embedded energy necessary for production of constituent materials. Such reduction in environmental effect and implementation of innovative production process would greatly benefit the agencies that have applied certification systems for sustainable construction practices (LEED, Greenroads, etc.).
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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconec loop.2014.07.007.

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