100 % Recycled Hot Mix Asphalt and the Use of Rejuvenators

Martins Zaumanis
Worcester Polytechnic Institute

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100 % RECYCLED HOT MIX ASPHALT AND THE USE OF REJUVENATORS

by

Martins Zaumanis

A Dissertation

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of the

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APPROVED:

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Dr. Juris Smirnovs

Dr. Tahar El-Korchi
To my parents Zita Zaumane and Tālis Zaumanis
It ain’t what you don’t know that gets you into trouble.

It’s what you know for sure that just ain’t so.

-Mark Twain
1. ABSTRACT

The desire to find more sustainable paving practices as well as the dramatically rising binder costs driven by the growing global demand for paved roads, has led to increased interest of the use of reclaimed asphalt pavement (RAP) in very high amounts. So far the major industry trend has been to develop procedures, invest in technologies and build confidence in mixtures with up to 40 % RAP content. However, a few innovators have refined 100 % recycling technologies over the past four decades to a level where routine production of 100 % recycled hot mix asphalt is in clear sight. Rejuvenators are an integral part of 100 % recycled asphalt production and they can also allow to significantly increase the RAP content for conventionally produced asphalt mixtures. An evaluation of the feasibility of production of 100 % recycled hot-mix asphalt was made and the use of rejuvenators is presented in this study. 100 % recycling is discussed by evaluating ten readily available production technologies along with proposing mix design procedures and identifying best RAP management strategies. A total of eleven different products were evaluated for restoring the RAP binder grade with a definite conclusion that achieving target grade (PG or empirical specification) is possible. In addition a rheological, micromechanical and chemical characterization was performed with select rejuvenators and binders from Strategic Highway Research Program (SHRP) library. To further assess the rejuvenators and feasibility of 100 % RAP recycling a series of 100 % mixture tests were performed that indicated significant improvement in low temperature and fatigue cracking resistance while providing a rut resistant mixture. With the use of some rejuvenators a performance equal to that of reference virgin mix was achieved. Based on these findings of rejuvenator effectiveness a methodology for choice of rejuvenator type and dose was proposed. Finally, a cradle-to-gate analysis of environmental effects was performed which indicated 35 % CO₂eq savings per ton of produced 100 % RAP asphalt mixture compared to virgin mix while cost analysis showed at least 50 % savings in material related expenses. A short video summarizing the research is available at http://youtu.be/y-rYvdGiEbY.
I am grateful to Fulbright program and Baltic-American Freedom Foundation which provided me with the chance to study in the United States.

I thank my advisor Prof. Rajib B. Mallick for providing me the opportunity to study at Worcester Polytechnic Institute. He encouraged to execute any of my ideas, guided through the research, and ensured the required funding for the study and attending conferences. I am grateful for the time I got to spend with and learn from him.

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None of the research would have be possible without D. Pellegrino who kept the machines running at WPI as well as A. Lajoie, M. Horanzy, and R. Lang who kept everything else running. The great amount of testing was possible only because of the help and great work ethics from my fellow students in the laboratory, including R. Pinkham, X. Yu, R. Worsman, G. Howard, R. Kennedy, J. Pearsall, M. Samaroo, S. Cote, N. Rice, A. Capiro, and M. Latt. During the research at EMPA, Switzerland I also got very generous help from S. Kutzel, S. dos Santos, H. Kienast, C. Meierhofer, M. Hugener, A. Treuholz, and M. Bueno.

Finally, I would like to thank for the support of my girlfriend Liga Patmalniece who has always reinforced my quest for knowledge and has been together with me all of these years. I am also grateful to my family and friends who have been ready spend their time chatting with me, day or night.
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7. GLOSSARY

AASHTO – American Association of State Highway and Transportation Officials
AAD – Binder from SHRP materials library [1]
ABD – Binder from SHRP materials library [1]
AFM – Atomic Force Microscopy
ASTM – American Society for Testing and Materials
BBR – Bending Beam Rheometer
BSG – Bulk Specific Gravity
BTDC – Bitumen Test Data Chart
CAST - Coaxial Shear Test
CEDR - Conference of European Directors of Roads
Consistency – refers to general binder viscosity without specifying the test method or temperature
DMT - Derjaguin, Muller, and Toporov contact mechanics approach [2]
DOT - Department of Transportation
DSR – Dynamic Share Rheometer
EAPA – European Asphalt Pavement Association
EMPA – Swiss Federal Laboratories for Materials Science and Technology
ESAL – Equivalent Single Axle Load
FE – Finite Element
FHWA – Federal Highway Administration
FT – Fischer Tropsch
FWD – Fracture Work Density
GHG – Greenhouse Gas
HMA – Hot Mix Asphalt
HMAC – High Modulus Asphalt Concrete
IDT – Indirect Tensile Test
ITSR – Indirect Tensile Strength Ratio
LAS – Linear Amplitude Sweep
LEED – Leadership in Energy and Environmental Design
LM-LC – Laboratory-Mixed, Laboratory-Compacted
LTPP – Long Term Pavement Performance program
MIST – Moisture Induced Stress Test
NCAT – National Center for Asphalt Technology
NCHRP – National Cooperative Highway Research Program
NMAS – Nominal Maximum Aggregate Size
PAV – Pressure Aging Vessel
PG – Performance Grade
PI – Penetration Index
PM-LC – Plant-Mixed, Laboratory-Compacted
PVN – Penetration Viscosity Number
QNM - Quantitative Nanomechanical Mapping mode for AFM
RTFO – Rolling Thin Film Oven
SARA – Saturates, Aromatics, Resins, Asphaltenes
SHRP – Strategic Highway Research Program
t_{crit} – mixture critical cracking temperature as calculated using LTSTRESS
USD - United States Dollar
VECD – Viscoelastic Continuum Damage
VFA – Voids Filled with Asphalt
VMA – Voids in Mineral Aggregates
WEO – Waste Engine Oil
WMA – Warm Mix Asphalt
WTT – Wheel Tracking Test
WV – Waste Vegetable
1. INTRODUCTION

Although Hot Mix Asphalt (HMA) is a 100 % recyclable material, and as of 2011, more than 40 state agencies in the US allows the use of more than 30 % Reclaimed Asphalt Pavement (RAP) in mix design [3]; currently the average RAP use is only about 20 % [4]. According to mix Superpave design specification by AASHTO M 323, when more that 15 % RAP is used in mix design, it is required to reduce the binder Performance Grade (PG) by one level to compensate for the aged RAP binder. When adding more than 25 % RAP, the virgin binder grade has to be determined based on the properties of extracted RAP binder. Such requirements are set to ensure that the virgin binder compensates for the stiff aged RAP binder in order to avoid cracking failures. Unfortunately, these requirements also create additional expenses for contractors for purchasing unconventional binder grade, installing additional hot storage tank, maintaining laboratory with extraction and testing equipment or outsourcing of testing. In many cases, this discourages the contractors to produce very high content RAP mixtures, both because of the inconvenience and the unclear economic benefits. The increased expenses often outweigh the savings from the relatively small increase of RAP content.

The use of rejuvenators (products that are aimed at restoring the required binder properties) are a relatively unexplored alternative due to concerns associated with their ability to diffuse in the binder film and provide the required long term performance and stability. However, the potential advantages (as listed below) over bumping the virgin binder grade are significant and warrant further research of rejuvenator use for producing high RAP mixtures:

- Unrestricted RAP content using a single rejuvenator.
- Cheap storage, since in most cases rejuvenators do not require heating.
- Simple addition to the mixture using volumetric pump or existing liquid additive dosing system.
- Ability to add the precise required dose based on the RAP binder properties.

The main advantage, arguably, is the ability to increase the RAP content beyond what would be possible by bumping down the virgin binder grade. In fact, production of 100 % recycled hot mix asphalt becomes a reality. If such mixtures provide similar performance to conventional pavements, they can potentially be very economically attractive and help in significant reduction of the environmental effect of road construction by closing the materials cycle and fully re-using the valuable RAP constituent materials in high quality applications.
If RAP aggregates are of the necessary quality, the feasibility of 100 % RAP mixture production largely depends on the ability to rejuvenate the aged RAP binder so that it can deliver the required pavement performance for another service period. The properties of RAP binder depend on the composition of the original binder and amount of aging during the service. Untreated, it is expected to be much stiffer and less elastic compared to unaged binder and would cause premature pavement cracking. A successful use of rejuvenators can potentially reverse the RAP binder aging process by introducing low viscosity maltene constituents and provide long term pavement cracking resistance without deteriorating the rutting resistance. In order to make the aged binder effectively "available" for blending with virgin materials and reduce the chance of rutting early in pavement life, rejuvenators are also required to rapidly diffuse into the RAP binder. Due to relatively little research on the use of rejuvenators the choice of an adequate dose of suitable product to ensure the expected binder and mixture performance provides a significant challenge. For these reasons, besides investigating 100 % recycling, research on the use of rejuvenators is emphasized in this doctorate research. The presented results of rejuvenator performance, especially concerning binder rejuvenation, in most cases can be attributed to recycling of conventional RAP containing mixtures of any recycling rate.

The rejuvenation definition itself causes some confusion in the industry and there are multiple terms used for describing the products that are used for this purpose, including "rejuvenator", "recycling agent", "recycling additive", "softening agent", etc. Due to unclear methods to categorize a specific product in one of these groups, a single term "rejuvenator" will be used in this study.

1.1. OBJECTIVES

The objectives of this study were defined:

1) Investigate the potential for practical production of 100 % recycled hot-mix asphalt and develop guidelines for design and production of such mixtures.
2) Evaluate multiple products for use as rejuvenators by determining their effect on binder and mixture properties.
3) Develop relationships between binder and mixture performance to simplify screening of rejuvenators.
4) Develop a simple method for choice of rejuvenator type and dose.
2. LITERATURE AND PRODUCTION TECHNOLOGY REVIEW

There is certain inertia in the road industry in regards towards accepting new technologies. In some respect such conservative approach is justifiable considering the complexity and time required for assessing road construction innovations. However, the current economic and environmental situation and continuously degrading infrastructure requires immediate action to provide the next generations the chance to have a well-developed infrastructure while living in a healthy environment.

A holistic evaluation of the feasibility of producing 100 % recycled mixtures is presented in this section. Ten technologies readily available for producing 100 % RAP hot asphalt mixtures are described here and in a supporting Video 2-1 [5]. The performance of 100 % RAP mixtures is analyzed along with identification of typical high RAP distresses. Recommended mix design procedures and best RAP management strategies are also discussed.

2.1. 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 HMA/WMA applications, while the rest (53 % or 22 million tonnes) were used in other applications or stockpiled [6]. In the US, a survey by National Asphalt Pavement Association (NAPA) [4] 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 volumes of surplus of RAP. An estimation by the 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 2-1).
Table 2-1. 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>

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. In developed countries, road maintenance overwhelm new construction creating great amounts of readily available material that can potentially be totally re-used for resurfacing of the same road pavements.

2.2. 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 [7] and a typical RAP range of batch plants is 10 to 20 % [8]. Producing mixtures of higher RAP content using conventional plants would require an unrealistically high superheating temperature of virgin aggregates, cause 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. Five of the owners/producers answered to the survey and two of the plant locations were visited. Basic information about the plants is reported in Table 2-2 and general overview of the main principles of each technology is summarized below the table as well as illustrated in the Video 2-1. The reported information was provided by representatives of the companies, and gathered from research reports, publications, and producers’ websites. All producers pointed out that conventional techniques and equipment can be used for placement and compaction. None of them revealed any serious issues with mixture workability or performance.
Table 2-2. 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</th>
<th>Rapmaster™</th>
<th>RA Tech</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 AG</td>
<td>BAB Belag AG</td>
<td>Pavement Recycling Systems &amp; Alex Sin Manufacturing</td>
<td>Evergreen Sustainable Pavements</td>
<td>Plant not visited</td>
</tr>
<tr>
<td>Plant Location</td>
<td>Long Island City, New York City, US</td>
<td>Birmenstor, canton Aargau, Switzerland</td>
<td>Riverside, California, US</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</td>
<td>Batch plant</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>Indirect rotary tube dryer</td>
<td>Separate heat generator with indirect heat triangular drier</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>180 t/h</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 tons</td>
<td>1000 tons</td>
<td>4500 tons</td>
<td>100,000 tons</td>
<td>n/a</td>
</tr>
<tr>
<td>Asphalt layers produced</td>
<td>Base, binder, wearing and specialty mixes</td>
<td>Base and binder coarse</td>
<td>n/a</td>
<td>Wearing, base, binder</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>
Video 2-1. 100 % Recycling of Hot Mix Asphalt (click to play or access at http://youtu.be/coj-e5mhHEQ)

The technologies that are suitable for 100 % recycling, but 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 [17].
- "Bagela" recycler is an ultra-portable (towable) drum with up to 10 t/hour production capacity. Flame in a separate combustion chamber heats RAP mainly through the hot wall of mixing drum [18].
- "Benninghoven" has developed a uniflow large volume drum with a burner that precludes direct contact between the flame and recycled material [19].
- "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 [20].
- "HyRAP" is a direct heating system that uses a parallel flow drum with four point material entry collars for different fractions of RAP [21].
"Cyclean" is a microwave heating technology that was utilized at the end of 1980’s and beginning of 1990’s. Due to the high energy requirements of microwaves and thermal oxidizer compared to conventional systems the process has only seen limited use [22, 23].

### 2.2.1. All-RAP Plant

RAP Technologies, LLC [9] process uses conventional hot mix asphalt plant components and a special blue smoke filtration system [10] (Figure 2-1). Since first producing mix in 2001-2004 demonstration project with NYC DOT, the All RAP process has been licensed to Green Asphalt, Long Island City, NY and produces 100,000 tons of 100 % RAP mixes annually for private paving contractors.

![Emissions Control Unit](Figure 2-1. 100 % All RAP Process Plant in New York City)

**Plant technology**

Separate cold feed bins for fine and coarse RAP fractions volumetrically meter design blends onto incline conveyors 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.

Rejuvenator is sprayed on the hot RAP at the dryer discharge chute as demonstrated in Figure 2-2. It mechanically mixes with the RAP binder during transportation by drag slat conveyor. The diffusion continues during storage, transportation, and laying of the asphalt.
A critical element of the All RAP process is pollution control. 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 into the atmosphere. RAP Technologies employ a multiple stage filtration system (Figure 2-1) to comply with local air quality rules as follows (the recorded emissions are summarized in Table 2-3):

- Inertial separator drops out small quantity of coarse fines that are then manually removed a few times per year.
- Disposable 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.

Figure 2-2. Addition of Rejuvenator at All-RAP Plant
Table 2-3. Emissions of NYC Plant [9]

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>0.02 Grains/SFC</td>
</tr>
<tr>
<td>CO</td>
<td>0.2 lb/ton</td>
</tr>
<tr>
<td>VOC</td>
<td>0.14 lb/ton</td>
</tr>
<tr>
<td>NOx</td>
<td>0.08 lb/ton</td>
</tr>
<tr>
<td>SO2</td>
<td>0.06 lb/ton</td>
</tr>
</tbody>
</table>

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 NMAS Superpave mixes. Oversize clumps of pavement are crushed to liberate sand from stone in a manner that avoids generation of excess 70 micron 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.

Optimum binder content is ensured by varying the proportions of aggregates and rejuvenator type and dose. The fine RAP fractions have higher binder content and therefore changing the dose of 6.4 mm fraction affects the total binder content. The rejuvenator dose is chosen based on extracted binder penetration test results. Switching between different rejuvenators allows changing the binder content, since the optimum dose can vary by a factor of two to provide the same softening.

100% RAP is used to pave utility trenches, commercial parking lots, and industrial areas. A study that evaluated one site is reported in Section 2.3.2. In 2013, a demonstration project of 100% RAP along with conventional asphalt was paved by New York City DOT at Jewel Avenue & 147th Street in Kew Garden Hills, Queens [24]. 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.

2.2.2. Ammann RAH 100 Plant

The Ammann "RAH 100" plant is located in the following sites in Switzerland: Birmensdorf (BHZ/BAB), Rubigen (Berag), Oberwil (Walo), Walliswil (Martl), Sigirino (Comibit), Untervaz (Catram). The location in Birmensdor, operated by BAB Belag AG, was visited and therefore commented in detail. The indirect heating system "RAH 100" is paired with the Ammann "Uniglobe 200" plant at the site.
**Plant technology**

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 Figure 2-3. 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 Figure 2-4. 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.

*Figure 2-3. BAB Belag AG RAH 100 Recycling Plant by Ammann*
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 [11]. After discharge gravity drives the material into a hot storage silo which has a capacity of 28 t. The RAP is further released to the weight hopper and asphalt pugmill of 3 t capacity. The rejuvenator and virgin binder, if any, is added in the pugmill and mixed together with RAP for 30 to 40 seconds.

Current Operation, RAP Processing, and Mix Design

RAP is crushed and screened to Nominal Maximum Aggregate Size (NMAS) of 22 mm. On average, the material has around 10 % fines and binder penetration of 30-40 dmm. Rejuvenator can be added to the heated RAP in the asphalt pugmill. However, the plant currently operates without addition of any rejuvenator.

RAP is mainly used for less-than 100 % RAP mixtures and its quality is tested at a frequency:

- Every 1000 t for binder content and aggregate particle size distribution.
- Every 2000 t for softening point and penetration of extracted binder.
- Every 4000 t for aggregate shape and flakiness index, and poliaromatic compounds content.

2.2.3. 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 [13]. Seven burners are located in a heating chamber and perpendicularly heat rotating drum dryer shell from exterior as demonstrated in Figure 2-5. 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 310 stainless steel. Hot combustion gases flow through the heating chamber and enter the drum at 680 °C to move in a 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 to 540 °C. The burners operate between 650 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 3.8 to 5.7 liters per ton 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.

A virgin binder or rejuvenator can be added at the mixing zone at the end of the drum though a pipe that penetrates the rear wall.

Figure 2-5. Alex-Sin Plant Drying Unit (a) and Cross Section (b) of the Heating Unit (the Internal Plates Have Been Replaced with "J" Flights) [13]

2.2.4. Rapmaster™ Plant

In the Rapmaster™ processor [25] 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 (Figure 2-6). 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 rejuvenator and, if necessary, virgin binder. The asphalt from pugmill is transported by a drag slat conveyor to heated silos.

![Figure 2-6. Rapmaster™ Drying Unit Overview (a) and Heating Principle (b)](image)

Emissions of 0.02 lb/t NOx, 0.006 lb/t CO, and 0.00005 lb/ton particulates have been recorded in a report by Engineering Technologies Group, Inc. [26]. The report notes that these emissions comply with the local requirements in Springfield, MA and the plant holds and active air permit.

**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" rejuvenator 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.

**2.2.5. RATech Plant**

E-MAK has designed a RAP heating unit named "RATech" that can be integrated in existing asphalt plant to provide partial or total recycling. It uses indirect heating from a separate hot air
generator to heat RAP in an originally designed triangle profile drier. Reports on the technology from 5th Euroasphalt & Eurobitumen congress [15] and the producers website [16] are summarized.

**Plant technology**

RAP is fed into triangular recycling drier [27] using vertical elevator where it is indirectly heated by hot air of 200-400 °C and directly exposed to 120-200 °C as illustrated in Figure 2-7. 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 second 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.

![Figure 2-7. RATech Triangle Drier](image)

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 (Figure 2-8). The released hot air from the burner is mixed with controlled amount of cold air and fed into circulation channels of triangle drier 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.
Chapter 2

Current operation, RAP Processing and Mix Design

The RATech plant can be combined with conventional asphalt for production of lower-than 100 % RAP mixtures. In this case the RAP, virgin aggregates and asphalt binder are mixed together at conventional pugmill. Such demonstration process was described by Gencer et al. [15] who reports using 50 % RAP for binder and 70 % RAP for base course. RAP fines content was the limiting factor for choice of these doses. Five to six percent of unspecified anti-aging additive was added to soften the RAP binder to the required level. For the binder coarse RAP was heated to 120-130 ℃ and mixed together with preheated heated virgin aggregates in plant mixer. For the base coarse, virgin aggregates were added directly in the triangle drier and mixed in the systems mixing unit. The volumetric properties of mixture confirmed with the requirements after production.

2.3. 100% RAP PERFORMANCE

Despite relatively long availability of the technologies that allow production of 100 % RAP mixtures, lately there have been only a few reports that describe the laboratory and field performance of such mixtures. In 2013 a study on 100 % RAP Warm Mix Asphalt entitled "AllBack2Pave" was initiated by Conference of European Directors of Roads (CEDR) [28] but the results are not available yet.

2.3.1. Laboratory Research Results

A laboratory study by Silva et al. [29] evaluated the potential of total hot mix recycling with the use of rejuvenators. The researchers chose a hard binder grade to replicate the RAP extracted 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 dmm and softening point of 68 ℃ to penetration grade of 20/30 and respective required softening point of 55-63 ℃. Through addition of three doses of each rejuvenator, it was found that both of them satisfied this requirement at 5 % dose from binder mass. The mixture tests showed that due to lower binder viscosity and higher binder content, the modified mixes had better workability. 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, it was observed that the stiffness of mixture has been reduced, phase angle increased and fatigue resistance improved with the addition of rejuvenators. The authors concluded that mixture performance results were even better than those of conventional HMA with using either of the rejuvenators.

A study by Mallick et al. [30] evaluated 100 % RAP hot mix asphalt produced with addition of 0.9 % Reclamite rejuvenator (by mass of the mix). The RAP was re-graded to meet 12.5 mm Superpave gradation specification for use in base course. Mixtures were prepared using gyratory compactor and addition of Reclamite allowed to reduce the compaction temperature from 150 °C to 70 °C without reducing workability (increased binder content likely had major effect). 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 the indirect tensile strength test to conclude that an increased resistance to embrittlement was obtained after introduction of Reclamite.

2.3.2. Full Scale Trials

The study by Mallick et al. [30] presents results of 100 % RAP full scale application in New York City using the asphalt plant described in Section 2.2.1. "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 rejuvenator. 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, which is an indicator of low temperature stiffness, showed similar results for both 15 % and 100 % RAP mixtures.

In summer of 2012 a visual inspection tour was performed of the sites paved in NYC DOT demonstration project at Woodhaven 85th Road and 75th Street at where 100 % RAP mixture was paved in 2001; no differences were noted in pavement performance compared to control sections of virgin mixtures (Figure 2-9). Tinkham Street in Springfield, MA was paved in 2003 using 100 % RAP mixture along with control virgin mixture and both sections are performing well.
In some cases the mix design requirements reportedly did not allow for production of 100 % RAP mixtures although the available plant technology would permit it. In a study reported by Gencer et al. [15] the limiting parameter was RAP fines content that restricted the RAP use to 50-70 %. In a German trial [31] binder content was increased above the necessary due to introduction of rejuvenator plus Fischer Tropsch wax. 90 % RAP mix was produced with a parallel drum heater in a batch plant. The resulting pavement passed the German mix volumetric requirements as well as the performance requirements of the Hamburg wheel tracking test and shear force test for adhesion between layers. The binder test results or cracking performance were not reported for this study, but after two winters with temperatures below -10 °C the pavement performs as well as a section built with virgin materials.

Historically, due to oil crisis in the 1970’s 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 1970’s and beginning of the 1980’s was aimed at reducing energy use and asphalt costs by maximizing recycling. Due to the available technology at the time, RAP content in most projects was limited to around 30-70 % [32, 33, 34, 35, 36]. The few field research projects that have used 100 % RAP are listed in Table 2-4. The observed problems of pavement performance, consistency, production and emissions at the very high RAP projects significantly reduced the research and trust in high RAP content mixtures [33, 37]. Bonaquist later 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 [7]. However, a comfortable approach to use low RAP content (10 to 25 %) has been adopted since then and is used in present day.
Table 2-4. 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</td>
<td>[36, 38]</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>Section required heavy maintenance and was removed in 1986</td>
<td>[36, 38]</td>
</tr>
<tr>
<td>US 84, Snyder, Texas</td>
<td>1976</td>
<td>Base</td>
<td>4.0 % AC-10</td>
<td>Central, Hot pug mix</td>
<td>-</td>
<td>[38]</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>[38]</td>
</tr>
<tr>
<td>US 50, Holden, Utah</td>
<td>1975</td>
<td>Surface</td>
<td>1.5 % AC-10</td>
<td>Central, Drum dryer</td>
<td>-</td>
<td>[38]</td>
</tr>
<tr>
<td>Georgia</td>
<td>1991</td>
<td>Unspecified</td>
<td>0 % and 4 % unspecified recycling agent</td>
<td>&quot;Cyclan&quot;</td>
<td>Good performance after 17 months of service</td>
<td>[37]</td>
</tr>
</tbody>
</table>

2.4. DISTRESSES ASSOCIATED WITH RECYCLED PAVEMENTS

Since performance of 100 % RAP pavements is not well investigated, an overview of relevant research results related to typical distresses from studies of traditional very high RAP content mixtures is included. Although the findings of such studies cannot be directly attributed to 100 % RAP mixtures, the trends in most cases are likely to remain similar.

The distresses in high RAP mixtures are mostly associated with the aged RAP binder. Aging increases binder stiffness and viscosity due to change in the ratio of asphaltenes and maltenes [39]. A major part of the asphalt aging occurs during mixing with aggregates, transportation and laying processes due to exposure to high temperatures. This is referred to as short-term aging and is caused by [40, 39, 41]:


- Oxidation which occurs excessively in the asphalt pugmill due to binder spread into thin films.
- Loss of volatile fractions (volatilization).
- Absorption of oily constituents, resins, and asphaltenes by aggregates.

The amount of in-service aging mostly depends on the void content in the pavement and layer position within the road construction (surface of the road hardens faster). The long-term aging mechanisms have been recognized as [40, 39, 41]:
- Oxidation because of constant supply of fresh air.
- Polymerization.
- Photo-oxidation for surface layers.
- Thixotropy due to the formulation of a structure within asphalt binder over a long period.
- Syneresis due to exudation of thin oily components.

### 2.4.1. Cracking

The stiff, less elastic binder in RAP typically increases mixture stiffness [42, 43] and therefore can cause fatigue damage [44, 45] and low temperature brittleness [46]. These are some of the main reasons for reluctance for government agencies to allow very high RAP content [47, 48]. For example, NCHRP 9-46 study [43] evaluated the use of 55% RAP mixes and showed that stiffness as measured by dynamic modulus at different temperatures and frequencies increased by 25% to 60% compared to virgin mixtures. Similarly, a pooled fund study that assessed plant produced mixtures with 40% RAP [47] indicated that the stiffness can increase by as much as 49% compared to virgin mixture. If no mix design actions are taken, the increase in RAP proportion will elevate the stiffness even more and escalate the cracking potential. This is confirmed in a study by West et al. [49] who summarized the long-term pavement performance (LTPP) for overlays of approximately 20 year service and 30% RAP content. They showed that fatigue, longitudinal and transverse cracking are the distresses that occur more often in RAP mixtures. According to Bennert and Maher [50], the cracking of LTPP sections in New Jersey started at about the same time in both virgin and RAP-containing pavements; however, in the 30% RAP-containing pavements, it progressed at a faster rate. The LTPP results, however, have generally shown mixtures containing RAP performed better than or equal to virgin pavements for a majority of the cases [49].

Contrary to general perception, the studies by Al-Quadi [42] Huang et al., [51, 52], Shu et al., [53], McDaniel et al. [54], Poulikakos et al. [55], as well as Sargious and Mushule [56] have all indicated increased fatigue life of mixtures containing at least 40% RAP compared to conventional mixtures. Similarly, the relationships developed between laboratory test results and the test track findings at NCAT suggest that 50% RAP is expected to have better fatigue performance than the
virgin control mix [57]. These results, although counter-intuitive, should not be considered incorrect. Fatigue failure is considered to be more of a structural problem than an asphalt material failure. It is often caused by number of pavement factors occurring simultaneously, including poor structural design, heavier than designed loads or more load repetitions, and poor subgrade drainage [58]. Increased modulus and reduced binder viscosity, as expected in RAP binder are reported to increase the fatigue life [59] and thus the laboratory studies can demonstrate such results. A more in-depth analysis of the entire pavement structure, including the stress and strain caused by loading may demonstrate different results. However, the laboratory fatigue characterization techniques generally require further advances to provide reliable prediction of field fatigue resistance [43]. Improved fatigue resistance may also be partially explained by reduced tensile strains in the mixture due to increased stiffness and improved bond between binder and aggregates. Huang et al. [52] 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 rejuvenator diffusion would likely neglect this effect over time.

2.4.2. Rutting
Multiple studies have shown that the resistance to rutting resistance is likely to be very good for high RAP mixes because of the aged RAP binder [60, 29, 61]. However, the use of rejuvenator is 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 rejuvenator dose must be carefully chosen not to over soften the binder.
- Sufficient rejuvenator diffusion into the binder film must have occurred before opening to traffic. Insufficient diffusion will form soft outer layer of binder film [47, 45] which may lead to increased dynamics of developing permanent deformations in early stages of pavement life until equilibrium is reached [62].

2.4.3. 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 moisture susceptibility as conventional asphalt [61, 63], and Mogawer et al. [47] has even reported increased moisture resistance of high RAP mixes. However, several factors can influence this behavior; for example, if the old recycled pavement had a stripping problem, the problem is likely to re-occur if adhesion additives are not added to the new mix [64]. Similarly to conventional mixtures, low discharge temperature of high RAP mixtures have been shown to increase the moisture susceptibility (Mogawer, et al., 2012).
2.4.4. **Flushing**

In field studies with the use of incompatible products or excessive dose of rejuvenators, 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 [61, 8].

2.5. **MIX DESIGN**

The traditional mix design methodology, especially with respect to design of optimal binder content, has to be modified for totally recycled hot asphalt 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. Some more process related considerations must also be taken into account. For example, minimization of excess RAP after re-grading, cost analysis, available rejuvenators and the requirements for specific construction site are all valid considerations to modify the mix design. Choice of rejuvenator and its dose is another significant aspect. The available research findings concerning these topics is summarized in this section and will include best practices suggestions from personal communications with representatives of companies conducting 100 % RAP recycling.

As a result of the experimental study described later, the mix design procedure guidelines are proposed as summarized in Figure 2-10. The chosen RAP fractions are combined in an initial mixture composition. The binder is extracted from the mixture to determine its properties and choose the necessary rejuvenator type and dose. The aggregates are tested for necessary properties. After the selection of an appropriate rejuvenator, the asphalt is mixed and compacted in laboratory to determine the volumetric properties. If the mixture passes the corresponding volumetric requirements, it is tested for the chosen mixture performance-related properties. The steps are repeated by taking appropriate modification if correspondence to the specification requirements is not ensured at any of the steps. In some cases, due to properties of milled RAP (especially fines and binder content) the design of mixture with 100 % RAP is not possible [31, 15]. In such situations, adding virgin binder and aggregates can aid in satisfying the specification requirements. However, care should be given to ensure sufficient blending of RAP and virgin binder as well as homogeneous coating of virgin and RAP aggregates. The specific mix design steps and testing methodology are discussed in detail below.
2.5.1. 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 [48], including design of mixture particle size distribution and aggregate properties. The verification of aggregate properties requires recovering them from RAP, and the recovery process may alter the properties. A study by NCAT and University of Nevada Reno [65, 43] 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.

2.5.2. Binder Content

The design of 100 % RAP mixture, especially with respect to controlling the binder content, has to be different from a conventional mix design procedure. The binder content will be defined by several parameters:
− Binder content in the source RAP.
− The particle size distribution of the re-graded RAP.
− Rejuvenator type.
− Rejuvenator content.

Optimization of the binder content can be performed by changing these parameters 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 [66, 67].
− Choose less effective rejuvenator. Organic products tend to be much more effective at a select dose compared to petroleum products ([68] and Section 6).
− Increase rejuvenator dose. Care should be given to comply with the performance specification requirements, especially rutting.
− Add virgin binder.

2.5.3. Rejuvenators

A successful use of rejuvenators 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 rejuvenator to provide the necessary short and long term properties, as follows:

− **Short term.** Rejuvenators 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. Rejuvenator 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.** Rejuvenators should reconstitute chemical and physical properties of the aged binder and maintain stability for another pavement service period. The binder rheology should be altered to reduce fatigue and low temperature cracking potential without over softening the binder to cause rutting failure. Sufficient adhesion and cohesion have to be ensured in the mix to prevent moisture damage and raveling.
**Dose Selection**

The dose of rejuvenators should be selected to meet the target performance grade of the aged RAP binder, resulting in improved cracking resistance without adversely affecting rutting resistance [63]. Mixing of the recovered RAP binder with rejuvenator to determine the rejuvenated binder grade is considered the best approach at this time for selection of appropriate rejuvenator dose. Such method is used in majority of research studies [29, 63, 43]. A study by NCAT [49] suggests using centrifuge extraction over other methods for recovery of the RAP binder from high RAP mixtures.

The research by Tram et al. [63] Lei et al. [69] Tao et al. [70] have all shown that the change in Superpave performance grade (both high and low) is almost linear at different doses of the same rejuvenator. Thus determining the RAP binder grade plus grade at one dose of rejuvenator permits determining the optimum additive dose. Dony et al. [68] showed that penetration increases exponentially with higher rejuvenator content and softening efficiency of organic products is generally much higher than that of petroleum rejuvenators. The research by Asli et al. [71] and Lin et at. [72], however, showed linear penetration increase.

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

- The entire RAP binder is extracted and blended with rejuvenator thus assuming full activation of RAP binder in the mixture. However, it has been reported by multiple studies [52, 39, 73] that part of RAP binder stays inherent and does not actively contribute to mix properties.
- Softening of binder to reach the desired viscosity, penetration or softening point can be achieved by different oils, but does not ensure binder rejuvenation.
- Many rejuvenators 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 Hesp et al. [74, 75] has shown that conformity to PG did not prevent pavement premature excessive thermal cracking when WEO bottoms (residue) was used as rejuvenator.
- Incompatible rejuvenator 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 2.5.4.
**Diffusion of rejuvenators**

Diffusion speed of the rejuvenator into the hard RAP binder depends on binder and rejuvenator properties and occurs most rapidly at elevated temperatures during mixing, storage, transportation, and compaction [76, 77]. It can continue during the service life until equilibrium is reached [63, 78, 52]. Part of the RAP binder in fact may not be activated stays as "black rock" [52, 79]. Karlsson and Isacsson [77] argued that the diffusion rate is governed by the viscosity of the maltene phase instead of the entire recycled binder. The rejuvenator diffusion process in RAP binder film is illustrated in Figure 2-11 as described by Carpenter and Wolosick [78]:

- 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 [78, 80].
- 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.

![Figure 2-11. Rejuvenator Diffusion into Binder Film and Binder Layer Viscosities](image)

The rejuvenator diffusion can significantly affect performance of the asphalt mixture as follows [81]:

- 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 [39, 79], which can lead to cracking and raveling failures of the pavement.
- In mix design 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 [33, 39], which can lead to plastic deformations of the pavement.
− If traffic is allowed on pavement where rejuvenator diffusion is not complete, its concentration in the outer layer of binder film will be high and can lead to increased rutting due to this soft film dominating performance of pavement [62].
− Incomplete diffusion can cause problems in predicting the pavement performance in laboratory, especially for long-term properties, like fatigue [78]. Research by Huang et al. [52] has shown that the layered structure, composed of aged RAP binder at the interface of RAP aggregate and a softer binder on the outside, is beneficial to the reduction of stress concentration in RAP. This can aid in improving fatigue resistance. The authors, however, note that this positive effect is likely to be neglected after diffusion is complete. Therefore laboratory evaluation of mixtures where diffusion has not finalized can create "false positive" results.

To improve the blending and diffusion of RAP and virgin binder the following actions can be considered:
− Increase the mixing and storage time.
− Use of warm mix technology.
− Raise the mixing and compaction temperature.

**Performance of Specific Products**

Multiple different rejuvenators are available in the market, including engineered and generic products having both petroleum and organic origins. The user has to carefully select the most suitable product for each specific case. No single rejuvenator will be suited for all applications. General performance indications of some rejuvenators that have been used for plant-produced hot mix asphalt are summarized here. Several products were already discussed previously in Section 2.3.

Various researchers have tried to distinguish between softening agents and rejuvenators:
− Softening agents are solely aimed at lowering the viscosity of RAP binder [61].
− Rejuvenators are used to recover the properties of aged binders to a consistency level that is appropriate for construction and pavement performance, and they should reconstitute the chemical composition to ensure durability [82, 61].

Roberts et.al [83] defines the softening agents asphalt flux oils, lube stock, lubricating or crankcase oil or slurry oil; the rejuvenating agents are defined as lube extracts and extender oils. Rejuvenators should provide homogeneous system where asphaltenes are well peptized/dissolved and prevented from precipitation or flocculation [61]. Nahar et al. [84] attempted to evaluate microstructure of rejuvenated binder using atomic force microscopy (AFM) images and correlated them with binder
rheology to conclude that chemo-physical mechanisms demonstrate true rejuvenation. The desired binder rheological performance was achieved by using both tested rejuvenators and AFM images after using one of them also resembled images of source un-aged binder. Brownridge [85] demonstrated that application of rejuvenator can almost entirely restore the chemical composition of aged asphalt as illustrated in Figure 2-12. Other research has shown that the best rejuvenation can be attained with high content of resin (naphthenic) or aromatic (polar aromatic) fractions [41] but low content of saturates, which are highly incompatible with asphaltenes and increase aging [86, 63]. The stability of the system in aging depends on the solubility, molecular size and to a large extent on molecular shape [61]. The study by Bailey [87], however, noted that for neither of two vegetable oils used in her study, SARA (Saturates, Aromatics, Resins, Asphaltenes) analysis provided meaningful results thus questioning the application of the test method.

![Figure 2-12. Binder Chemical Composition at Different States [85]](image)

The use of petroleum products has been most widely reported for rejuvenation. "Reclamite" has also been reported as a rejuvenator that provides good performance in multiple sites [88, 30] and it has been used for more than 50 years [85]. "Cyclogen" rejuvenator has been used for production of 100 % RAP pavements in Arizona [89] and research by Tran et al. [63] 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 rejuvenator, measured with the LAS test [90], was also improved but not to the level of virgin binder.

More recently different types of organic oils have been tested as rejuvenators to restore the viscosity and elasticity of aged asphalt. Bailey et al. has performed laboratory and field trials of vegetable oils (both virgin and waste) as rejuvenators [91, 92] and concluded that the use of such...
oils can reduce the viscosity to reach the target grade, ensure similar rheology as measured with DSR, reduce the mixture stiffness to a level of virgin mix, 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. [93] concluded that recycled cooking oil is a good candidate for improving the low-temperature grade. Dony et al. [68] 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, modified with vegetable oil, exhibited the highest hardening during short term aging (RTFO) which was explained by slow oxidation of fatty acid unsaturations present in the vegetable oil (siccativation phenomenon).

Research by Hesp et al. [74, 75] has shown that waste engine oil residue can be used to extend the binder performance grade to the required level. However, the use of these oils creates physical and chemical hardening of binder and has resulted in premature excessive thermal cracking of asphalt pavements in Ontario province in Canada.

2.5.4. Mixture Volumetric and Performance-Related Tests

To obtain dry RAP, it can be placed in an oven at 110 °C for up to six hours without further aging the material [43]. Alternatively fan drying can be used. Before mixing, the RAP should be pre-heated at the design temperature between 1.5 to 3 hours in order to ensure homogeneous temperature while having the least effect on the properties of RAP binder [43].

Ensuring the required voids in mineral aggregate (VMA) is the most important volumetric parameter to ensure mix durability [43]. Calculation of VMA requires the use of $G_{sb}$ of the RAP aggregates and NCHRP Report 752 [43] 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 dose. This error would be even higher at total recycling.

Because of the possible uncertainty in calculation of volumetric properties and the small experience of high RAP and rejuvenator use, a set of performance related tests is recommended to further assess the mix design for their susceptibility to common distresses, including rutting, fatigue cracking, low temperature cracking, and moisture damage. 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. NCHRP report 752 [43] suggests methods specified in Table 2-5, but notes that further research is necessary to develop reliable methods and criteria for fatigue, top-down and reflection cracking. Before testing of performance-related properties, it is important to provide enough time for diffusion of the rejuvenator, 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 [60].
Table 2-5. Proposed Performance-Related Test Methods for Different Failure Modes [43]

<table>
<thead>
<tr>
<th>Failure mode</th>
<th>Test method</th>
<th>Procedure</th>
<th>Test parameter</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>Dry and moisture conditioned tensile strength</td>
<td>AASHTO T 283</td>
<td>Min. tensile strength ratio</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Hamburg wheel tracking test</td>
<td>AASHTO T 324</td>
<td>Stripping inflection point</td>
<td>Not established</td>
</tr>
<tr>
<td>Rutting</td>
<td>Hamburg wheel tracking test</td>
<td>AASHTO T 324</td>
<td>Max. rut depth</td>
<td>10 mm (3-10mil ESAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 mm (10-30mil ESAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 mm (≥30mil ESAL)</td>
</tr>
<tr>
<td></td>
<td>Asphalt pavement analyzer</td>
<td>AASHTO TP 63-07</td>
<td>Max. rut depth</td>
<td>5.5 mm (3-10mil ESAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.0 mm (10-30mil ESAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.5 mm (≥30mil ESAL)</td>
</tr>
<tr>
<td></td>
<td>Flow number</td>
<td>AASHTO TP 62-07</td>
<td>Min. flow number</td>
<td>53 (3-10mil ESAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>190 (10-30mil ESAL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>740 (≥30mil ESAL)</td>
</tr>
<tr>
<td>Low temp cracking</td>
<td>Disc-shaped compact tension test</td>
<td>ASTM D 7313-07</td>
<td>Min. fracture energy</td>
<td>400 J/m² (moderate cracking tolerance)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>460 J/m² (standard cracking tolerance)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>690 J/m² (low cracking tolerance)</td>
</tr>
<tr>
<td></td>
<td>Semi-circular bend test</td>
<td>M. Marasteanu [94]</td>
<td>Min. fracture energy</td>
<td>400 J/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>800 kPa·m²0.5</td>
</tr>
<tr>
<td>Load related cracking</td>
<td>Energy ratio (top down)</td>
<td>R. Roque [95]</td>
<td>Energy ratio</td>
<td>Preliminary established</td>
</tr>
<tr>
<td></td>
<td>Overlay test (reflection)</td>
<td>Tex-248-F</td>
<td>Cycles to failure</td>
<td>Preliminary established</td>
</tr>
<tr>
<td></td>
<td>Disk-shaped compact tension test (reflection)</td>
<td>ASTM D 7313-07</td>
<td></td>
<td>Not established</td>
</tr>
<tr>
<td></td>
<td>Bending beam (fatigue)</td>
<td>AASHTO T 321-07</td>
<td></td>
<td>Not established</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASTM D 7460</td>
<td></td>
<td>Not established</td>
</tr>
<tr>
<td></td>
<td>Simplified viscoelastic continuum damage</td>
<td>R. Kim [96]</td>
<td></td>
<td>Not established</td>
</tr>
<tr>
<td></td>
<td>(fatigue)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IDT fracture energy (fatigue)</td>
<td>R. Roque [97]</td>
<td></td>
<td>Not established</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R. Kim [98]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Semi-circular bend test (fatigue)</td>
<td>L. Mohammad [99]</td>
<td></td>
<td>Not established</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.6. 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 necessary steps are discussed in this section.

2.6.1. RAP Milling and Processing

The asphalt can be milled in partial or full depth. Road constructions where the different layers have aggregates or binder of various quality or grade can be removed by partial milling, in order to later allow the use of RAP in higher value layers [31, 100]. Choice of the milling apparatus, depth and speed will influence the quality of RAP [100]. Special attention should be given to minimize fines content. For example, slow forward speed or fast drum rotation will generate more undesirable fines.

In most cases, production of 100 % RAP mixture will require processing of RAP in order to provide multiple fractions. Screening of the material will provide flexibility to the mix designer for ensuring the necessary particle size distribution and give control over the binder and fines content [67, 4, 42, 43] (discussed in Section 2.5). Crushing, however, should be avoided in order to reduce generation of excessive fines content that is usually already present from milling operation [101]. 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 [102, 103, 104]. Crushing or screening may be necessary if oversized agglomerations of RAP have formed because they may not break apart during heating [101].

Palmer Paving and RAP Technologies representatives report using sieves of 6.4 mm, 12.5 mm, and 19.0 mm for screening the RAP (personal communication with R.Frank and L.Hanlon). SmartPave System designers indicate that generally the RAP milled with upward cut milling heads stay within 10 % of original gradation [14].

2.6.2. Storage of RAP

RAP stockpiles should be treated just like any virgin aggregate stockpiles to avoid contamination and separation of different materials [67]. The startup waste should not be mixed together with RAP material [67]. Optimally RAP from different sources that have different properties should be stockpiled separately to increase consistency. However, because of limited storage area, this is often impractical. In these cases, RAP from different sources can be blended to increase homogeneity before processing or feeding into the cold feeder [101]. RAP may tend to pack together in a hot climate and long storage times. This can be avoided by processing RAP shortly before mixing.
Moisture content in RAP is an important factor to consider at high recycling rates. High moisture content can be found directly after milling operations (water is used to cool down teeth of milling machine) and in uncovered stockpiles. RAP also has a tendency to hold water and not to drain over time like virgin aggregate stockpile [23]. Therefore the moisture content in RAP in general is higher compared to aggregate stockpiles and low flat stockpiles can have 7-8% moisture [43, 105]. Increased moisture content will cause higher drying and heating costs and a reduction of the plant production rate [16]. Moisture content can be reduced by the following actions, in the order of most to least effective [106]:

- Covered stockpiles under a roof. However, RAP should not be covered with plastic, because of limited air flow, heating and formation of caked layers.
- Use of paved, sloped storage area. The slope should be away from the side where the front-end loaded moves the materials to cold feed bin.
- Use of conical stockpiles. Tall conical stockpiles are preferred instead of flat horizontal piles for lower moisture accumulation.
- If no enclosed storage area is available, RAP can be crushed and screened in small portions at the day of use to limit moisture [67, 43].

2.6.3. RAP Quality Control and Variability Analysis

RAP should be well characterized for mix design and quality control purposes. The RAP material should be sampled from multiple locations around stockpile by using back-dragging technique to determine its properties and variability [43]. While for small contents of RAP it may be enough to determine the binder content and aggregate gradation, for high RAP content mixtures the aggregate and binder properties should be determined as well [102]. The proposed guidelines by NCHRP Report 752 are summarized in Table 2-6.

The studies in 1980’s and 1990’s have concluded that RAP exhibits variability in composition [107, 108]. 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 [109, 110]. This has been confirmed through personal communication with asphalt producers.
Table 2-6. Proposed RAP Sampling and Testing Guidelines from NCHRP Report 752 [43]

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Frequency</th>
<th>Minimum number of tests per stockpile</th>
<th>Maximum standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt binder content</td>
<td>AASHTO T 164 or AASHTO T 308</td>
<td>1 per 900 t</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>Recovered Aggregate Gradation</td>
<td>AASHTO T 30</td>
<td>1 per 900 t</td>
<td>10</td>
<td>5.0 all sieves</td>
</tr>
<tr>
<td>Recovered Aggregate</td>
<td>AASHTO T 84 and T 85</td>
<td>1 per 2700 t</td>
<td>3</td>
<td>1.5 on 75 micron</td>
</tr>
<tr>
<td>Bulk Specific Gravity</td>
<td></td>
<td></td>
<td></td>
<td>0.030</td>
</tr>
<tr>
<td>Binder Recovery and PG Grading</td>
<td>AASHTO T 3019 or ASTM 5404 and AASHTO R 29</td>
<td>1 per 4500 t</td>
<td>1</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

2.7. SECTION SUMMARY

Ten 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 supporting Video 2-1 [5]. 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. Nine of the technologies require installation of a new drying/heating system and one is designed to retrofit existing drum plants fitted 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 totally recycled mixtures, most notably in respect to binder content and use of rejuvenators. The binder has to be extracted from RAP to verify its properties and determine the necessary rejuvenator type and dose to ensure correspondence to the specification requirements. Linear reduction of high and low PG temperature and exponential increase in penetration is expected with increased rejuvenator dose. The binder content can be modified by switching between RAP sources, using rejuvenators of different efficiency, modifying the fine RAP 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 rejuvenator 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 rejuvenators have shown to be able to modify the aged binder to a level that corresponds to the required Superpave or conventional 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 rejuvenator 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 rejuvenators stems from isolated unsuccessful projects in 1970’s and 1980’s which showed rutting and raveling problems. These failures have been associated with the rejuvenator diffusion and effect on adhesion, but are equally 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 section demonstrates the availability of the necessary tools and know-how for production of such mixtures. Further research is necessary to evaluate the performance in laboratory and most importantly in full scale demonstration projects. Successful cases should allow for legislation of such mixtures by state agencies for paving on public roads. Until then the application is limited mainly to lower level roads and privately owned construction sites.
3. EXPERIMENTAL METHODS

The test methods of the research are described here and the used materials and experimental plan are discussed before presenting the results at each chapter. Modifications, if any, to these test methods or sample preparation are discussed before describing test results.

3.1. BINDER TESTS

Binder was extracted from RAP using toluene according to ASTM D2172, method A and recovered using a rotary evaporator, according to ASTM D5404. Since the extraction results are very operator sensitive [40] and residual solvent may be present [11] all extraction was performed by the same individual. To further ensure uniform properties for all extracted binder the separately extracted binder samples were mixed together before batching for blending with each rejuvenator after 40 minutes heating at 140 °C temperature.

Empirical Tests

To determine the softening efficiency of these products, penetration was determined according to ASTM D5 at 25 °C and additionally at 4 °C to calculate the Penetration Index (PI). Kinematic viscosity was determined according to ASTM D2170 at 135 °C and softening point – according to ASTM D3461.

Performance Grading (PG) and Aging

The rejuvenated binder was graded according to the Superpave Performance Grading (PG) requirements defined by AASHTO M 320. High temperature grade was determined using the Dynamic Shear Rheometer (DSR) according to AASHTO T 315 at 10 rad/s using 25 mm plates with 1 mm gap. The low temperature stiffness was tested using the Bending Beam Rheometer according to AASHTO T 313. The PG system specifies constant physical property requirements as indicated in Table 3-1 and the temperature at which binder can meet these requirements (with 6 °C increments) defines its high and low temperature grade. High PG temperature is determined before and after short term aging with the Rolling Thin Film Oven (RTFO) and the minimum G*/sinδ has a different requirement at each of these states. The final high PG temperature is defined as the lower of the two temperatures at which the corresponding requirement is met. For low PG temperature both requirements (stiffness and m-value) must be passed. The required grade is based on the specific climatic conditions and traffic load at construction site. Based on the origin of the RAP (New Jersey, US), the target binder grade for this research was defined as PG 64-22.
Superpave specifications defines that for this grade the intermediate temperature fatigue parameter \( G^* \cdot \sin \delta \) must be determined at 25 °C using DSR 8 mm plates at 2 mm gap at 10 rad/s frequency.

Short term aging was performed using Rolling Thin Film Oven at 163 °C for 85 minutes (specified by ASTM D2872) and long term aging was executed using Pressure Aging Vessel (PAV) for 20 hours at 2.10 MPa pressure at 100 °C (ASTM D652). Aging before performance grading of all test specimens (including RAP and rejuvenated RAP) was performed in the same way as done for grading of virgin binder as indicated in Table 3-1. Original binder was tested for rotational viscosity (AASHTO T 316). Original and short term aged binder were used for determining the high PG temperature. Short plus long term aging was performed before determining low PG temperature and intermediate temperature fatigue parameter \( G^* \cdot \sin \delta \). Mass loss after short term aging with RTFO at 163 °C was calculated according to AASHTO T 240.

### Table 3-1. Superpave Binder Specification Requirements (AASHTO M 320)

<table>
<thead>
<tr>
<th>Test method</th>
<th>Temperature</th>
<th>Test Parameter</th>
<th>Binder state</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic Shear Rheometer</td>
<td>High PG</td>
<td>( G^* \cdot \sin \delta )</td>
<td>Original</td>
<td>( \geq 1.0 \text{ kPa} @ 10 \text{ rad/s} )</td>
</tr>
<tr>
<td></td>
<td>Intermediate PG (test @ 25 °C for PG 64-22)</td>
<td>( G^* \cdot \sin \delta )</td>
<td>RTFO Residue</td>
<td>( \geq 2.2 \text{ kPa} @ 10 \text{ rad/s} )</td>
</tr>
<tr>
<td></td>
<td>Low PG</td>
<td>Creep Stiffness</td>
<td>RTFO + PAV Residue</td>
<td>( \leq 300 \text{ MPa} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>m-value</td>
<td></td>
<td>( \geq 0.3 )</td>
</tr>
<tr>
<td>Rotational Viscometer</td>
<td>135 °C</td>
<td>Viscosity</td>
<td>Original</td>
<td>( \leq 3 \text{ Pa} \cdot \text{s} )</td>
</tr>
<tr>
<td>RTFO</td>
<td>163 °C</td>
<td>Mass loss</td>
<td>Before and after RTFO</td>
<td>( \leq 1 % )</td>
</tr>
</tbody>
</table>

**Construction of DSR Master Curves**

The rheological properties of virgin, aged, and rejuvenated asphalt binders were measured using a DSR (Anton Paar Physica MCR 301). According to AASHTO T 315, a 8 mm plate-plate geometry with 2 mm gap in strain controlled mode was used. The tests were performed at 40, 50, 60, 70, and 80 °C and frequencies of 0.1~20 Hz within each temperature. These results were shifted to a reference temperature of 40 °C using the time-temperature superposition principle to construct master curves of complex modulus (\( G^* \)) and phase angle (\( \delta \)). Such interpretation allows to describe the temperature dependence of viscoelastic behavior of the binder. Shift factors were computed.
using Williams-Landel-Ferry (WLF) Equation (3-1) and a sigmoidal function defined by Equation (3-2) was used for fitting the shifted shear modulus data.

\[
\log a_T = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)}
\]

\[
\log(G^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log a_T + \log f)}}
\]

where,
- \( a_T \) – horizontal shift factor at temperature \( T \)
- \( T \) – test temperature, °C
- \( T_r \) – reference temperature, °C (40 °C in this study)
- \( f \) – testing frequency, rad/s
- \( \delta, \alpha, \beta, \gamma, C_1, C_2 \) – fitting parameters determined using least squares method

**Linear Amplitude Sweep Test**

The Linear Amplitude Sweep (LAS) (AASHTO TP-101) test has been proposed as a replacement to currently used PG grading intermediate temperature parameter \( G^* \cdot \sin \delta \) (complex shear modulus viscous portion). The LAS procedure uses conventional DSR testing unit with 8 mm plate and 2 mm gap setting, but in contrast to the existing fatigue parameter, the test is performed by means of cyclic loading employing increasing load amplitude to characterize the non-linear strain response of binder. To allow direct comparison to \( G^* \cdot \sin \delta \) the test was performed at the Superpave intermediate temperature for PG 64-22 of 25 °C after short plus long term aging.

The test is conducted in two steps. Firstly, a frequency sweep is run from 0.1 to 30 Hz at a strain level of 0.1 % to determine undamaged linear viscoelastic properties of asphalt binder (complex shear modulus and phase angle). This data is used to calculate the slope \( m \) of the best-fit linear log-log plot of storage modulus versus frequency. The material constant \( \alpha \) is then calculated. Secondly, a strain sweep test is performed in strain-controlled mode at a constant frequency of 10 Hz with linearly increasing strain from 0.1 to 30 %. At each strain level \( G^* \), phase angle, and oscillatory shear stress are recorded. A typical plot of damage accumulation is illustrated in Figure 3-1. It is used to calculate the curve fit coefficients for calculation of damage accumulation in the specimen at any strain level using the viscoelastic continuum damage (VECD) approach. The results are expressed as cycles to failure \( (N_f) \), where the failure is defined as 35 % reduction from undamaged \( G^* \cdot \sin \delta \). Any strain level can be used for calculation of \( N_f \), accounting for the differences in pavement structure or traffic loads (higher loads or thinner pavements will generate higher strain).
Chapter 3

Experimental Methods

Asphalt Binder Fractionation

Saturates, Aromatics, Resins, and Asphaltenes (SARA) separation is a frequently used technic for chemical analysis of asphalt binders from different crude sources and binders subjected to variant treatments [112]. Resins are sometimes referred as polar aromatics while aromatics as napthenic aromatics [113]. In this study, SARA separation was conducted according to the standard ASTM D4124-09 2010. Asphaltenes and maltenes were separated using isooctane (2,2,4-trimethyl pentane, HPLC grade, Fisher Scientific, Waltham, MA, USA). The precipitating solvent was added to the binder sample at a ratio of 40:1 by mass, and the mixture was stirred overnight at room temperature. The sample solution was then filtered through both a Fischer brand filter paper Q2 (pore size 1-5 µm) and a Millipore cellulose ester membrane (pore size 0.22 µm). The asphaltenes retained on the filter paper were washed with additional solvent until the filtrate was colorless and dried in a fume hood until a constant weight was obtained. The maltene fraction was recovered by roto-evaporation and dried to a constant weight. Separation of the maltene into saturates, aromatics and resins was carried out by injecting the solution (1 g of the maltene dissolved into 10 ml of n-heptane) into a 70-cm long, 105-cm diameter glass LC (liquid chromatography) column with approximately 100 g of chromatographic grade activated alumina (80-200 mesh, VMR International, US). The three fractions were eluted by introducing the following solvents into the column: 50 ml n-heptane (HPLC grade, Fisher Scientific), 100 ml of toluene (HPLC grade, Fisher Scientific), 75 ml of methanol (HPLC grade, Fisher Scientific)/toluene (50:50 v/v) and 150 ml trichloroethylene (ACS grade, Fisher Scientific). Saturates were collected prior to elution of a fluorescent band migrating up the column. Aromatics characterized by the fluorescent band were collected prior to a dark band migrating up the column below the fluorescent band. Trichloroethylene was finally introduced to strip the column of any

Figure 3-1. Example $|G^*| \cdot \sin \delta$ at Time $t$ Divided by Initial $|G^*| \cdot \sin \delta$ Versus Damage Plot for Linear Amplitude Sweep Test
remaining “dark band” material defined as the polar aromatics fraction. Fractions were recovered by roto-evaporation and dried to a constant weight.

**Atomic Force Microscopy (AFM) Measurements**

With a sharp tip attached at the free end of a cantilever probing the specimen surface, AFM can measure materials’ morphology and mechanical properties with high resolution. Compare to the conventional DSR and BBR tests, AFM characterization can provide more direct evidence of how the rejuvenator interacts and modifies the aged binders at the micro scale.

Thin-film of asphalt binder samples was prepared by heat-cast approach which helps maintain binders’ original solid-state structure [114]. For morphological measurements, a bead of binder (ca. 50 mg) was dropped onto a glass slide, which was heated for ~2 minutes in an oven at ~115 °C, a temperature adequate to melt the binder, but not so high that it would oxidize rapidly. Once the binder became liquid, it was spread out with a blade to form a thin film. This hot film was left undisturbed for an additional 10 minutes to allow the surface to flow to a smooth finish. For mechanical property measurements conducted in a different laboratory using a different AFM, ca. 10 mg of bitumen were spread over a 0.9 × 0.9 mm² area of a glass slide and the samples were placed in the oven at 110 ± 2 °C for 20 minutes. The film was then cooled in air to room temperature, and stored to prevent dust pick-up for a minimum of 24 h before AFM imaging.

An Asylum Research MFP-3D AFM was used for morphology characterization, and intermittent-contact mode was employed because it minimizes possible tip contamination caused by the sticky binder residue [115]. Budget Sensors silicon tips Tap300Al-G (nominal resonant frequency of 300 kHz and nominal stiffness of 40 N/m) were used for morphological measurements. Tip geometry and stiffness were calibrated using a reference sample (TGT 01, MicroMasch) and a thermal tune procedure, respectively. Scans of the topographical properties were recorded over 40×40 µm² or 20×20 µm² area with 256×256 pixels. Asphalt binders’ mechanical properties were measured using a Bruker AFM (MultiMode 8) with a Nanoscope V controller in peak force tapping quantitative nanomechanical mode (PFT QNM). The data was collected using Nanoscope 8.15. Budget Sensors silicon tips Tap150Al-G tip (nominal resonant frequency of 150 kHz and nominal stiffness of 5 N/m). The tip radius was calibrated using the Bruker PS-LDPE reference and set as 20 nm. The peak force was set as 15 nN and the feedback gain was set as 20, with a scan rate of 0.5 Hz. The peak force amplitude and peak force frequency were set as 150 nm and 2 kHz, respectively. Scans of the topographical and mechanical properties are recorded over 40×40 µm² or 20×20 µm² area with 256×256 pixels. All measurements were conducted at room temperature.

Peak Force Tapping QNM mode is a technique recently developed by Bruker, and it allows simultaneous capture of topographical and mechanical properties by recording instantaneous force
curves as the AFM probe approaches and retracts from the sample surface as shown in Figure 3-2. As the AFM tip approaches the surface, it experiences an attractive force which causes the cantilever to jump into contact with the sample. After contact, repulsive forces dominate the sample-tip interaction, leading to a peak force point in the approaching curve. As the tip is retracted, it goes through a minimum force corresponding to the adhesion force and, finally, the contact breaks apart. In PFT QNM mode, the peak force and the indentation depth can be controlled. The mechanical properties of the binders are extracted from the force curves. To obtain the reduced Young’s modulus and adhesion, a portion of the retraction curve (i.e., 30% to 90% from the adhesion force to the maximum peak force) is fitted using Derjaguin-Müller-Toporov (DMT [2]) model, as shown in Equation (3-3). Dissipated energy is defined as the area in between the approach and retraction curves, which is related to a material’s damping property. These properties are calculated for each pixel and a map of each mechanical property is obtained.

\[
F - F_{\text{pull-off}} = \frac{4}{3} E^* \sqrt{R \delta^3}
\]  

(3-3)

where,

\( F \) — instantaneous force on the tip
\( F_{\text{pull-off}} \) — adhesion force
\( E^* \) — reduced elastic modulus, \( \delta \) is the tip-sample indentation depth
\( R \) — effective radius of curvature of the system.

![Figure 3-2. Schematic of a typical AFM force curve](image-url)
3.2. MIXTURE TESTS

Mixing and compaction temperature of the mix samples was selected based on the viscosity results and was set at 145 °C for all the mixes. RAP and rejuvenator were heated at this temperature for 2 hours before mixing together (at 12 % rejuvenator from RAP binder content) using a planetary mixer. All samples were short term conditioned for 4h at 145 °C before compaction using gyratory compactor according to ASTM D6925. The samples tested for fatigue (FWD and CAST tests) were also long term aged at 85 °C for 120±5 h (five days) according to AASHTO R 30. In order to perform volumetric calculations, the bulk specific gravity of RAP aggregates was determined according to ASTM C127 (coarse aggregates) and ASTM C128 (fine aggregates) after recovering the aggregates from tests with an ignition oven according to ASTM D6307. The same procedure was used to determine the RAP binder content and obtain RAP aggregates for the reference virgin mixture. Automatic vacuum sealing method (Corelock™) was used for determining the bulk specific gravity of compacted samples according to ASTM D6752/D6752M and the maximum specific gravity of loose RAP was determined according to ASTM D6857. The air voids for all mix samples were kept at 7±0.5 % (for the samples that required cutting, the measurements were performed after cutting).

The mean value of two test results for CAST (Coaxial Shear Test) fatigue test and Hamburg rutting test, three for FWD (Fracture Work Density) fatigue test, tensile strength and creep compliance, and four for workability along with one standard deviation is presented for each test for every sample set. The creep compliance was determined according to the standard procedure which stipulates using trimmed mean from all three sample (dropping the maximum and minimum) displacement values before calculating the result; thus the standard deviation cannot be expressed.

Hamburg Wheel Tracking Test (WTT)

Hamburg wheel tracking test samples were prepared by gyratory compactor using 150 mm molds to approximately 60.5 mm height and they were placed in molds as illustrated in Figure 3-3(a). Two pairs of samples of each mixture type were tested for rutting according to AASHTO T324 in 50 °C water. This test temperature was chosen based on the Texas DOT procedure for PG 64-22 binder where the test is used for acceptance of mixtures. The test also gives an indication of stripping susceptibility is defined as the number of passes at which the deformation of sample is the result of moisture damage and not rutting alone as illustrated. This is illustrated by calculating the inflection point in the rut depth versus loading cycles curve (Figure 3-3(b)) using a third order polynomial function.
Workability

The samples prepared for Hamburg WTT were also used for evaluation of the mixture workability by calculating the number of gyrations to 8 % air voids according ASTM D6925.

Tensile Strength and Creep Compliance

Three samples of 46.5 mm height and 150 mm diameter of each mix were tested for creep compliance at three temperatures (0, -10, -20 ℃), followed by tensile strength test at -10 ℃ according to AASHTO T 322 standard procedure on indirectly positioned specimens. Creep compliance was measured by applying static load to initiate asphalt deformation in the viscoelastic range (0.00125 to 0.0190 mm horizontal deformation at 1000 s). The deformation was measured with horizontal and vertical displacement transducers glued on both sides of the saw-cut sample (cutting improves the consistency of results) to determine the time dependency of strain resulting from stress. Indirect tensile (IDT) strength was determined on creep compliance samples by applying 12.5 mm/min vertical loading rate for tests at -10 ℃ and 50.4 mm/min for testing at 25 ℃ (ITSR). Only the vertical ram movement was measured and the uncorrected IDT strength was derived from the maximum load according to Equation (3-4).

\[
S = \frac{2000 \cdot P}{\pi \cdot b \cdot D}
\]  

(3-4)

where,

- \(S\) – tensile strength, kPa
- \(P\) – maximum load, N
- \(b\) – sample thickness, mm
- \(D\) – sample diameter, mm
The low temperature creep compliance and tensile strength were used to determine the master relaxation modulus 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 [116], was used for this calculation. The spreadsheet is based on mechanistic prediction model developed under the Strategic Highway Research Program (SHRP) [50]. The thermal stress is expressed as a hereditary integral, which includes the relaxation function, the shift factor function, the coefficient of thermal expansion of the mixture, the initial temperature, and the rate of temperature drop (5.6 °C/h in this case). The hereditary integral is integrated numerically to give thermal stress as a function of pavement temperature. To determine the fracture resistance of the mixture, the uncorrected IDT strength is corrected to account for the non-linear behavior as explained in NCHRP Report 530 [117] and correlated with field-core testing results by multiplying by 0.63 according to the data from Advanced Asphalt Technology, LLC [118]. The critical pavement cracking temperature \( (T_{\text{crit}}) \) is estimated as the temperature at which the surface thermal stress reaches the fracture resistance of the mixture. A simplified illustration of the calculation principle is demonstrated in Figure 3-4.

![Figure 3-4. Critical Cracking Temperature Calculation Example](image)

**Coaxial Shear Test (CAST)**

The coaxial shear test (CAST) was developed at EMPA (Swiss Federal Laboratories for Materials Science and Technology) in Switzerland. It is a cyclic, axial loading system to determine the complex modulus \( (E^*) \) and phase angle of asphalt mixtures [119]. The shear load is applied perpendicular to the specimen’s circular surface through the central core, with lateral confinement provided by a metal ring surrounding the specimen as illustrated in Figure 3-5. Such setup allows loading along the same axis as that of traffic while the lateral confinement simulates a semi-infinite situation experienced on the road. The complex modulus is calculated by the acquisition software integrated with a finite element model by taking into account the glue properties, specimen
dimensions and geometry of the set-up as explained by Sokolov et al. using Equation (3-5) [120, 121].

\[ G^* = \frac{F_a}{\delta_a} A(G^*) \]  \hspace{1cm} (3-5)

where

- \( G^* \) – complex modulus in shear
- \( F_a \) – force amplitude along the steel core
- \( \delta_a \) – displacement amplitude along the steel core
- \( A(G^*) \) – coefficient function derived from FEA by recursive iteration

Tests were performed on long term aged (five days at 85 °C) donut shaped samples cut to 47 mm height and having a 55 mm hole in the center. A servo-hydraulic tension-compression machine was used for loading and the sample surface temperature during the test was maintained at 30 °C. Sinusoidal vertical deformation in a strain controlled mode with amplitude of 0.01 mm at the central core was applied at 10 Hz frequency.

Fracture Work Density (FWD)

Mixture bottom-up fatigue resistance was also evaluated by determining the fracture work density using indirect test method on 150 mm diameter samples with 50 mm height as described by Wen [122]. The test is conducted at a constant ram movement of 50.4 mm/min at 19 °C temperature. Fracture work is determined by measuring the area under the load-vertical deformation curve until
the load returns to zero as illustrated in Figure 3-6. The work done by the machine ram is dissipated by the specimen, and therefore the fracture work can be determined based only on the load and vertical ram movement. The fracture work density is then calculated by dividing the fracture work by the volume of the specimen. According to Wen [122] the FWD results correlated well with the number of passes to 3 % cracking at FHWA Accelerated Load Facility.

![Figure 3-6. Schematic Diagram of Fracture Work](image)

**Moisture Induced Stress Test (MIST)**

The Moisture Induced Stress Test (MIST) was developed to simulate conditions of repeated pore pressure in saturated a pavement created by moving vehicle tires and has been found to characterize moisture susceptibility of asphalt [123]. MIST consists of a system to use a supply of compressed air to load and apply vacuum to force water out and in through a HMA sample. The conditioning was run according to ASTM D7870 procedure and for this study 5000 cycles of loading with water pressure of 0.28 MPa at 40 °C were applied. The test device is illustrated in Figure 3-7.

![Figure 3-7. MIST Device](image)
4. REJUVENATOR SCREENING STUDY

The first phase of the research was intended as a screening study of multiple rejuvenators and as a proof of concept of 100 % hot mix asphalt recycling. Nine differently originated rejuvenators were tested, including plant oils, waste derived oils, engineered products, as well as traditional and non-traditional refinery base oils. Two different doses of the agents were added to binder extracted from RAP to evaluate their softening potential through testing of kinematic viscosity and penetration at two different temperatures. At 25 °C the softening efficiency varied by a factor of twelve between the most and least effective rejuvenators. Consistency results at different temperatures were used to express temperature susceptibility by means of Penetration Index (PI), Penetration-Viscosity Number (PVN) and Bitumen Test Data Chart (BTDC) of the softened binders. The PI results varied measurably depending on the rejuvenator and supported the low temperature mixture test results, showing that PI may be a good and simple measure of rejuvenation effectiveness. Low temperature mixture embrittlement was evaluated at -10 °C through determination of the indirect tensile strength and creep compliance for rejuvenated 100 % RAP mixture samples. It was concluded that four of the nine tested rejuvenators reduced extracted binder consistency to the necessary level and reduced susceptibility of RAP mixtures to low temperature embrittlement.

4.1. OBJECTIVE

The objective of the first stage of the research was to screen multiple products as potential rejuvenating agents based on their binder softening potential and effect on low temperature properties of asphalt mixture.

4.1. MATERIALS AND EXPERIMENTAL PLAN

4.1.1. Materials

RAP that for the study was reclaimed in the state of New Jersey. This material was used both for design of asphalt mixtures and for extraction of binder to later modify with rejuvenators. Typically a PG 64-22 binder is used for virgin pavements in this region and therefore this grade (from Nustar refinery) was selected as a reference binder and used in mixture design, where necessary. The RAP material had a binder content of 5.1 % and aggregate gradation that corresponds to Superpave 9.5 mm with high dust content (10 %). No modifications were made to the gradation.
Nine different rejuvenating agents were used in the study. Some of them are designed specifically for this purpose, others are versatile materials that are used in different industries and the rest are waste materials of other products that have been previously used for rejuvenating aged asphalt. The products have been labeled by generic descriptor that briefly describes the origin of the product and some of their basic characteristic are included in Table 4-1. The WEO plus Fischer-Tropsch (FT) wax is an outlier from these products since FT wax is used as a compound for lowering the temperature for production of Warm Mix Asphalt [74]. The product was included in the research as recommended by asphalt producers; however evaluation of its properties as WMA additive is out of the scope of this research.
Table 4-1. Rejuvenator Characteristics

<table>
<thead>
<tr>
<th>Rejuvenator</th>
<th>Spec. gravity</th>
<th>Viscosity @135 °C, mm²/s</th>
<th>Engineered or Generic</th>
<th>Petroleum or Organic</th>
<th>Refined or Waste</th>
<th>Molecular structure</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Oil</td>
<td>0.947</td>
<td>5.4</td>
<td>Engineered</td>
<td>Organic</td>
<td>Refined</td>
<td>Ring and Strand</td>
<td>Mild</td>
</tr>
<tr>
<td>Refined Tallow</td>
<td>0.891</td>
<td>3.0</td>
<td>Generic</td>
<td>Organic</td>
<td>Refined</td>
<td>Strand</td>
<td>Mild</td>
</tr>
<tr>
<td>Paraffinic base oil</td>
<td>0.867</td>
<td>2.7</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>Aliphatic</td>
<td>Non</td>
</tr>
<tr>
<td>Aromatic Extract</td>
<td>0.995</td>
<td>9.2</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>Aromatic Ring</td>
<td>Very</td>
</tr>
<tr>
<td>Napthenic flux oil</td>
<td>0.940</td>
<td>11.2</td>
<td>Engineered</td>
<td>Petroleum</td>
<td>Refined</td>
<td>Ring and Strand</td>
<td>Mild</td>
</tr>
<tr>
<td>WEO + FT wax</td>
<td>0.857</td>
<td>40.1</td>
<td>Engineered</td>
<td>Petroleum</td>
<td>Refined</td>
<td>Aliphatic</td>
<td>Slight</td>
</tr>
<tr>
<td>WEO bottoms</td>
<td>0.917</td>
<td>300.1</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Waste</td>
<td>Aliphatic</td>
<td>Slight</td>
</tr>
<tr>
<td>Waste engine oil</td>
<td>0.872</td>
<td>3.9</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Waste</td>
<td>Aliphatic</td>
<td>Slight</td>
</tr>
<tr>
<td>Distilled Tall Oil</td>
<td>0.950</td>
<td>5.6</td>
<td>Generic</td>
<td>Organic</td>
<td>Refined</td>
<td>Ring and Strand</td>
<td>Mild</td>
</tr>
</tbody>
</table>

4.1.2. Experimental Plan

A simple methodology was adopted to allow evaluating multiple products. Penetration (at 25 °C) and kinematic viscosity (at 135 °C) tests were chosen for bitumen characterization while the mixtures were tested for creep compliance and indirect tensile strength at -10 °C. These tests are considered to characterize thermal cracking potential [117, 116]. Ten different sets of 100 % RAP mixture samples were prepared, including reference and nine rejuvenated mixes. The samples were mixed with the respective dose of rejuvenator (discussed later) after 2 hour heating at 150 °C and aged for 2 hours before compaction at the same temperature. All tests were performed according to description in Section 3, except that tensile strength was tested on samples of 100 mm diameter and 55.6 mm height.

In addition, application of Penetration Index (PI) and Penetration-Viscosity Number (PVN) was evaluated for characterization of binder rejuvenation. This type of result expression has been reported as good indication for oxidative hardening and cracking [75, 74]. These types of distresses are of particular concern for high RAP mixtures and use of rejuvenators.
4.2. BINDER TEST RESULTS

Based on the expected performance and industry experience on the effectiveness of the rejuvenators, two different dose rates were applied (18.26 % or 9 % from asphalt mass). The test results are summarized in Table 4-2 and show that all products soften the reference unmodified RAP extracted binder which has a very low penetration value (4.0 ×0.1 mm at 4 °C, 16.3 ×0.1 mm at 25 °C) and very high kinematic viscosity (2054 mm²/s). The virgin Nustar PG 64-22 has been included in the table for reference purposes to demonstrate the consistency results of a typical binder that is used in this climatic region. The consistency of the RAP rejuvenated binder varies significantly among the different products. Some of the rejuvenators have reduced the viscosity at 25 °C to a level that has been observed for virgin binders in this climatic region (around 80-90 ×0.1 mm), while others have a significantly smaller effect on the change in penetration. The column "dose to reach virgin binder penetration" shows that refined tallow is the most effective at reducing viscosity of the aged asphalt while the use of napthenic flux oil, WEO+FT wax or Waste Engine Oil (WEO) bottoms does not allow to reach the penetration level of virgin binder within a reasonable dose rate. Overdose of rejuvenator will lead to adhesion and stripping problems.

Most of the rejuvenators have significantly decreased kinematic viscosity of the extracted binder and it has reached a level that is comparable with that of the virgin binder, which has a viscosity of 474 mm²/s. The kinematic viscosity is closely linked with the required mixing and compaction temperature. Approximately 0.2 to 0.6 Pa·s is the recommended viscosity range for mixing to ensure sufficient coating of the aggregates and 5 to 30 Pa·s is the suggested range to guarantee adequate workability for paving [40]. To demonstrate this, the rejuvenated binders are plotted in Bitumen Test Data Chart (BTDC) in Figure 4-2. Only two tests are used to develop this chart which does not allow the evaluation of the linearity of viscosity change. However, for demonstrating the relative change in compaction and mixing temperature this is considered appropriate. WEO bottoms show significantly higher viscosity compared to other products meaning that mixing and compaction temperature would have to be increased by approximately 22 °C compared to the virgin binder. Paraffinic base oil, WEO and aromatic extract provide similar viscosity to virgin binder, while other products are somewhat more viscous. Low viscosity at mixing temperature is even more important in a conventional recipe that consists of both virgin and RAP materials. It is necessary to ensure enough binder flow to guarantee similar film thickness of virgin and RAP aggregates and uniform blending of fresh and RAP binder. Temperature/viscosity dependence is critically important factor for ensuring this and since using very high temperature will damage binder, it is recommended to choose a rejuvenator that can ensure sufficient reduction of the high temperature viscosity.
### Table 4-2. Bitumen Test Results

<table>
<thead>
<tr>
<th>Rejuvenator</th>
<th>Rejuvenator dose, % from binder mass</th>
<th>Penetration @ 4 °C, ×0.1mm</th>
<th>Penetration @ 25 °C, ×0.1mm</th>
<th>Dose to reach virgin penetration, %</th>
<th>Kinematic viscosity @135 °C, mm²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted RAP binder</td>
<td>0</td>
<td>4.0</td>
<td>16.3</td>
<td>na</td>
<td>2054</td>
</tr>
<tr>
<td>Virgin Nustar PG 64-22</td>
<td>0</td>
<td>8.7</td>
<td>85.0</td>
<td>na</td>
<td>474</td>
</tr>
<tr>
<td>Organic oil</td>
<td>9</td>
<td>9.3</td>
<td>54.0</td>
<td>11.2</td>
<td>831</td>
</tr>
<tr>
<td>Refined tallow</td>
<td>9</td>
<td>17.0</td>
<td>83.7</td>
<td>9.7</td>
<td>612</td>
</tr>
<tr>
<td>Paraffinic base oil</td>
<td>18.26</td>
<td>20.3</td>
<td>91.3</td>
<td>18.3</td>
<td>379</td>
</tr>
<tr>
<td>Aromatic extract</td>
<td>18.26</td>
<td>14.3</td>
<td>95.0</td>
<td>18.3</td>
<td>406</td>
</tr>
<tr>
<td>Napthenic flux oil</td>
<td>18.26</td>
<td>11.3</td>
<td>51.3</td>
<td>&gt;20</td>
<td>699</td>
</tr>
<tr>
<td>WEO+FT wax</td>
<td>18.26</td>
<td>8.3</td>
<td>28.0</td>
<td>&gt;20</td>
<td>1006</td>
</tr>
<tr>
<td>Waste engine oil bottoms</td>
<td>18.26</td>
<td>10.0</td>
<td>32.3</td>
<td>&gt;20</td>
<td>2054</td>
</tr>
<tr>
<td>Waste engine oil</td>
<td>18.26</td>
<td>20.3</td>
<td>87.7</td>
<td>18.2</td>
<td>457</td>
</tr>
<tr>
<td>Distilled tall oil</td>
<td>9</td>
<td>10.0</td>
<td>46.3</td>
<td>12.7</td>
<td>893</td>
</tr>
</tbody>
</table>

*interpolated penetration value at 90 ×0.1mm from two penetration measurements was used for calculation

na = not applicable

**Figure 4-2. BTDC with Rejuvenators from Screening Study**
4.2.1. Calculation of Viscosity

The Refutas equation (4-1)-(4-3) has been previously used to predict the viscosity of blends of petroleum products [124]. It was used in this study to verify its suitability of prediction of the viscosity of rejuvenator and extracted binder blends.

\[
\nu_{blend} = \exp\left[\exp\left(\frac{VBI_{blend} - 10.975}{14.535}\right)\right] - 0.8 \tag{4-1}
\]

\[
VBI_{blend} = \sum_{i=1}^{N} f_i VBI_i \tag{4-2}
\]

\[
VBI_i = 14.354 \cdot \ln[\ln(\nu_i + 0.8)] + 10.975 \tag{4-3}
\]

where,
- VBI – viscosity blending index of the components I
- \(\nu\) – kinematic viscosity, cSt (Table 4-1and Table 4-2)
- \(f_i\) – mass fraction of component i (density in Table 4-1)

The measured versus calculated viscosity are presented in Figure 4-3 and show good linear correlation \(R^2=0.89\), meaning that the viscosity of the blend can be predicted with high precision, without the need to perform extensive amount of extraction and testing. This allows screening products that cannot soften the RAP binder enough to produce workable mixture. Interestingly, all petroleum-based products, expect aromatic extract, have aligned above the line of equality, while data points for organic products are located below this line. This means that the viscosity of the blend would be slightly under-predicted for the rejuvenators above the line of equality and vice versa.
Penetration Index (PI) describes the temperature susceptibility of a binder and the PI ranges in this system for road pavement materials vary from around -3 for highly temperature susceptible asphalt to +7 for highly blown or low-temperature susceptible (high PI) asphalt [40]. S. Hesp et al. in their research on field performance of binder that has been modified with refined WEO residue [74, 75] suggest the use of PI for ranking asphalt in respect to its expected performance of thermal and fatigue cracking. Their research proposes the PI and PVN as good measures of steric hardening (asphaltenic structure formulation over time) that promotes accelerated oxidative hardening and gel-type structure which retains higher stress levels at low temperatures. When bitumen ages, its PI usually increases, indicating more structured and brittle material that is less able to flow and thus more prone to cracking [74]. According to their research an increase in PI compared to the source bitumen, despite correspondence to the required low temperature Performance Grade (PG), indicates low-temperature cracking susceptibility. A successful restoring of aged RAP binder properties should reverse this process and thus the decreasing of PI compared to the extracted asphalt may be a good indicator of the rejuvenation quality.

The most common method for calculating PI is through the use of the Pfeiffer and Van Doormaal formula which requires determination of penetration at 25 °C and softening point (equation (4-4)). It is based on the hypothesis that at the temperature of softening point, the penetration is 800mm [40]. However, while this is true for most "normal" temperature susceptibility bitumen, modified binders, oxidized binders and binders from waxy crude oils may deliver erroneous PI due to a
spread of actual penetration at softening point temperature and therefore require a different approach for the calculation of PI.

\[
PI = \frac{1952 - 500 \cdot \log \text{penetration} - 20 \cdot \text{softening point}}{50 \cdot \log \text{penetration} - \text{softening point} - 120}
\]  

(4-4)

PI was calculated from penetration results at temperatures of 4 °C and 25 °C according to the formula in Equation (4-5) and (4-6), developed by Pfeiffer and Van Doormaal (9).

\[
PI = \frac{20(1 - 25 \cdot A)}{1 + 50 \cdot A}
\]  

(4-5)

\[
A = \frac{(\log \text{PEN at } T_1) - (\log \text{PEN at } T_2)}{T_1 - T_2}
\]  

(4-6)

where,

\[T_1, T_2 – \text{test temperatures one and two, } ^\circ\text{C}\]

\[\text{PEN – Penetration, } \times 0.1 \text{ mm}\]

The results of PI for the rejuvenated asphalts are summarized in Figure 4-4. Most of the rejuvenators have decreased the PI, but WEO+FT wax and WEO bottoms have increased it meaning that these samples are more temperature sensitive compared to the extracted binder and possibly have higher potential of cracking. Aromatic extract and Organic oil have decreased the PI considerably more than the other rejuvenators, but they still have significantly higher value compared to the reference virgin PG 64-22 binder with a PI of -1.06. This, however, might be because of different crude oil source of this binder compared to the RAP binder.

A drawback of this method is that the determination of penetration at low temperature (in this case 4 °C) may have relatively large statistical deviation since the actual measured values are small; therefore minor inaccuracies in measurement can significantly influence the calculated PI. For this reason the use of Penetration-Viscosity Number (PVN) as an alternative was also evaluated.
4.2.3. Penetration Viscosity Number

Penetration-Viscosity number (PVN) was developed by McLeod as an alternative to the PI [125]. PVN is calculated from the kinematic viscosity at 135 °C and penetration at 25 °C according to equations (4-7) to (4-9) [125]. High PVN indicates low thermal susceptibility while low PVN indicates high thermal susceptibility.

\[
PVN = \frac{\log L - \log X}{\log L - \log M} \cdot (-1.5),
\]

(4-7)

\[
\log L = 4.2580 - 0.79674 \cdot \log P
\]

(4-8)

\[
\log M = 3.46289 - 0.61094 \cdot \log P
\]

(4-9)

where
X – kinematic viscosity at 135 °C, cSt
L – viscosity at 135 °C for a PVN of 0.0, cSt
M – viscosity at 135 °C for a PVN of -1.5, cSt
P – penetration at 25 °C, 1/10 mm

All of the rejuvenators have decreased the PVN of the RAP extracted binder with exception of WEO bottoms (Figure 4-5). Five of the rejuvenated asphalts have PVN’s that are in the same range or lower than that for Nustar virgin binder.

The calculated PVN results show significantly different numerical values compared to the PI and the results do not correlate with each other. In general the results are of smaller range and much lower than for PI. There are two reasons for this. Firstly, the PVN was intended to characterize unmodified binders and calibrated to have the same numerical values as the PI within the PI range of -1.5 to 0.0 [125], which is outside the range observed in this study. Secondly, the actual measured consistency at the three measured temperatures does not form a linear relationship as, according to Heukelom’s Bitumen Test Data Chart (BTDC) [126], it would be for normal paving grade (S class) bitumen with limited wax content [40]. An example of the results, plotted in BTDC is shown in Figure 4-6. The available data allows assuming that the tested binders correspond to the B class (from Blown) [40], with possible exception of WEO+FT wax which has wax in it. The association with blown binders is reasonable, since the RAP binder has been oxidized during the service period. The non-linear temperature susceptibility in BTDC shows that the PVN for RAP binders may be beneficial for characterization of medium to high temperature properties but, since there is no linear correlation with low temperature viscosity, it cannot be used for characterization of low temperature properties and cracking.
4.3. MIXTURE TEST RESULTS

4.3.1. Rejuvenator Dose

The asphalt mixture samples were prepared based on the following considerations:

1) The penetration at 25 °C for the rejuvenated samples must be similar to virgin binder (PG 64-22), if possible without exceeding reasonable rejuvenator content.

2) All samples must have equal binder content and hence, film thickness.
The target binder penetration at 25 °C of the rejuvenated samples was defined as 90 ×0.1mm which is close to the Nustar PG 64-22 penetration. The dose was calculated after some additional penetration measurements and defined according to supposition as illustrated in Figure 4-7. The required rejuvenator amount to attain the required penetration for the WEO, aromatic extract and paraffinic base oil was close to the dose used in the asphalt binder study; therefore the verified amount (18.26 % of asphalt binder mass) was chosen for the preparation of the respective asphalt mixture samples.

The products that cannot ensure the required penetration, without exceeding reasonable dose range, were added at a rate of 18.26 % (from binder mass) in order to reach equal film thickness with the rest of samples. For the mixtures for which lower dose rate of rejuvenator was required to reach the target penetration, the difference between the binder contents was compensated by the addition of virgin Nustar PG 64-22 asphalt. It should not affect the resulting penetration since the penetration values of rejuvenated and fresh binders are very close. Such normalization of binder content to 6.03 % (5.1 % in the RAP + 0.93 % virgin materials) may not be the optimum procedure according to the mixture design principles. However, for the purposes of directly comparing the different rejuvenator performance, this method was found to be most suitable since it allows comparing the performance in testing of different agents without introducing new variables (e.g. virgin aggregates to reduce binder content). In fact, the relatively high final binder content allows highlighting the rejuvenator performance. The rejuvenator and virgin binder doses that were used for the mixture study are summarized in Table 4-3.
### Table 4-3. Rejuvenator and Virgin Binder Dose in Mixture Samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Rejuvenator dose, % from binder mass</th>
<th>Virgin asphalt dose, % from binder mass</th>
<th>Penetration at 25 °C, ×0.1mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>na</td>
<td>18.26</td>
<td>-</td>
</tr>
<tr>
<td>Organic oil</td>
<td>11.52</td>
<td>6.74</td>
<td>90.0*</td>
</tr>
<tr>
<td>Refined tallow</td>
<td>9.68</td>
<td>8.58</td>
<td>90.0*</td>
</tr>
<tr>
<td>Paraffinic base oil</td>
<td>18.26</td>
<td>na</td>
<td>91.3</td>
</tr>
<tr>
<td>Aromatic extract</td>
<td>18.26</td>
<td>na</td>
<td>95.0</td>
</tr>
<tr>
<td>Napthenic flux oil</td>
<td>18.26</td>
<td>na</td>
<td>51.3</td>
</tr>
<tr>
<td>Storbit Plus</td>
<td>18.26</td>
<td>na</td>
<td>28.0</td>
</tr>
<tr>
<td>Waste engine oil bottoms</td>
<td>18.26</td>
<td>na</td>
<td>32.3</td>
</tr>
<tr>
<td>Waste engine oil</td>
<td>18.26</td>
<td>na</td>
<td>87.7</td>
</tr>
<tr>
<td>Distilled tall oil</td>
<td>12.71</td>
<td>5.55</td>
<td>90.0*</td>
</tr>
</tbody>
</table>

*calculated based on test results

na = not applicable

#### 4.3.2. Test Results

The mixture test results are presented in Figure 4-8 and Figure 4-9. The reader should keep in mind that the reference mixture has 18.26 % of PG 64-22 virgin binder added to it, in order to reach equal asphalt content compared with the rejuvenated mixtures. Therefore, it can also be attributed as having somewhat improved low temperature performance compared to the milled RAP material.

Creep compliance is a way of characterizing the stiffness of material. The less stiff the pavement is at low temperature, the lower the possibility of cracks. The results in Figure 4-8 show that in most cases creep compliance has been increased after addition of rejuvenating agent, therefore reducing cracking potential. The most effective is the paraffinic base oil; however, it is also reflected in the IDT strength (Figure 4-9) where this sample shows much lower result than the other mixtures. Reduction of the rejuvenator content may resolve this problem but doing so would not allow reaching the required penetration of 90 1×0.1 mm.

The products that compared to the reference mixture have maintained or increased the creep compliance, without reducing the tensile strength, can be considered to have reduced the embrittlement of the mixture. Five rejuvenators comply with this provision: organic oil, refined tallow, aromatic extract, napthenic flux oil and distilled tall oil. This finding complies with the PI study where these five exact rejuvenators have showed five most significant reductions in the PI (see Figure 4-4).
WEO+FT wax did not demonstrate the expected performance. It is produced as an asphalt rejuvenator and WMA additive in one. Lowering of production temperature, as intended by the developers of this additive, may highlight the benefits of using this additive; however such evaluation is out of the scope of this paper.

**Figure 4-8. IDT Creep Compliance**

**Figure 4-9. Tensile Strength**
The creep compliance results correlate reasonably well with calculated consistency at -10 °C (Figure 4-10), especially by keeping in mind that the mixture samples unlike binder samples in some cases have virgin binder added to it (see Table 4-3). Binder consistency in this graph is extrapolated based on linear regression from the two measured penetration values and expressed according to the Heukelom consistency calculation from BTDC [126].

![Graph showing correlation between consistency at -10 °C and creep compliance.](image)

*Figure 4-10. Correlation between Consistency at -10 °C and Creep Compliance*

### 4.4. SECTION SUMMARY

The testing data has shown that there are definite differences between the performances of the recycled mixes with the various rejuvenators that are included in the study. The results, that from the discussions above are considered relevant for evaluation of the rejuvenators in this part of the research, are summarized in Table 4-4. They are evaluated based on arbitrary requirement of achieving the required binder consistency and being more effective than simply increasing the binder content as done with the reference mixture:

- Rejuvenator softening effectiveness to reach penetration of a virgin binder (90 ×0.1 mm) at a reasonable dose rate (<20% from binder mass) is required. The selection criteria should also depend on mix properties, but this criterion is offered as a starting point in the process of selection of an appropriate rejuvenator.
- PI of max 2.23 is required to reduce the cracking potential of the RAP extracted binder.
- Creep compliance of more than 0.0151 1/GPa and tensile strength of more than 2469 kPa are arbitrary requirements to make sure that the use of rejuvenating agent is more effective in improving low temperature performance than simply increasing the binder
content. The minimum values have been set within a reasonable error range and in some cases little lower values have been accepted.

The summary of the results in Table 4-4 shows that four rejuvenators - organic oil, refined tallow, aromatic extract and distilled tall oil, have fulfilled the arbitrary requirements at this stage of the research.

Table 4-4. Summary of the Relevant Results for Rejuvenator Acceptance

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dose to reach virgin penetration, %</th>
<th>PI</th>
<th>Creep compliance 1/GPa</th>
<th>Tensile strength, kPa</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement:</td>
<td>&lt; 20</td>
<td>&lt; 2.23</td>
<td>&gt; 0.151</td>
<td>&gt; 2469</td>
<td>na</td>
</tr>
<tr>
<td>Reference</td>
<td>na</td>
<td>na</td>
<td>2.23</td>
<td>na</td>
<td>2469</td>
</tr>
<tr>
<td>Organic oil</td>
<td>11.2 pass</td>
<td>0.64</td>
<td>pass</td>
<td>0.135*</td>
<td>pass</td>
</tr>
<tr>
<td>Refined Tallow</td>
<td>9.7 pass</td>
<td>1.33</td>
<td>pass</td>
<td>0.260</td>
<td>pass</td>
</tr>
<tr>
<td>Paraffinic base oil</td>
<td>18.3 pass</td>
<td>1.74</td>
<td>pass</td>
<td>0.437</td>
<td>pass</td>
</tr>
<tr>
<td>Aromatic Extract</td>
<td>18.3 pass</td>
<td>0.14</td>
<td>pass</td>
<td>0.158</td>
<td>pass</td>
</tr>
<tr>
<td>Napthenic flux oil</td>
<td>&gt;20 fail</td>
<td>1.70</td>
<td>pass</td>
<td>0.317</td>
<td>pass</td>
</tr>
<tr>
<td>WEO+FT wax</td>
<td>&gt;20 fail</td>
<td>3.29</td>
<td>fail</td>
<td>0.199</td>
<td>pass</td>
</tr>
<tr>
<td>WEO bottoms</td>
<td>&gt;20 fail</td>
<td>3.56</td>
<td>fail</td>
<td>0.212</td>
<td>pass</td>
</tr>
<tr>
<td>Waste engine oil</td>
<td>18.2 pass</td>
<td>1.94</td>
<td>pass</td>
<td>0.227</td>
<td>pass</td>
</tr>
<tr>
<td>Distilled Tall Oil</td>
<td>12.7 pass</td>
<td>1.61</td>
<td>pass</td>
<td>0.142*</td>
<td>pass</td>
</tr>
</tbody>
</table>

na = not applicable
*accepted based on reasonable error range of the requirement

4.5. SECTION CONCLUSIONS

The following conclusions can be drawn from the rejuvenator screening study:

- The penetration test is an easy and fast method for the evaluation of softening properties of the rejuvenators. Measuring penetration at two temperatures allows determining PI. This may be a good initial measure for predicting the low temperature mixture performance since the test ranked the rejuvenators in the same order as the mixture test results at -10 °C.
- Because of the original calculation formula that was developed for characterizing binders of much lower PI than used in this study and the non-linear viscosity relation in the
BTDC, PVN does not give dependable results for asphalt binder characterization in the low temperature range.

– The addition of five rejuvenators was found to be effective in maintaining or increasing the low-temperature creep compliance and at the same time increasing the IDT tensile strength, therefore improving low-temperature performance of the mixtures. Four of these rejuvenators also reduced the penetration of the RAP binder to the required level of virgin mixture. They are organic oil, refined tallow, aromatic extract and distilled tall oil.

– Overall this screening study proved that rejuvenation of the binder to the level of the virgin binder is possible and thus the research was carried on to the next phases.
5. COMPLETE CHARACTERISATION OF REJUVENATED BINDER AND 100 % RAP MIXTURE

In this phase the rejuvenator effect on restoring RAP binder and performance-related properties of rejuvenated 100 % RAP mixture were thoroughly evaluated. Six rejuvenators were used in the study: waste vegetable oil, waste vegetable grease, organic oil, distilled tall oil, aromatic extract, and waste engine oil. Test results showed that at 12 % dose most products can ensure the required binder performance grade of PG 64-22 with organic products being more effective than petroleum additives. All products provided rut resistant 100 % RAP mixture and several of them ensured cracking resistance equal to that of virgin reference mixture.

5.1. OBJECTIVE

The objective of this part of the study was to evaluate and compare the use of different rejuvenators for restoring the desirable properties of aged RAP binder and to evaluate the potential to produce rut resistant 100 % RAP hot mix asphalt pavement with improved cracking resistance.

5.2. MATERIALS AND EXPERIMENTAL PLAN

5.2.1. RAP and Mixture Design

The mixture was produced from re-graded 100 % RAP that has been milled from pavements in the state of New Jersey (NJ), US. This material, however, was sampled at a different time than the material used for the screening study (Section 4) so the properties are slightly different. The RAP was crushed and screened in asphalt production plant to nominal maximum aggregate size of 9.5 mm. This is probably the reason for the high dust (filler) content (10.5 %) which did not meet the Superpave gradation requirements (Figure 5-1) for 9.5 mm Nominal Maximum Aggregate Size (NMAS) mixture. The RAP also had a relatively high binder content of 6.19 %. In order to reduce the binder and dust content and to meet the requirements of a 9.5 mm NMAS design the RAP was screened in laboratory. A proportion of 85 % remaining on 2.36 mm sieve and 15 % passing it were used for the re-graded design. The final RAP aggregate composition satisfied Superpave gradation requirements (Figure 5-1) with asphalt binder content of 5.3 % and dust content of 7.9 %. The total binder content increased to 5.94 % after the addition of 12 % rejuvenator by mass of the binder and this rejuvenator content was kept constant for all mixtures evaluated in the study.
5.2.2. Asphalt Binder

Typically, a virgin PG 64-22 binder is used in the climatic area where the RAP was obtained (NJ) and therefore this grade was selected as a reference binder. This binder was also used for design of virgin reference mixture.

5.2.3. Rejuvenators

Six different rejuvenators were used in the study and their origins are briefly described here. Measured kinematic viscosity and the specific gravity along with the some basic characteristics obtained from manufacturers are included in Table 5-1. For comparison, the table also includes characteristics of the used virgin binder.
Table 5-1. Rejuvenator Properties and Description

<table>
<thead>
<tr>
<th>Rejuvenator</th>
<th>Viscosity at 135 °C, mm²/s</th>
<th>Specific gravity</th>
<th>Engineered or Generic</th>
<th>Petroleum or Organic</th>
<th>Refined or Waste</th>
<th>Molecular structure</th>
<th>Polarity</th>
<th>Traditional or Novel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Vegetable Oil</td>
<td>5.17</td>
<td>0.917</td>
<td>Generic</td>
<td>Organic</td>
<td>Waste</td>
<td>Ring and Strand</td>
<td>Non</td>
<td>Novel</td>
</tr>
<tr>
<td>Waste Vegetable Grease</td>
<td>4.28</td>
<td>0.924</td>
<td>Generic</td>
<td>Organic</td>
<td>Waste</td>
<td>Ring and Strand</td>
<td>Mild</td>
<td>Novel</td>
</tr>
<tr>
<td>Organic Oil</td>
<td>5.43</td>
<td>0.947</td>
<td>Engineered</td>
<td>Organic</td>
<td>Refined</td>
<td>Ring and Strand</td>
<td>Very</td>
<td>Novel</td>
</tr>
<tr>
<td>Distilled Tall Oil</td>
<td>5.60</td>
<td>0.950</td>
<td>Generic</td>
<td>Organic</td>
<td>Refined</td>
<td>Ring and Strand</td>
<td>Mild</td>
<td>Traditional</td>
</tr>
<tr>
<td>Aromatic Extract</td>
<td>9.20</td>
<td>0.995</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>Aromatic Ring</td>
<td>Very</td>
<td>Traditional</td>
</tr>
<tr>
<td>Waste Engine Oil</td>
<td>3.86</td>
<td>0.872</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Waste</td>
<td>Aliphatic</td>
<td>Slight</td>
<td>Traditional</td>
</tr>
<tr>
<td>Virgin PG 64-22</td>
<td>474</td>
<td>1.02</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>Ring and Strand</td>
<td>Mixed</td>
<td>Traditional</td>
</tr>
</tbody>
</table>

Waste Vegetable Oil (WV Oil)

WV Oil is increasingly used for bio-diesel production with compositional specifications including low free fatty acid content (<15 %), less than 2 % MIU (Moisture, Impurities, Unsaponifiables) [127]. Derived from fast and convenience food frying oil, it is also referred to as "yellow grease". The product used in this study consists predominately of peanut, sunflower, and canola oils, with large concentrations of Oleic and Linolic acids.

Waste Vegetable Grease (WV Grease)

WV Grease is also a food industry organic waste stream but semi solid at ambient temperatures due to the predominance of saturated Lauric and Myristic triglycerides and needs to be heated most of the year. The product used in this study is high in free fatty acids (>40 %) but with its free glycerin and moisture removed industrially.

Organic Oil

Hydrogreen St™ is an engineered product from PVS Meridian Technologies, Inc. and is designed to be a binder rejuvenator and a low temperature additive. It is composed of products of fast pyrolysis of pine tree biomass with other oils added to balance performance. The product is free flowing at room temperature, but slight heating may be necessary when used in cold weather.
**Distilled Tall Oil**

Tall oil is a byproduct of paper manufacturing and is concentrated from kraft liquors. Tall oil is available either in crude form or as refined product which was used in the study. Crude tall oil contains fatty acids, resin acids and unsaponifiables in varying ratios depending on the tree type used. Tall oils have a long history of use in hot mix manufacturing with many emulsifiers, anti-strip agents and warm mix additives.

**Aromatic Extract**

An aromatic extract is a traditional rejuvenator with dominant polar aromatic rings. Recent findings express concern with unsaturated polar aromatic ring structure that has been shown to be carcinogenic [128]. Therefore, most industries are moving away from polar aromatic oils and towards less polar substitutes. This research is not intended to promote the use of aromatic extract, but rather to allow for the comparison of other products to a rejuvenator that has been used historically and has demonstrated acceptable long term performance.

Aromatic extracts contain approximately 75% aromatic oils and resin compounds with balance saturate oils. Polar aromatics are known to associate with asphaltene molecules and in the process make the binder less brittle, by balancing the chemistry of the oxidized aged binder.

**Waste Engine Oil (WEO)**

Engine lubricating oil is produced from paraffinic base oils with small dose of specialty compounds added to improve viscosity characteristics, stability, cleaning, and flammability. WEO may also contain short chain polar molecules that break apart during lubricating service. Recent interest in waste engine oil re-refineries around the world is making WEO increasingly difficult to obtain and more costly [129]. Waste engine oil should not be confused with waste engine oil bottoms which is the residue from re-refining.

**5.2.4. Experimental Plan**

The test methods of this research phase are indicated in the research plans below and described in full in Section 3. This stage of the study can be divided in two parts and the results in this section are also reported respectively:

1) The rejuvenated binder was characterized with empirical test methods as demonstrated in Figure 5-2 and results are reported in Section 5.3. Additionally a method was developed for evaluation of rejuvenator flushing and it will be described before discussing test results.
2) The rejuvenated binder was graded according to Superpave PG system and, along with 100 % RAP mixture, was characterized using performance-related test methods as summarized in Figure 5-3 and the results are reported in Section 5.4.

For each of these stages each rejuvenator was dosed at 12% of binder mass for both the extracted RAP binder and 100 % RAP mixture. This dose selection is based on the screening study results reported in Section 4. Such rejuvenator content is considered somewhat higher than required for organic additives but lower than optimum for petroleum products. Although this is not the
optimum dose for each specific product, it was selected as a compromise to provide equal total binder content for all mixtures.

Addition of rejuvenators to extracted 100 % RAP binder demonstrates the softening efficiency of the products and allows determining the required dose to satisfy the binder specification requirements. However, it artificially simulates full blending of rejuvenator and RAP binder, which might not be true in asphalt mixtures. Many research results have shown that in reality the blending is somewhere between full and no blending at all [52, 39, 73, 103]. The part of RAP binder that does not significantly change its properties with addition of recycling agent is often attributed to as "black rock" and only performance-related mixture tests can demonstrate the effect of this phenomena. Use of incompatible rejuvenators or overdose are two other concerns that can be addressed by performing mixture testing since these effects would be highlighted by loss of cohesion and adhesion thus leading to raveling and moisture damage. For these reasons 100 % RAP rejuvenated mixtures were prepared for performance-related testing and compared with two reference mixtures:

- To quantify performance of this specific 9.5 mm gradation as a virgin mixture, aggregates were obtained by removing binder from the re-graded RAP in an ignition oven. They were blended with 5.94 % of virgin PG 64-22 bitumen which is equal dose to that of the rejuvenated samples (binder + rejuvenator). This is labeled as "Virgin Mix" in the results.
- To evaluate the benefit of simply increasing binder dose rather than adding rejuvenators, virgin binder was added to the RAP at 12 % of binder mass (equal to dose of rejuvenators). This mixture is named "RAP Mix" and used as representation of un-rejuvenated mixture to correlate with RAP binder in the figures.

5.3. BINDER EMPIRICAL TEST RESULTS
The binder empirical test results at 12 % rejuvenator dose are summarized in Table 5-2. It is evident that the RAP binder has severely aged, having penetration of 19 ×0.1mm, softening point of 74 ℃, and viscosity of 2597 cSt. All rejuvenators have reduced the RAP binder consistency at different temperatures and as expected based on the screening study results (Section 4), organic products are more effective compared to petroleum products. All organic products have increased penetration above that of virgin binder. However, at elevated temperatures (as evident from the softening point and kinematic viscosity tests) the viscosity has remained somewhat higher than that of virgin binder, regardless of the used rejuvenator.
### Table 5-2. Binder Empirical Test Result Summary

<table>
<thead>
<tr>
<th>Rejuvenator</th>
<th>Penetration @ 4 °C, ×0.1 mm</th>
<th>Penetration @ 25 °C, ×0.1 mm</th>
<th>Softening Point, °C</th>
<th>Kinematic Viscosity @ 135 °C, cSt</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP Binder</td>
<td>5.0</td>
<td>19.2</td>
<td>74</td>
<td>2597</td>
</tr>
<tr>
<td>Waste Vegetable Oil</td>
<td>19.3</td>
<td>90.3</td>
<td>54</td>
<td>670</td>
</tr>
<tr>
<td>Waste Vegetable Grease</td>
<td>26.7</td>
<td>140.7</td>
<td>53</td>
<td>591</td>
</tr>
<tr>
<td>Organic Oil</td>
<td>20.0</td>
<td>99.0</td>
<td>54</td>
<td>687</td>
</tr>
<tr>
<td>Distilled Tall Oil</td>
<td>17.2</td>
<td>83.0</td>
<td>54</td>
<td>676</td>
</tr>
<tr>
<td>Aromatic Extract</td>
<td>7.7</td>
<td>41.0</td>
<td>63</td>
<td>1071</td>
</tr>
<tr>
<td>Waste Engine Oil</td>
<td>15.7</td>
<td>66.2</td>
<td>60</td>
<td>818</td>
</tr>
<tr>
<td>Virgin PG 64-22</td>
<td>7.3</td>
<td>77.7</td>
<td>51</td>
<td>425</td>
</tr>
</tbody>
</table>

### 5.3.1. Penetration Index (PI)

As discussed earlier in Section 4.2.2, according to research of Burke and Hesp [74], an increase in PI compared to source bitumen, despite correspondence to the required low temperature Performance Grade (PG), indicates low-temperature cracking susceptibility. To replicate their study PI was calculated from penetration test results at 4 °C and 25 °C temperatures according to Equations (4-5) and (4-6).

Figure 5-4 shows that in all cases the PI has been lowered compared to the extracted binder, suggesting that low temperature performance has been in fact improved. The PI of the virgin binder was not reached, but this might be a result of a differently originated bitumen. The PI was also calculated for another rejuvenator dose (described later in Section 6.3.2) and in all cases higher dose provided lower PI with reduction ranging between 0.01 and 0.88.

![Figure 5-4. Penetration Index at 12 % Rejuvenator Dose](image-url)
5.3.2. Calculation of Kinematic Viscosity

As indicated by Table 5-2, all rejuvenators have significantly decreased the viscosity of RAP binder. Like in the screening study (Section 4.2.1) a calculation of binder and rejuvenator blend viscosity was performed using Refutas equation (4-1) to (4-3) [124].

The measured and calculated kinematic viscosity of all recycled binder samples is demonstrated in Figure 5-5. The results show good correlation. Thus such calculation can allow screening the rejuvenators that cannot soften the RAP binder enough to produce workable mixture. The results also demonstrate an interesting trend: petroleum products have aligned to the left of line of equality while organic products are located to the right of this line. This trend is similar to observations in Screening study reported in Section 4.2.1, where all petroleum products, except Aromatic Extract, also aligned above the line of equality. This may demonstrate compatibility of the different types of oils with the specific asphalt binder but has to be verified in further studies.

![Figure 5-5. Measured and Calculated Kinematic Viscosity](image)

5.3.3. Bitumen Test Data Chart

Kinematic viscosity, softening point and penetration results are summarized in Bitumen Test Data Chart (BTDC) [126]. BTDC was designed to determine the optimum mixing and compaction temperature range that corresponds to the viscosities that are generally recommended for good workability [40]. The results in Figure 5-6 demonstrate that, by addition of rejuvenators, the production and compaction temperature can be reduced by around 20 °C from that of the RAP binder. None of the rejuvenators, however, have quite improved the binder workability to the level of virgin binder at the 12 % dose used in this study.
The BTDC results were also used for determining the laboratory compaction and mixing temperature for the study and 145 °C was chosen since it is within acceptable range for all products tested.

5.3.4. Bleeding Test

The compatibility between rejuvenators and binder needs to be verified in order to ensure a stable, safe and long-lasting mixture. In field studies with the use of incompatible products or inadequate dose or rejuvenators, 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 instable rejuvenation resulting in bleeding or flushing [61, 8]. A hypothesis was framed that the lighter molecules of rejuvenators would tend to migrate towards the surface of the asphalt binder, and a simple test setup was developed for measuring the amount of oils that would result on the surface of the binder sample as illustrated in Figure 5-7(a). It was expected that the process would occur more rapidly under influence of heat so slightly elevated temperature was ensured. The test was executed as follows:

- Extracted binder samples having PG 82-22 were mixed with two doses of each rejuvenator and poured into aluminum foil containers at a thickness of about 35 mm and allowed to cool.
A radiant heat lamp was placed above the samples at a distance to ensure 40±1 °C in the binder sample. The temperature was measured with a thermocouple inserted in a dummy sample.

The samples were pre-heated for 5 minutes and covered with a filter paper that was applied to samples with constant pressure of 0.6 g/cm² for 5 minutes at ambient temperature.

The samples were placed back under the lamp and heated for 7 hours. A photo was taken each hour.

The results were evaluated by visually assessing the darkness (wetness) of the filter paper at each hour on a scale from 0 to 3, where 0 – not wet and 3 – totally wet.

![Figure 5-7. Test Setup (a) and an Image of Test Results After 7 h (b)](image)

The test was executed for two different rejuvenator doses. In Figure 5-7 (b) the inner circle demonstrates 12 % dose while the outer circle is a second dose (6 % for organic products and 18 % for petroleum). The figures taken at each hour are compiled in Video 5-1. It is clear from the figure that RAP binder and the two samples that are rejuvenated with virgin PG 64-22 binder do not exhibit any bleeding. This is likely because of the small amount of volatile fractions in the sample compared to unaged binder. The cumulative test results are illustrated in Figure 5-8 and the score of virgin binder is highlighted with a thick dotted line. The samples that are located above virgin binder score exhibit more bleeding, while the samples below the line did not wet the filter paper as much. As expected, a higher dose of a particular rejuvenator increases bleeding. If the results are evaluated according to the optimum dose from penetration results (discussed later in dose study in Section 6), it is clear that WEO will reduce the bleeding compared to virgin binder, while the
other rejuvenators seem to have a slightly higher bleeding compared to that of the virgin binder and therefore require more attention towards the diffusion and stability in long term.


**Figure 5-8. Bleeding Test Results for Two Doses of Each Rejuvenator**

### 5.4. PERFORMANCE-RELATED PROPERTIES

The correspondence of binder to Superpave PG requirements will be discussed first, followed by subsections of performance-related properties, including both mixture and binder results as well as relationships between the two.

#### 5.4.1. Superpave Performance Grade (PG)

The extracted RAP binder was tested for PG after addition of each of the rejuvenators at 12 % dose and the results, along with true grade of virgin PG 64-22 binder, are illustrated in Figure 5-9. The RAP binder had severely aged and graded as PG 94-12, but the addition of all products allowed reducing both the high and low PG temperature. The required low performance grade temperature
of -22 °C was reached in all cases except when using WEO. The organic products (WV Oil, WV Grease, Organic Oil, Distilled Tall Oil) proved to be more efficient at the 12 % dose compared to petroleum products (Aromatic Extract, WEO) and actually reduced the PG temperature much more than required and below the temperature of the virgin binder (-26 °C). In all cases the PG temperature was defined by the m-value requirement (≥0.3) and for several rejuvenators the temperature at which the binder passes the stiffness requirement (≤300 MPa) was significantly lower than the temperature defined by the m-value. For example 12 % WEO and WV Oil stiffness temperature were below -53 °C. This indicates that both for evaluating binder and mixture properties at low temperature the ability to rapidly disperse the accumulating thermal stress (defined by m-value) should be of primary interest when using rejuvenators.

At the same time all rejuvenators provided the high grade above the level of virgin binder indicating increased resistance to rutting and delivering grade sum that is greater than that of the virgin binder. This shows that, despite the general concern, if adequate dose of rejuvenator is used and proper diffusion and blending occurs in the asphalt binder film, there is no danger of increased rutting susceptibility with the use of rejuvenators. All of the rejuvenated binders passed the Superpave intermediate temperature requirement (≤5,000kPa) at the standard test temperature for PG 64-22 binder at 25 °C. These results are discussed in detail later along with other fatigue results in Section 5.4.5.

![Figure 5-9 Continuous Performance Grade of Rejuvenated Binders](image)

### Susceptibility to Aging

The volatilization results from aging the samples in RTFO, along with the Superpave requirement of less than 1 % mass loss, are shown in Figure 5-10. The virgin binder results demonstrate only 0.2 % mass loss while the extracted RAP binder exhibits significant reduction of volatile fractions
and barely passes the requirement. This is likely a result of incomplete distillation of solvent from the RAP binder during extraction. At the RTFO aging any residual solvent would evaporate thus contributing to the mass loss. Most of the rejuvenated binders exceed the allowable 1 % mass loss; however, this is partly because of the high "initial" mass loss of RAP binder. Therefore, in order to demonstrate the "true" off gassing that is caused by the use of rejuvenators, the "initial" mass loss portion that is caused by RAP binder (0.93 %) has been subtracted from total mass loss and colored with lighter shade in the plot. Consecutively the dark bar demonstrates the rejuvenator portion of the mass loss. This shows that only the WEO exceeds the allowable limits of volatilization, while other rejuvenators have less than 0.5 % loss and WV Oil as well as aromatic extract does not cause any additional mass loss compared to that of the RAP binder.

![Figure 5-10. Mass Loss After RTFO](image)

Superpave specifications require the determination of high PG temperature on both original and short term aged (RTFO) binder. Different minimum G*/sinδ requirement is defined at each of these states as indicated in Table 3-1 and temperature at which binder can pass these requirements is determined. Lowest of the two temperatures at which the requirement is met is defined as the high PG. While these requirements are empirical, they allow comparing the effect of rejuvenators on the aging of the samples. As illustrated in Figure 5-11 both virgin and RAP binder PG temperature remained constant after aging whereas the use of WEO and WV Grease increased the temperature by around 4 °C. This shows that the resistance to rutting will increase over time, but may be an indicator of accelerated aging that can lead to cracking failures. Closer analysis of the data did not reveal dominance of either increased stiffness (G*) nor higher elasticity (reduced phase angle) as the sole cause of the different aging properties of the rejuvenators compared to the neat binders.
5.4.2. Rutting and Moisture Susceptibility

The Hamburg WTT results are illustrated in Figure 5-12 along with the Texas DOT requirement for maximum rut depth (12.5 mm at 10,000 wheel passes for PG 64-22 binder). As expected due to the aged binder, the RAP mixture has the highest rutting resistance. Rejuvenators have slightly increased the rut depth but all of them pass the rutting requirement. The only sample that fails this requirement 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 (5.94 %).

Figure 5-12 also illustrates stripping inflection point. Most of the rejuvenated mixtures did not reach this within the test period of 20,000 wheel passes. According to Colorado DOT [130] inflection point before 10,000 passes indicates moisture susceptibility. WV Oil and Virgin Mix failed this requirement, but the Organic Oil, although reduced moisture resistance of the source RAP, passed this criterion.
Chapter 5

Complete Characterisation of Rejuvenated Binder and 100 % RAP Mixture

Correlation of Hamburg WTT with High PG Temperature

Figure 5-13(a) demonstrates rut depth at 20,000 wheel passes while Figure 5-13(b) indicates wheel passes to 12.5 mm rut depth (third order polynomial function was used to extrapolate the results to 12.5 mm). These results are plotted versus the binder high PG temperature. As expected, the results demonstrate increase higher rutting for lower PG temperature. The relatively good correlation indicates that binder PG grade, when using rejuvenators, is as good rutting performance indicator as it is for any virgin binder. The initial selection of rejuvenator maximum dose can therefore be based on the desired binder high PG temperature. However, this might hold true only if rejuvenator diffusion is completed and good blending with binder occurs (assuming no "black rock" effect).
**Correlation of Hamburg WTT with Penetration**

The correlation between binder penetration and Hamburg WTT rut depth at 10,000 passes and penetration at 12.5 mm rut depth are illustrated in Figure 5-14a and Figure 5-14b respectively. High conformity with exponential ($R^2=0.97$) and linear ($R^2=0.87$) regressions exists. This suggests that excessive rutting due to binder softening should not be an issue if the rejuvenator dose is calculated according to penetration results.

![Figure 5-14. Correlation of Hamburg WTT Results and Binder Penetration](image)

In all cases except correlation of high PG with passes to 12.5 mm (Figure 5-13b) the virgin mixture does not fit into the trend of recycled mixtures (in Figure 5-13a and Figure 5-14a virgin mix is not demonstrated in figure since it failed before reaching 10,000 wheel passes). This mixture was prepared by burning RAP binder and replacing with equal amount of virgin binder. The possible explanations for the rutting failure of this mix include:

- loss of fines during burning process and therefore excessive binder content.
- moisture damage failure.
- somewhat lower binder consistency.
- "black rock" situation (lower effective binder content) in rejuvenated mixtures.

Mixture design optimization according to volumetric and performance criteria would likely require reduction in binder content of this mixture, but such design was out of the scope of this research.

**Correlation of Hamburg WTT with Softening Point**

The relationship between softening point and Hamburg WTT is illustrated in Figure 5-15 but shows somewhat lower correlation then the penetration and PG results with linear regression $R^2$ values between 0.48 and 0.75.
Moisture Susceptibility of Field Samples

A short study was performed to evaluate the moisture susceptibility of road cores of 100% recycled mixes. The samples were obtained from 154th street between 25th and 26th avenue in Queensborough, NYC (Figure 5-16). This 100 % RAP pavement was paved in 2011 using WEO as rejuvenator. Samples were cored in 2011 soon after construction and repeatedly at the same locations in July of 2013.

In addition, samples were produced from the same mixture in laboratory providing a total of three sets of samples:
1) Plant-mixed, road-compacted (PM-RC): samples obtained from road cores. One set of samples was cored soon after construction while another two years later.

2) Plant-mixed, laboratory-compacted (PM-LC): mixture was sampled during production and compacted after reheating in laboratory.

3) Laboratory-mixed, laboratory-compacted (LM-LC): materials were sampled during production and prepared according to the same mix design in laboratory.

The results are presented in Table 5-3 and show that air voids after road construction match the aimed 7.0 %. After two years of service the asphalt pavement had further densified having air voids of 2.0-4.8 %. Before determining tensile strength, half of the samples were exposed to MIST while other half was tested dry. The Tensile Strength Ratio (TSR) for all sample is very high, having no loss of strength after moisture conditioning. Thus all samples well exceed the traditional requirement of saturated to dry strength of 0.8. The tensile strength of LM-LC was the highest of all samples, but due to different sample dimensions, this cannot be directly compared to the road cores. One other parameter indicating moisture damage is large change (more than 1.25 % [131]) in bulk specific gravity (BSG) after MIST test, but as demonstrated in table none of the samples experienced such problem.
Table 5-3. Tensile Strength Ratio for Differently Prepared Samples

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Diameter, mm</th>
<th>Height, mm</th>
<th>Air voids after construction, %</th>
<th>Dry air voids, %</th>
<th>BSG change after MIST, %</th>
<th>Tensile strength, kPa</th>
<th>Paired TSR</th>
<th>Average TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road cores: Plant-Mixed Road-Compacted</td>
<td>100</td>
<td>50.0</td>
<td>7.1</td>
<td>2.0</td>
<td>-0.5</td>
<td>492</td>
<td>1.01</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>50.1</td>
<td>7.1</td>
<td>2.4</td>
<td></td>
<td>485</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>38.5</td>
<td>7.0</td>
<td>3.6</td>
<td>-0.5</td>
<td>399</td>
<td>0.90</td>
<td></td>
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<tr>
<td></td>
<td>100</td>
<td>39.7</td>
<td>7.0</td>
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<td></td>
<td>441</td>
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<td></td>
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<tr>
<td></td>
<td>100</td>
<td>53.0</td>
<td>6.9</td>
<td>4.4</td>
<td>-0.3</td>
<td>409</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>53.7</td>
<td>6.9</td>
<td>4.8</td>
<td></td>
<td>393</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant-Mixed Laboratory-Compacted</td>
<td>150</td>
<td>95.5</td>
<td>-</td>
<td>7.1</td>
<td>0.0</td>
<td>427</td>
<td>0.97</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>94.6</td>
<td>-</td>
<td>7.0</td>
<td></td>
<td>439</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
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<td>-</td>
<td>6.9</td>
<td>0.1</td>
<td>451</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>94.5</td>
<td>-</td>
<td>6.9</td>
<td></td>
<td>420</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>94.9</td>
<td>-</td>
<td>7.3</td>
<td>0.0</td>
<td>445</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>95.4</td>
<td>-</td>
<td>7.0</td>
<td></td>
<td>457</td>
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<td></td>
</tr>
<tr>
<td>Laboratory-Mixed Laboratory-Compacted</td>
<td>150</td>
<td>94.3</td>
<td>-</td>
<td>5.7</td>
<td>-0.4</td>
<td>562</td>
<td>1.15</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>94.3</td>
<td>-</td>
<td>5.8</td>
<td></td>
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<td>6.1</td>
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<td>579</td>
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<td>-</td>
<td>5.9</td>
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<td>571</td>
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</tr>
<tr>
<td></td>
<td>150</td>
<td>94.4</td>
<td>-</td>
<td>5.9</td>
<td>-0.6</td>
<td>500</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>94.3</td>
<td>-</td>
<td>5.9</td>
<td></td>
<td>561</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.4.3. Workability

Mixture workability was evaluated by the number of gyrations to reach 8 % air voids and the results are illustrated in Figure 5-17. As expected from the bitumen viscosity results (BTDC in Figure 5-6), virgin mix has the highest workability and all the rejuvenators have increased mix compactability compared to RAP mix. However, the correlation of rejuvenator viscosity and gyratory workability is very poor. For example, viscosity results in BTDC show that binders modified with waste vegetable oil and grease have almost equal consistency, but the mixture compactability demonstrates distinct differences between these mixtures.
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Figure 5-17. Gyratory Workability

Correlation of Mixture Workability with Binder Viscosity

To further evaluate the relationship between binder and mixture workability, Superpave rotational viscosity of binder is correlated with mixture gyrations to 8 % air voids. It is hypothesized that, since the mixture compaction temperature (around 145 °C) is close to the test temperature of viscosity (135 °C), the two results should be in good agreement unless other factors affect mix workability. The correlation is illustrated in Figure 5-18 and, as expected, all of the recycled mixtures/binders align between the virgin and RAP data points both based on binder viscosity and on mix workability. They, however, show poor correlation, which might be affected by diffusion rate of the rejuvenators. The binder results by default provide 100% rejuvenator blending, while in the mixture the extent of diffusion and binder activation depends on the time, temperature, rejuvenator and binder type. It is possible that at the time of compaction part of RAP binder might be behaving as "black rock" [132], thus increasing the required compaction energy. The "black rock" binder content extremes in this case are the Virgin binder/mix and the RAP binder/mix (squares). The former demonstrates the mixture workability of virgin mix with all of binder contributing to the mixture workability and the latter, along with highest viscosity, can be reasonably assumed to have the least activated binder content. Further research is necessary to evaluate this phenomenon.

Superpave requirement for rotational viscosity of less than 3 Pa·s is also indicated in the figure and show that all rejuvenators have reduced the viscosity from 4.3 Pa·s to the required level.
At the least, these results demonstrate that caution should be used when evaluating the workability of rejuvenated binder since the results might not be reflected in compactability of mixture. Unlike for conventional binders, the increase in temperature will not only reduce the viscosity but also significantly facilitate the diffusion, affecting the effective binder content and lubricity of binder surface.

### 5.4.4. Low Temperature Cracking

Neither stiffness nor strength alone determines when a mixture will crack. A stiff mixture will not crack if its strength is high enough; and a weaker mixture will not crack if it is sufficiently flexible [54]. Strength of rejuvenated mixtures was tested by indirect tensile strength test, while creep compliance can be characterized as the reverse property of asphalt stiffness. Evaluation of this property at low temperature shows the pavement’s potential to creep under thermal load stress at low temperatures. The less stiff the pavement at low temperature, the lower the possibility of cracks.

Figure 5-19, Figure 5-20, and Figure 5-21 demonstrates the test results of creep compliance up to 1000 seconds at 0 °C, -10 °C, and -20 °C respectively. As expected RAP mixture has the highest stiffness (lowest compliance) due to the presence of aged RAP binder in most temperatures. Virgin mix has the lowest stiffness at 0 °C while at other temperatures WEO and WV Oil are less stiff. Other rejuvenators have reduced the stiffness (except distilled tall oil and organic oil at -20 °C) compared to RAP mixture but the rejuvenated mix is more stiff than the virgin mix.
Chapter 5  Complete Characterisation of Rejuvenated Binder and 100 % RAP Mixture

Figure 5-19. Creep Compliance at 0 °C

Figure 5-20. Creep Compliance at -10 °C

Figure 5-21. Creep Compliance at -20 °C
The creep compliance results up to 100 seconds (indicated by a dotted line in the figures above) along with tensile strength were used for calculation of critical cracking temperature using LTSTRESS. It is a MS Excel™ based spreadsheet developed by Don Christensen (see description in Section 3.2.) that uses both stiffness and strength for calculation of critical cracking temperature ($t_{\text{crit}}$) as demonstrated in Figure 3-4. Figure 5-22 shows the calculated $t_{\text{crit}}$ for each mixture along with tensile strength at -10 °C (used for calculation). The strength is plotted on a reverse scale relative to the source RAP mixture to provide visual comparison with cracking temperature.

Most of the rejuvenators have improved the cracking resistance compared to the source RAP mixture. The Aromatic Extract and WV Oil even provide cracking temperature similar to the virgin mixture. Note that, as shown by the rutting test, this mixture would require reduction of binder content or change of binder grade thus likely the cracking temperature would increase (become more positive). On the other hand the dose of rejuvenators may be increased for most cases without increasing susceptibility to rutting. This would reduce stiffness and likely lower the cracking temperature.

Most of the rejuvenated mixes have very similar tensile strength compared to the source RAP Mix, hence the lowering in cracking temperature is generally caused by reduced stiffness as illustrated in Figure 5-19 through Figure 5-21. Only Aromatic Extract has provided statistically higher tensile strength compared to RAP Mix, which is the cause of reduction in cracking temperature (the mixture stiffness by application of this additive was reduced similarly to others). The good performance of WV Oil rejuvenated mixture, conversely, is caused by most reduction in mixture stiffness. WEO also provides relatively large reduction in stiffness, but due to lowered strength demonstrates only average $t_{\text{crit}}$. The relatively poor performance of Distilled Tall Oil sample is caused by insignificant change in mixture stiffness.

![Figure 5-22. Mixture Critical Cracking Temperature and Tensile Strength at -10 °C](image-url)
**Correlation of Mixture Cracking and Binder Low PG Temperatures**

Critical cracking temperature of mixture is compared with the respective binder low PG temperature in Figure 5-23. The samples that are rejuvenated using petroleum additives (illustrated as rhombs) provide similar mixture cracking temperature to the samples using organic products (squares). This is despite the fact that petroleum products have higher (more positive) PG low temperature at the selected 12 % dose. There seem to be two almost parallel trends with a PG temperature shift of 10 °C for correlation between the bitumen and mixture critical low temperature of rejuvenated mixtures of the petroleum and organic additives. The reasons for the superior performance of mixtures recycled with petroleum rejuvenators are not identical in all instances as discussed previously and can be seen in Figure 5-19 through Figure 5-22.

![Figure 5-23. Mixture Cracking Temperature VS Bitumen Low Temperature PG](image)

5.4.5. Fatigue

**Bitumen Lineal Sweep (LAS) Test and Superpave Fatigue Requirement**

The binder Linear Amplitude Sweep (LAS) test results in Figure 5-24 on a logarithmic scale demonstrate cycles to failure at four different strain levels. Interestingly at the lowest strain level, RAP binder has the highest fatigue life compared to other samples but as the strain increases its performance gradually decreases until it has the lowest cycles to failure at 10 % strain. Virgin binder has the opposite trend: at high strain level it performs better than at low strain level relative to most other samples. Since the strain level can be attributed to pavement response, this infers that RAP binder would perform better at lower loads or thicker pavements while the virgin binder would be superior at higher loads or thinner pavements.
Chapter 5  Complete Characterisation of Rejuvenated Binder and 100 % RAP Mixture

Figure 5-24. Linear Amplitude Sweep Test Results at Four Strain Levels

Research by Tran et al. [63] found that 5 % strain has the best correlation with mixture fatigue (energy ratio test) and research by Hintz et al. [90] showed that 4 % strain correlates reasonably with cracked area from field sections evaluated through Long-Term Pavement Performance (LTPP) program. Based on these considerations, the performance at 5 % strain is discussed for ranking of rejuvenators. At this strain level, the results demonstrate that the aged RAP binder has a reduced fatigue life compared to the virgin binder. Addition of tall oil and organic oil has increased the number of cycles to fatigue failure compared to extracted binder, but the result is lower than that of virgin binder. The use of WV grease and WV oil provides performance that is similar to the virgin mix. These are the rejuvenators that along with organic oil also provided the lowest binder consistency and relatively higher rut depth compared to the other recycled mixtures. Predictably, this confirms that a reduced binder viscosity provides longer fatigue life. What is unexpected, WEO and Aromatic Extract have almost no effect on cycles to failure compared to RAP binder. This is surprising considering that these products have been extensively used for rejuvenation and provided good field performance. This unsatisfactory performance of WEO and aromatic extract can be partly attributed to the 12 % rejuvenator dose that was used in the study (rather than optimal), which did not provide sufficient reduction in viscosity of the binders. The test method itself, also has to be further correlated with the field performance to demonstrate its ability to simulate fatigue failure mechanisms and determine the optimum strain level for reporting results.

The Superpave intermediate temperature fatigue parameter $G^* \cdot \sin \delta$ (complex shear modulus viscous portion) results are indicated with diamonds in Figure 5-25. For easy visual comparison
with the LAS test, the $G^* \cdot \sin \delta$ results are plotted relative to target virgin binder on a reverse scale so that in both cases higher position indicates better fatigue resistance. The results demonstrate that all rejuvenators have decreased the $G^* \cdot \sin \delta$ from 12,600 kPa for extracted RAP binder to a level that passes the Superpave requirement of maximum 5,000 kPa. Both test method results provide clear distinction between the aged and virgin binder. However, Superpave requirement rates all rejuvenated binders close to performance of virgin binder while LAS test ranking judges some of them as performing similarly to RAP binder.

![Figure 5-25. Linear Amplitude Sweep Test Cycles to Failure at 5 % Strain and Superpave $G^* \cdot \sin \delta$ results](image)

**Mixture Fracture Work Density (FWD)**

The mixture Fracture Work Density (FWD) results in Figure 5-26 demonstrate that most rejuvenators provide FWD similar or slightly better than for the RAP mix. The only exception is WEO, thus suggesting negative effect on bottom-up fatigue resistance. The virgin mix has the highest FWD which is a result of high strain before failure. Just like discussed regarding the low temperature performance, total binder content optimization would likely lower the result.
Figure 5-26. Fracture Work Density

Mixture Coaxial Shear Test (CAST)

Figure 5-27 demonstrates the complex modulus of mixtures as determined using the CAST. In most cases, the mean of two results is reported for each mixture with error bars indicating the average statistical deviation between the samples throughout the test. For RAP Mixture and VW Grease samples only one test was finalized since one of the specimens was damaged during testing. In addition to the mixtures used in the study a mixture with 9.5 mm NMAS design having 20 % RAP content and produced using PG 64-28 binder was also tested. This mix was added to the test matrix in order to compare the rejuvenated mixtures with a conventionally designed mixture that has been approved for application on public roads. This mix was designed according to Superpave specifications by applying 50 gyrations for roads having traffic intensity of 0.3 to 3 ESAL’s (Equivalent Single Axle Loads). All materials and mix design for this sample were obtained from a contractor in the state of Maine, US.

As expected due to the presence of aged binder, the RAP mixture has higher stiffness compared to the virgin and 20 % RAP mixtures. Comparing to the RAP mixture most products have reduced the stiffness while Distilled Tall Oil and, surprisingly considering the previous results, Organic Oil have increased it. The stiffness of all of these samples in general can be considered low. Other studies that have used CAST for up to 1,400,000 cycles at 30 °C and 10 Hz loading frequency report modulus values above 800 MPa [119, 133, 120, 134, 135].
Traditionally, the number of repetitions of loading required to reach a 50% reduction in initial stiffness is considered to be an appropriate parameter for evaluating fatigue performance [136, 137]. However, at the applied strain level (212 micro strain) during the 1.4 million cycles none of the samples exhibited such loss in modulus. Therefore, the procedure described in AASHTO D7460-10 (developed by Tsai et al. [138, 139]) was used for extrapolating the results to failure point based on One-Stage Weibull Survivor Function according to Equation (5-1). The equation is solved for cycles to failure (N) where the stiffness ratio (SR) equals 0.5.

\[
\ln\left(-\ln\left(\frac{SR}{2}\right)\right) = \gamma \cdot \ln(N) + \ln(\lambda)
\]  

(5-1)

Where,
SR – stiffness ratio, beam stiffness at cycle i / initial beam stiffness (at 1000 cycles in this study)
N – number of cycles
\(\gamma\) – the slope of the linear regression of the \(\ln(-\ln(SR))\) versus \(\ln(N)\) as demonstrated in Figure 5-28
\(\ln(\lambda)\) – the y intercept of the linear regression of the \(\ln(-\ln(SR))\) versus \(\ln(N)\) as demonstrated in Figure 5-28
The cycles to failure (50 % reduction in modulus from initial stiffness at 1,000 cycles) are illustrated in Figure 5-29 on a logarithmic scale with bars indicating the maximum and minimum results for the two test samples. As demonstrated earlier in Figure 5-27 Distilled Tall Oil sample had almost no change in the complex modulus therefore it is not illustrated in the figure.

Virgin and 20 % RAP mixtures exhibited very similar performance. The WEO rejuvenated sample has the lowest cycles to failure compared to all other mixes and thus, similar to the FDW results discussed above, has the highest susceptibility to fatigue cracking. All other samples demonstrate longer fatigue life compared to virgin mixture. This may seem counter-intuitive but in fact, fatigue failure generally occurs when the applied loads are too heavy for the pavement structure or more repetitions of a given load are applied than accounted for in design [58]. If the structural design of pavement is sound and thus strain levels in HMA are ensured low, high stiffness materials of low viscosity (such as high RAP mixtures) can be expected to have high resistance to fatigue cracking [59]. Similarly, increased fatigue resistance of high RAP mixtures has been previously demonstrated by multiple laboratory studies [51, 52, 42, 55, 56, 53] as discussed previously in literature review (Section 2.4.1). A more thorough study of the samples by performing tests at other strain levels and temperatures and an analysis of the results with respect to traffic load and anticipated stress levels would be required to provide more conclusive evidences of the expected fatigue behavior of these samples. For example, if the traffic load at a certain temperature causes high strain in the pavement a mixture with high stiffness and high binder viscosity (as in the case of rejuvenated mixtures) would exhibit increased stress and the inability to relieve the stress by flow, could lead to brittle pavement and potential fatigue cracking [140].

---

Figure 5-28. Linear Regression of Ln of the Negative of the Ln of Stiffness Ratio Versus Ln of Loading Cycles for Virgin Mixture

\[ y = 0.2338x - 4.7562 \]

\[ R^2 = 0.9176 \]
Although all of the tests described in this section are designed to demonstrate fatigue performance, they correlate poorly. This is likely due to the very different loading modes between the tests methods and various test temperatures as well as the applied failure criteria.

**5.5. SECTION SUMMARY**

This stage of the study evaluated performance of six different rejuvenators for softening the aged asphalt binder and for improving performance-related properties of extracted RAP binder and 100 % RAP mixtures. The rejuvenators were dosed at 12 % rather than the optimum for each product and performance of each rejuvenator is discussed below and the results are summarized in Table 5-4. The following arbitrary scale is introduced in the table:

- Positive (+1): sample passes the specification pass/fail requirement or if none, performs equal or better than virgin binder/mix.
- Negative (-1): sample fails the specification pass/fail requirement or if none, performs equal or worse than RAP binder/mix.
- Neutral (±0): sample performs better than RAP binder/mix but not as good as virgin binder/mix. Applied only if no pass/fail criteria are available by specifications.

The summary row presents sum of the seven measured performance parameters. Half of each property score is represented by binder test result and the other half is mixture test result (if both results available). This indicates that overall the WV Grease and Organic Oil rejuvenated mixtures had the best performance. In most tests these samples passed the specification requirement or performed similar or better than the virgin mixture. Like all other rejuvenated mixtures these could
not provide mixture workability equal to virgin mix and performed slightly below the level of virgin mix at FDW and mixture low temperature cracking tests.

### Table 5-4. Summary of Test Results

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Requireda</th>
<th>Virgin mix/binder</th>
<th>RAP mix/binder</th>
<th>WV Oil</th>
<th>WV Grease</th>
<th>Organic Oil</th>
<th>Disti. Tall Oil</th>
<th>Arom. Extract</th>
<th>WEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder softening</td>
<td>Penetration</td>
<td>≥77.7 .1mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Softening point</td>
<td>≥51°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rutting</td>
<td>High PG temperature</td>
<td>≥64°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WTT rut depth @10,000</td>
<td>≤12.5mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>WTT inflection point</td>
<td>≥10,000</td>
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<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Aging</td>
<td>Loss of volatiles</td>
<td>≤1%</td>
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<td></td>
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<td></td>
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<tr>
<td>Workability</td>
<td>Rotational viscosity</td>
<td>≤3 Pa · s</td>
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<tr>
<td></td>
<td>Mix workability</td>
<td>≤10gyb</td>
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<tr>
<td>Low temp. cracking</td>
<td>Low PG temperature</td>
<td>≤-22°C</td>
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<tr>
<td></td>
<td>Mixture cracking temp.</td>
<td>≤-22°Cb</td>
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<td></td>
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<tr>
<td>Fatigue</td>
<td>$G^* \cdot \sin \delta$</td>
<td>≤5000kPa</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td>LAS @ 5% strain, cycles</td>
<td>&gt;1078 cycles</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>FWD</td>
<td>&gt;8.0kPa</td>
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<tr>
<td></td>
<td>CAST 50% stiffness loss</td>
<td>&gt;3E+09 cycles</td>
<td></td>
<td></td>
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<tr>
<td>Summary</td>
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<td>4.00</td>
<td>-0.50</td>
<td>3.00</td>
<td>5.25</td>
<td>5.00</td>
<td>4.25</td>
<td>4.75</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>

aRequirement for positive (green) score is indicated
bNo pass/fail requirement available, positive score based on virgin binder/mix performance.

cOnly the rejuvenator portion is considered (see section 5.4.1)

**Virgin Mixture**

Virgin mixture was prepared by burning off the RAP binder and mixing the aggregates with a virgin binder (continuous PG 67-26) at a dose that is equal to that of the rejuvenated mixtures (5.94%). This mixture was the only one to fail the Hamburg WTT test requirement, partly as a result of higher than optimum binder content. Accordingly, this the virgin mixture has the best workability and good low temperature cracking resistance.

**RAP Mixture**

RAP Mixture has 12% of virgin bitumen added to equalize the total binder content with all other mixtures. It was used as a representation of mixture that is close to original reclaimed asphalt and

---

1 Kinematic viscosity is not included in the table, since rotational viscosity provides pass/fail criteria. PI is not included in the table because it is not an established low temperature performance parameter.
compared with the performance of pure RAP binder. As expected due to severe ageing of binder (PG 94-22) this mixture has the lowest workability, high rutting resistance but low thermal cracking resistance. The binder fatigue resistance did not pass the Superpave requirements but the mixture fatigue provided controversial conclusions. According to FWD test the mix fatigue was lower than that of virgin mixture while the CAST test promised increased fatigue life due to lower loss of modulus and higher elasticity.

**WV Oil**

Waste Vegetable Oil at the selected dose of 12% showed the most rejuvenation potential on the aged binder. From all of rejuvenators it provided the highest increase in binder fatigue life and most reduction in performance grade. Along with mixture cracking temperature similar to virgin mixture this promises good overall cracking resistance. However, the Hamburg WTT results suggest that this additive has increased the susceptibility to moisture damage and therefore reduction from the dose of 12% or use of adhesion promoting additives may be necessary.

**WV Grease**

Waste Vegetable Grease increased fatigue resistance of the aged binder to the level of virgin and similarly to other mixtures showed improved performance in CAST repeated loading fatigue test while keeping the FWD similar to RAP mix. At the same time, it significantly reduced the low PG and demonstrated the best mixture workability from recycled mixtures. The selected dose of 12% is likely the maximum that should be used for this rejuvenator for the tested RAP so that plastic deformations would not occur. A possible effect of accelerated aging was observed based on the increase of complex shear modulus elastic portion.

**Organic Oil**

Organic Oil ("Hydrogreen S") significantly improved the workability and along with VW Oil provided the most reduction of low temperature PG and the largest grade sum. The mixture cracking temperature was also significantly improved compared to RAP mixture. The Hamburg WTT results, although indicated slightly increased susceptibility to stripping, demonstrate high resistance to rutting. Organic Oil was the only rejuvenator that increased the FWD of RAP mixture while reducing the stiffness loss compared to virgin mix in CAST test.

**Distilled Tall Oil**

Distilled Tall Oil had an average performance in most of the tests. Critical mixture cracking temperature, due to almost no reduction of RAP mix stiffness, was the highest (most positive) from all samples. At the same time, low temperature PG was reduced even lower than that of virgin
binder. The fatigue resistance was improved compared to extracted binder and mixture demonstrated high elasticity and no loss of modulus during 1.4 million loading cycles thus promising high fatigue resistance.

**Aromatic Extract**

The use of Aromatic Extract is not encouraged due to possible carcinogenic effect [141]. The 12 % dose that was used in this study is likely too small for the rejuvenator, since it did not allow reaching the low PG of virgin binder, provided the least reduction in viscosity and, although it passed the Superpave fatigue requirement, the performance remained lower than that of virgin binder. The LAS fatigue test at 5 % strain even showed slightly reduced fatigue life compared to source RAP binder. The mix stiffness at 30 °C and fatigue resistance was somewhat similar to the virgin mix in CAST and unlike most other rejuvenated samples FWD was improved compared to RAP. The mixture low temperature cracking resistance was significantly improved and equal to that of virgin mix.

**Waste Engine Oil**

WEO at 12 % dose did not allow to reduce the PG to the required level of -22 °C, but despite slightly reduced low temperature strength, the mixture low temperature cracking susceptibility was considerably improved. The Superpave fatigue parameter G*-sinδ was reduced to the required level, but the LAS test results showed no improvement in fatigue performance compared to the source RAP binder and in both mixture fatigue tests this mixture performed worse than un-rejuvenated RAP mix. WEO exhibited slightly increased loss of volatile fractions in mass loss test and indicated increased susceptibility to aging based on DSR test before and after aging. The lowest overall score among the rejuvenators might be a result of the straight-chain aliphatic molecular structure of this product resulting in inability to provide balanced chemical composition of the RAP (incompatibility). This has to be verified in chemical analysis.

**5.6. SECTION CONCLUSIONS**

The following conclusions can be drawn from the study:

1) Five of the six tested rejuvenators at 12 % dose ensured correspondence to the required PG 64-22 temperature and provided grade sum greater than that of the virgin binder. Organic additives proved to be more efficient at reducing PG temperature compared to petroleum products.

2) At 12 % dose organic products were able to reduce the binder viscosity to the level of virgin binder at intermediate temperature (25 °C) while petroleum products would require
higher dose. At increased temperature, as measured by softening point and kinematic viscosity tests, the binder viscosity remained higher than that of a virgin binder for any of the products. The Superpave binder workability criteria was passed in all cases.

3) None of the rejuvenators reduced the high temperature PG to the level of virgin binder indicating increased rutting resistance. High PG temperature correlated well with the Hamburg WTT proving that all recycled mixtures have high rutting resistance.

4) Penetration test was found a good measure of predicting rutting resistance of rejuvenated mixture due to binder softening. Thus, it can be used as a reference point to determine the optimum dose of rejuvenator for designing rut resistant mixtures.

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

6) Despite higher (more warm) binder low PG temperature the petroleum additives provided equal mixture low temperature cracking resistance to the organic additives.

7) All rejuvenators provided correspondence to the Superpave binder fatigue requirement but in LAS test only the organic products improved RAP binder fatigue life. WV Oil and Grease performed similarly or better than virgin binder in both tests.

8) Mixture fatigue tests provided controversial results in respect to virgin mix. None of the products increased fracture work density to level of virgin mix but all of them, except WEO, had smaller loss of stiffness modulus due to repeated loading in CAST.

9) Workability of RAP binder and mixture was increased by the use of all rejuvenators, but none of them was able to improve the workability to the level virgin binder or mixture.

10) Kinematic viscosity of binder and rejuvenator blend can be predicted using Refutas equation.

11) Overall at 12 % dose WV Grease and Organic Oil provided the most rejuvenating potential. However, optimization of additive dose and mix design (for example, adding adhesion promoter for WV Oil) would likely improve the performance of most other additives.
6. OPTIMISATION OF REJUVENATOR DOSE

It is evident from the complete 100 % RAP mix characterization study in Section 5 that rejuvenator dose plays critical role for design of well performing asphalt pavement. Dose has to be optimized to ensure reduced stiffness and improved resistance to cracking without over softening the binder to cause rutting. Therefore, a study to simplify optimization of rejuvenator content was performed. To develop a procedure for selecting optimum rejuvenator dose the changes in RAP binder performance grade and penetration with the application of two contents of the six previously tested rejuvenators were evaluated. The study showed that for all of the rejuvenators the high and low PG temperature were reduced linearly with an increased dose while the penetration grew exponentially. All rejuvenators at an optimum dose could restore the RAP binder to the performance grade of the source PG 64-22 binder and multiple grades could be formulated by changing the dose. Interestingly, adding the rejuvenators at a dose that is required to reach the penetration of virgin binder also ensured achievement of its desired performance grade. An outline for optimizing the rejuvenator dose was developed to account for the variability of the RAP binder due to differences in aging and source.

6.1. OBJECTIVE

The objective of this part of the study was to develop a procedure for selecting the optimum rejuvenator dose for modifying reclaimed asphalt binder to meet Superpave asphalt binder specifications. The target was to provide a simple method with minimum number of required tests for use in practical applications.

6.2. MATERIALS AND EXPERIMENTAL PLAN

6.2.1. Materials

RAP from one source and six different rejuvenators were used in the study. These are the same materials that were used in the complete characterization study and are described in detail in Section 5.2. The extracted RAP binder graded as a PG 94-12 with a penetration of 19 ×0.1 mm. A virgin asphalt binder with a continuous PG 67-26 and penetration of 78 ×0.1 mm was obtained from Nustar refinery and used as a reference.

6.2.2. Experimental Plan

Penetration and Performance grade was determined after RAP binder modification with two doses of each rejuvenator. The experimental plan is shown in Figure 6-1 which also indicates the test
methods, doses of each rejuvenator, and aging procedures that were carried out before performing the tests. The test methods are described in detail in Section 3. The testing for determining the PG (aging, BBR, and DSR) was performed by two different laboratories. Each of them tested samples modified with one dose of each rejuvenator. Although not intentional, this is considered to introduce variability and provides robustness to the calculations.

![Figure 6-1. Experimental Plan](image)

### 6.3. REJUVENATOR EFFICIENCY

#### 6.3.1. Performance Grade

The effects on Superpave binder grading parameters after adding two doses of each rejuvenator to the RAP binder (PG 94-12) are illustrated in Figure 6-2. The complex shear modulus elastic portion (G*/sinδ) was reduced by addition of all rejuvenators which according to Superpave PG specification leads to high performance grade (PG) temperature decrease. In most cases the critical temperature was defined by RTFO residue test requirement (≥2.2 kPa) but for 12 % dose of Organic Oil, Aromatic Extract, and WV Oil, as well as for both neat binders the high PG was set by tests on original binder G*/sinδ (≥1.0 kPa).

Similarly, the low temperature grade was effectively reduced in all cases. For all binders, except Organic Oil, Distilled Tall Oil, and Aromatic Extract at 18 % dose, the low temperature grade was defined by the m-value requirement (≥0.3). In several cases, the temperature at which the binder would pass stiffness requirement (≤300 MPa) was significantly lower than the temperature defined by m-value. For example 12 % WEO and WV Oil stiffness temperature was below -53 °C. This indicates that both for evaluating binder and mixture properties at low temperature the ability to
rapidly disperse the accumulating thermal stress should be of primary interest when using rejuvenators.

The reduction rate for both low and high PG temperature is almost linear as indicated by high $R^2$ values in the figure (the regression equations are also illustrated). This concurs with the research by Tran et al. [63], Shen et al. [142, 143] Lei et al. [69], and Tao et al. [70] who have all demonstrated almost linear decrease in high and low temperature parameters with increasing rejuvenator dose.

Figure 6-2 also demonstrates rejuvenator dose effect on the intermediate temperature parameter $G^\ast \cdot \sin \delta$ (complex modulus viscous portion) at constant test temperature of 25 °C. All rejuvenators decrease this parameter with increased dose but the relationship is not linear in the entire dose range. This is expected since when the phase angle ($\delta$) approaches zero the $G^\ast \cdot \sin \delta$ will also approach zero. However, as demonstrated by results of WV Oil and WV Grease the relationship is linear at least until passing the Superpave $G^\ast \cdot \sin \delta$ requirement of less than 5,000 kPa. This is likely to be the case for other products as well since linear reduction of $G^\ast \cdot \sin \delta$ with increased rejuvenator content is supported by all other studies found in literature demonstrating $G^\ast \cdot \sin \delta$ results in a single test temperature [143, 142].
6.3.2. Penetration

The softening efficiency of rejuvenators was also determined using penetration test at 25 °C. The results in Figure 6-3 demonstrate that all rejuvenators can reduce the penetration of extracted binder to the target level of virgin binder (78 × 0.1 mm) but organic oils require lower dose to provide the same effect as petroleum products and this trend concurs with findings from screening study in Section 4.2. The figure also demonstrates that an exponential function can be fitted extremely well on the data points ($R^2 > 0.99$). The exponential increase in penetration with higher rejuvenator dose concurs well with the results of a study by Dony et al. [68], but does not agree with the results from some other studies that have demonstrated somewhat linear change of penetration [71, 72].
Figure 6-3. Penetration at Two Doses of Each Rejuvenator and Exponential Trendline Connecting Data Points

The exponential function can be transformed to allow calculation of the required rejuvenator dose to reach the target penetration as demonstrated in Equation (6-1). This allows the determination of the dose based on only two data points (e.g. extracted binder and modified with one rejuvenator dose).

\[
Dose = \frac{log_e \frac{PEN}{A}}{B}
\]  

(6-1)

where,
- PEN – penetration, ×0.1 mm
- Dose – Dose of the recycling agent, % from binder mass
- A – penetration at 0 % dose (y-intercept of the exponential function), ×0.1 mm
- B – constant calculated by least squares fit through data points

The calculated "A" and "B" values of each rejuvenator are illustrated in Table 6-1. The "B" value in fact can be used to rank the rejuvenators based on their softening efficiency. Higher value corresponds to greater efficiency.
Table 6-1. Exponential Function Parameters for Calculation of Penetration

<table>
<thead>
<tr>
<th>Product</th>
<th>&quot;A&quot; value</th>
<th>&quot;B&quot; value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VW Oil</td>
<td>19.2</td>
<td>0.129</td>
</tr>
<tr>
<td>WV Grease</td>
<td>19.2</td>
<td>0.166</td>
</tr>
<tr>
<td>Organic Oil</td>
<td>19.2</td>
<td>0.137</td>
</tr>
<tr>
<td>Distilled Tall  Oil</td>
<td>19.2</td>
<td>0.122</td>
</tr>
<tr>
<td>Aromatic Extract</td>
<td>19.2</td>
<td>0.068</td>
</tr>
<tr>
<td>WEO</td>
<td>19.2</td>
<td>0.099</td>
</tr>
</tbody>
</table>

6.4. CALCULATION OF OPTIMAL DOSE

Based on the linear regressions developed from Figure 6-2, the dose to reach target PG 64-22 can be calculated. The minimum dose is defined by the requirement to ensure low temperature cracking resistance (low PG) and fatigue resistance (intermediate PG), while the maximum dose is set by the requirement to ensure sufficient rutting resistance (high PG). The calculation results are illustrated in Figure 6-4. The minimum dose to satisfy the low PG temperature (-22 °C) and intermediate PG parameter in all cases was much lower than the dose that would decrease the high PG temperature below the required +64 °C temperature. Thus any dose in the gray shaded area would ensure correspondence to PG 64-22. Of course this zone of favorable rejuvenator dose would depend both on the RAP binder PG and the target PG but, as explained later it is likely that dose of rejuvenators can be optimized for any binder to restore the PG equal to that of the original source binder before aging. The figure also shows that, similarly to penetration results (Figure 6-3), the organic products require much lower dose compared to the petroleum product dose to deliver the same effect on PG. Thus switching between the different rejuvenators can be advantageous for designing the mixture binder content. Products of higher effectiveness will reduce the total mixture binder content and vice versa.

The required dose to reach penetration of the reference PG 64-22 binder (78 ×0.1 mm), calculated according to Equation (6-1), is also plotted in Figure 6-2. It is always in between the allowed maximum and minimum PG dose. Hence it seems that adding the recycling agents 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 the performance grading and would allow to adjust recycling agent dose to account for slight changes.
in RAP binder properties with source and age of RAP stockpiles. This relationship has to be verified with other binder/rejuvenator combinations.

Figure 6-4. Minimum Rejuvenator Dose to Reach Performance Grade and Penetration of PG 64-22 Binder

The equations in Figure 6-2 demonstrate the regression based on three doses of each rejuvenator: 0 %, 12 %, and 6 % or 18 %. Since it was found that the relationship is mostly linear, the optimum dose calculation can actually be performed using only two data points, e.g. 0 % and 12 % dose. A simple analysis was performed to determine the deviation between dose calculations using two or three data points. The results in Table 6-2 demonstrate that, except for two cases the deviation does not exceed 1.1 %. For practical applications this is relatively insignificant. In the two cases where deviation is relatively higher, petroleum products were used and, due to their lower efficiency, the extrapolation for maximum dose to ensure high PG was more than twice. In practice if these products would be used a dose more close to the optimum should be chosen. This would likely reduce the error.
Table 6-2. Rejuvenator dose calculated according to two and three data points

<table>
<thead>
<tr>
<th>Rejuvenator</th>
<th>Dose according to three data points</th>
<th>Dose according to tests at 0 % and 12 %</th>
<th>Deviation between two and three data points</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High PG</td>
<td>Low PG</td>
<td>High PG</td>
</tr>
<tr>
<td>WV Oil</td>
<td>16.4 %</td>
<td>5.4 %</td>
<td>16.2 %</td>
</tr>
<tr>
<td>WV Grease</td>
<td>16.4 %</td>
<td>6.4 %</td>
<td>16.3 %</td>
</tr>
<tr>
<td>Organic blend</td>
<td>18.4 %</td>
<td>7.0 %</td>
<td>17.4 %</td>
</tr>
<tr>
<td>Distilled Tall Oil</td>
<td>18.8 %</td>
<td>8.3 %</td>
<td>17.8 %</td>
</tr>
<tr>
<td>Aromatic Extract</td>
<td>27.8 %</td>
<td>11.5 %</td>
<td>22.8 %</td>
</tr>
<tr>
<td>WEO</td>
<td>25.0 %</td>
<td>16.0 %</td>
<td>22.8 %</td>
</tr>
</tbody>
</table>

Based on the above discussion it is considered that for practical applications to calculate the optimum rejuvenator dose only two data points are necessary: extracted RAP binder plus one rejuvenator dose that is relatively close to the predicted optimum. This would allow to minimize the amount of necessary extraction and testing. The calculation can be performed as follows:

- The maximum rejuvenator dose should be calculated to pass the targeted high PG temperature according to Equation (6-2).
- The minimum rejuvenator dose should be calculated to ensure the required low PG temperature according to Equation (6-3) and intermediate PG requirement – according to Equation (6-4). The higher of the two should be defined as the minimum.

\[
\text{Max dose, } \% = \left( \frac{\text{high PG}_{\text{target}} - \text{high PG}_{\text{RAP}}}{\text{high PG}_{\text{RAP}} - \text{high PG}_{\text{trial}}} \right) \cdot (\text{-}\%_{\text{trial}}) \quad (6-2)
\]

\[
\text{Min dose, } \%_{\text{low PG}} = \left( \frac{\text{low PG}_{\text{target}} - \text{low PG}_{\text{RAP}}}{\text{low PG}_{\text{RAP}} - \text{low PG}_{\text{trial}}} \right) \cdot (\text{-}\%_{\text{trial}}) \quad (6-3)
\]

\[
\text{Min dose, } \%_{\text{intermed PG}} = \left( \frac{5000 - \text{intermed PG}_{\text{RAP}}}{\text{intermed PG}_{\text{RAP}} - \text{intermed PG}_{\text{trial}}} \right) \cdot (\text{-}\%_{\text{trial}}) \quad (6-4)
\]

where,

Max dose, % - maximum rejuvenator dose to satisfy high PG_{target} requirement, % from binder mass
Min dose, \%_{low \text{PG}} – minimum rejuvenator dose to satisfy low PG_{target} requirement, % from binder mass

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

\% \text{trial} – rejuvenator dose for trial blend, %

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

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

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

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

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

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

intermed PG_{RAP} – RAP G^* \cdot \sin\delta at Superpave intermediate temperature, kPa

intermed PG_{trial} – G^* \cdot \sin\delta for trial blend at Superpave intermediate temperature, kPa

### 6.5. EFFECT OF AGING AND REJUVENATION

In order to assess the typical changes of PG due to aging and consecutive rejuvenation in comparison with the source virgin binder an analysis was performed. Table 6-3 summarizes the PG of extracted RAP binder from 14 locations. The specific original binder grade applied at these construction sites was not available so the most often used PG in the area is included as a reference for each location. The table shows that average grade sum of RAP binder is by 10% higher compared to the grade sum of the corresponding virgin binder and in no case it was lower than that of the virgin binder. Such effect occurs because the high PG temperature increases relatively more compared to low PG as a result of aging. It must be noted that while the continuous RAP grade was available from multiple locations, only the actual PG (with 6 °C increments) was used for calculations to provide a fair comparison (the virgin binder continuous grade sum is also expected to be higher than that of the actual PG sum).
### Table 6-3. Performance Grade of Virgin, and Aged Binders from Various Studies

<table>
<thead>
<tr>
<th>Location</th>
<th>Binder State</th>
<th>high PG (continuous), °C</th>
<th>Low PG (continuous), °C</th>
<th>PG sum, °C</th>
<th>Ratio aged/virgin</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE Texas</td>
<td>RAP PG</td>
<td>88 (90.8)</td>
<td>-10 (-11.1)</td>
<td>98</td>
<td>114 %</td>
<td>Brian Prowel</td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64</td>
<td>-22.0</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kansas City, MO</td>
<td>RAP PG</td>
<td>88 (90.4)</td>
<td>-4 (-5.4)</td>
<td>92</td>
<td>100 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64</td>
<td>-28</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Carolina DOT</td>
<td>RAP PG</td>
<td>88 (89.7)</td>
<td>-10 (-13.8)</td>
<td>98</td>
<td>114 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64</td>
<td>-22</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NYC DOT</td>
<td>RAP PG</td>
<td>82 (82.5)</td>
<td>-16 (-21.2)</td>
<td>98</td>
<td>107 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>70</td>
<td>-22</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wrentham, MA</td>
<td>RAP PG</td>
<td>76 (77.4)</td>
<td>-22 (-23.5)</td>
<td>98</td>
<td>114 %</td>
<td>[144]</td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>58</td>
<td>-28</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rochester, N.H.</td>
<td>RAP PG</td>
<td>94</td>
<td>-10</td>
<td>104</td>
<td>113 %</td>
<td>[44]</td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>70</td>
<td>-22</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hooksett, N.H.</td>
<td>RAP PG</td>
<td>88</td>
<td>-10</td>
<td>98</td>
<td>107 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>70</td>
<td>-22</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Londondonderry, N.H.</td>
<td>RAP PG</td>
<td>82</td>
<td>-10</td>
<td>92</td>
<td>107 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>original PG</td>
<td>64</td>
<td>-22</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Litchfield, N.H.</td>
<td>RAP PG</td>
<td>88</td>
<td>-10</td>
<td>98</td>
<td>114 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64</td>
<td>-22</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hooksett, N.H.</td>
<td>RAP PG</td>
<td>88</td>
<td>-10</td>
<td>98</td>
<td>107 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>original PG</td>
<td>64</td>
<td>-28</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poland, Maine</td>
<td>RAP PG</td>
<td>76</td>
<td>-22</td>
<td>98</td>
<td>107 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64</td>
<td>-28</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hooksett, N.H.</td>
<td>RAP PG</td>
<td>82</td>
<td>-16</td>
<td>98</td>
<td>107 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64</td>
<td>-28</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opelika, AL</td>
<td>RAP PG</td>
<td>94 (99.1)</td>
<td>-4 (-9.2)</td>
<td>98</td>
<td>114%</td>
<td>[63]</td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64 (67.0)</td>
<td>-22 (-23.2)</td>
<td>86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keasbey, NJ</td>
<td>RAP PG</td>
<td>94 (94.0)</td>
<td>-10 (-12.3)</td>
<td>104</td>
<td>121%</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>PG in the area</td>
<td>64 (67.4)</td>
<td>-22 (-25.6)</td>
<td>86</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The report showed three RAP grades at Hooksett. The respective virgin binder grade from the report is indicated in the table.

As previously shown in Figure 6-2 use of rejuvenators tends to reduce both high and low PG temperature almost equally, thus "maintaining" the grade sum of RAP binder. Literature analysis
revealed only one more study where both high and low grade of RAP binder is reported before and after rejuvenation [63]. This report by NCAT likewise demonstrated that average grade sum of Cyclogen rejuvenated binder was only slightly lower than that of RAP binder. Table 6-4 summarizes the changes in continuous PG grade sum from both of these studies for total of seven rejuvenators at two different doses each. By average the rejuvenators reduced the RAP binder grade by 3.7 %.

**Table 6-4. Performance Grade of Aged and Rejuvenated Binders using Seven Rejuvenators**

<table>
<thead>
<tr>
<th>Location</th>
<th>Binder State</th>
<th>Continuous high PG, °C</th>
<th>Continuous low PG, °C</th>
<th>PG sum, °C</th>
<th>Rejuvenated grade sum change</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opelika, AL</td>
<td>RAP</td>
<td>99.1</td>
<td>-9.2</td>
<td>108.3</td>
<td>-</td>
<td>[63]</td>
</tr>
<tr>
<td></td>
<td>RAP+12 % Cyclogen</td>
<td>83</td>
<td>-26.4</td>
<td>110.0</td>
<td>+2 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP + 20% Cyclogen</td>
<td>69</td>
<td>-30.6</td>
<td>99.8</td>
<td>-8 %</td>
<td></td>
</tr>
<tr>
<td>Keasbey, NJ</td>
<td>RAP</td>
<td>94.0</td>
<td>-12.3</td>
<td>106.3</td>
<td>-</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>RAP+12 % Organic Oil</td>
<td>73.3</td>
<td>-30.7</td>
<td>104.0</td>
<td>-2 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+18% Organic Oil</td>
<td>65.3</td>
<td>-34.7</td>
<td>100.0</td>
<td>-6 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+12 % Aromatic Extract</td>
<td>78.2</td>
<td>-22.4</td>
<td>100.6</td>
<td>-5 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+18 % Aromatic Extract</td>
<td>77.1</td>
<td>-27.5</td>
<td>104.6</td>
<td>-2 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+12 % WEO</td>
<td>78.2</td>
<td>-19.1</td>
<td>97.3</td>
<td>-8 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+18 % WEO</td>
<td>73.2</td>
<td>-23.5</td>
<td>96.7</td>
<td>-9 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+12 % Distilled Tall Oil</td>
<td>73.8</td>
<td>-27.8</td>
<td>101.6</td>
<td>-4 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+18 % Distilled Tall Oil</td>
<td>66.0</td>
<td>-32.0</td>
<td>98.0</td>
<td>-8 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+6 % WV Oil</td>
<td>87.6</td>
<td>-24.0</td>
<td>111.6</td>
<td>+5 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+12 % WV Oil</td>
<td>71.8</td>
<td>-32.9</td>
<td>104.7</td>
<td>-2 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+6 % WV Grease</td>
<td>83.6</td>
<td>-23.3</td>
<td>106.9</td>
<td>+1 %</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RAP+12 % WV Grease</td>
<td>71.9</td>
<td>-28.6</td>
<td>100.5</td>
<td>-5 %</td>
<td></td>
</tr>
</tbody>
</table>

The results of Table 6-3 and Table 6-4 are summarized in Figure 6-5. Here the average grade sum of virgin binder from all studies is assumed as 100 % and as noted earlier the average RAP binder grade sum from these same locations was 10 % higher. The rejuvenated binder grade was calculated based on the average grade reduction relative to the RAP binder as indicated in Table 6-4. The Figure 6-5 demonstrates that the rejuvenated RAP binder by average is expected to have
6% greater grade sum than that of virgin binder. Although these results summarize the grades of binders from different binders and rejuvenators that are not necessarily applied to the same binders, the trend is of importance. It is considered that since fourteen RAP binders and seven rejuvenators at two doses each were included in the comparison similar relationship is likely to hold true for most virgin aged-rejuvenated binder combinations.

This analysis then allows concluding that typically the application of rejuvenators at an optimum dose would allow achieving the grade of original virgin binder. As demonstrated later, this also increases the confidence of achieving the targeted grade since small changes in the RAP binder properties would not require change in rejuvenator dose. Finally, the increased grade sum can ensure higher rutting and/or cracking resistance for pavements which can be especially beneficial for structural design purposes, including design of perpetual pavements and High Modulus Asphalt Concrete (HMAC). Care should be given to ensure sufficient workability of the binder at production and compaction temperatures.

![Figure 6-5. Changes in High and Low PG Due to Aging and Rejuvenation](image)

### 6.6. AVAILABLE PERFORMANCE GRADES

As demonstrated earlier, the RAP binder used in the study had a true grade of PG 94-12 and all rejuvenators at optimal dose were able to restore it to the original grade PG 64-22. In fact, rejuvenators would allow modifying the binder to multiple different grades, depending on the selected dose. The available performance grades will depend on the type of rejuvenator, its dose and properties of the aged RAP binder. For example, the aged PG 94-12 binder modified with WV Oil, would allow the user to obtain the grades indicated in Figure 6-6. The outer circle shows the maximum dose to satisfy high PG (vertical axe) while the inner circle shows the minimum dose to
ensure low PG (horizontal axe). Any dose between these circles would ensure correspondence to the chosen grade. For the grades with no circle the minimum dose is higher than maximum, thus rejuvenation to such PG is not possible. Similar figure can be plotted using intermediate dose as the criteria for minimum dose.

Figure 6-6. Available Binder Grades for Modification of PG 94-12 Binder with Various Doses of WV Oil

6.7. DOSE OPTIMIZATION TO ACCOUNT FOR RAP VARIABILITY

In practice the properties of the RAP binder inevitably vary due to differences in source of RAP and extent of aging. A unique chart can be developed for each product to demonstrate the possibility to rejuvenate the locally available RAP binders to the target performance grade. This is demonstrated in Figure 6-7 in following form:

1. Test results of extracted RAP binder from different locations were gathered and the continuous high and low performance grade is plotted in Figure 6-7. As an example, PG 64-22 is chosen as target grade (lower left corner of the chart).
2. WV Oil PG temperature reduction efficiency was calculated by fitting linear regression to both high and low PG temperature according to equations demonstrated in Figure 6-2. The dose axes on right side and top of the graph demonstrate the required rejuvenator content to reduce the low and high PG temperature from any level of RAP binder to the required temperature of -22 °C and +64 °C, respectively.
3. The solid line of WV Oil efficiency "boundary" distinguishes between binders that can be successfully rejuvenated from those that cannot. Extracted binder grades that plot below this boundary (Kansas City in the example) require higher dose for restoring low temperature PG than allowed by high temperature PG.
4. The graph permits to visually determine an optimum dose that can be used to rejuvenate most binders to the required PG 64-22. As illustrated in the chart WV Oil content of 9% (shaded area) would permit to soften any binder having low PG temperature below -9 ℃ and high PG temperature above 88 ℃ to the required PG 64-22. From the RAP binders included in the chart this dose captures all but NYC DOT and Kansas City RAP.

5. While this chart balances high and low temperature PG grade, as demonstrated by Figure 6-4 in some cases dose required to achieve the intermediate temperature <5,000 kPa requirement can be slightly greater than that needed for meeting the low temperature grade requirement. Since the intermediate PG parameter at 25 ℃ for the binders in table was not available, it was assumed that it is equal to the RAP binder tested in this study (12,600kPa). In such case, the minimum dose to satisfy intermediate PG requirement is 7.7 % and it is illustrated in the chart. Alternatively, if intermediate temperature test data is available, a similar plot can be made, with the horizontal axis demonstrating the decrease in G*sinδ change with an increase in the rejuvenator dose.

![Figure 6-7](image_url)

*Figure 6-7. Calculation of Waste Vegetable Oil Dose to Reach Target High PG of +64 ℃ and Low PG of -22 ℃ for Different RAP Binders*

Through the figure above one major advantage of the fact that binder increases grade sum due to aging is demonstrated. If the RAP binder exhibits variability, larger grade sum compared to targeted binder grade sum provides a higher confidence of reaching the desired PG with using just one rejuvenator dose. It also allows to reduce the number of required mixture design formulas since changing the rejuvenator dose would change the volumetric properties of the mixture. In case
the binders demonstrated in Figure 6-7 would have similar grade sum to the target virgin binder (93 °C), each RAP would require unique rejuvenator dose to attain the 64-22 performance grade and thus require much more careful quality control of RAP stockpile as well as individual mix design for each RAP source.

Figure 6-7 assumes equal rejuvenator effectiveness for all binders, which is likely not true for all of the illustrated binders. The regression parameters are expected to be dependent on the combination of the binder and rejuvenator. This table is intended only to illustrate the evaluation principle and statistical analysis of the effect of rejuvenators on local binders would be necessary.

6.8. SUMMARY

The study reported in this paper evaluated the effectiveness of six rejuvenators that were used to recycle a RAP material. Based on the test results a procedure to determine the rejuvenator dose to satisfy the binder PG grading was developed, which can be summarized as follows:

1) Estimate the initial dose by determining the dose to reach penetration of extracted RAP binder (Equation (6-2)).
2) Test the aged binder for high, low, and intermediate Superpave parameters before and after rejuvenation at one dose (Equations (6-3) and (6-4)).
3) Estimate the maximum rejuvenator dose to satisfy the high PG temperature.
4) Estimate the minimum required rejuvenator dose to satisfy the intermediate and the low PG requirement and select the higher of the two as the minimum.
5) Select an optimum dose between the maximum and minimum, after statistical evaluation of the PG of RAP in the region or in the stockpile. Use of plots of data similar to those shown in Figure 6-7 can aid in choice of dose to ensure required PG for RAP having different properties and to identify the RAP that cannot be rejuvenated with the selected rejuvenator and its dose.

6.9. SECTION CONCLUSIONS

The following conclusions can be drawn from the dose study:

1) Dose of all evaluated rejuvenators can be optimized to provide equal performance grade and penetration as that of virgin asphalt binder.
2) High and low PG temperature reduces linearly with an increase in the rejuvenator dose. Intermediate PG parameter reduces linearly up to the $G^* \cdot \sin \delta$ requirement of maximum 5,000 kPa.
3) Penetration increases exponentially with an increase in the rejuvenator dose. For the binders used in this study adding the rejuvenators at a dose calculated to reach the penetration of virgin binder also ensured conformity to its Superpave performance grade (PG). This can be beneficial to initial selection of rejuvenator dose before testing performance grade.

4) Organic rejuvenators require smaller dose compared to petroleum rejuvenators to cause similar softening effect on aged RAP binder.

5) Rejuvenator dose can be optimized according to the developed procedure to ensure conformity to the required PG for a range of aged binders. In practice this would allow to account for the inevitable RAP variability due to source and/or age of the pavement.

6) PG sum of RAP binder is likely to be higher than that of source virgin binder. Rejuvenators typically decrease it slightly compared to RAP binder but it remains higher than that of virgin binder.

7) The study only evaluated one RAP binder, a more comprehensive research including multiple RAP sources and a statistical analysis is necessary to validate the findings.
7. RHEOLOGICAL, CHEMICAL AND MICROMECHANICAL CHARACTERISATION OF REJUVENATED BINDER

In many studies, the rejuvenating effect has been evaluated in terms of the improvement of rejuvenated binders' rheological properties whereas the fundamental rejuvenation mechanism remains unclear. In this research, two asphalt binders from the Materials Reference Library of the Strategic Highway Research Program (SHRP) were aged, and rejuvenated with two distinctive rejuvenators, and the rheological properties of the virgin, aged, and rejuvenated binders were tested using dynamic shear rheometer. In order to better understand the rejuvenating effect, microscopic properties and chemical composition of the binders were also measured using atomic force microscope (AFM) and SARA (Saturates, Aromatics, Resins, Asphaltenes) fractionation, respectively. Results indicated that the mechanical properties (complex modulus and viscosity) of the rejuvenated binders were in between those of the virgin and aged binders, which is qualitatively consistent with the AFM mechanical measurements. Chemical analysis suggested that changes in chemical compositions were responsible for the stiffening effect of aging and the improvement of mechanical properties with the addition of the rejuvenators.

7.1. OBJECTIVE

The objective of this stage of this study was to verify the capability of rejuvenators to restore the mechanical properties in both macro and micro scales as well as investigate the changes in chemical composition due to aging and rejuvenation.

7.2. MATERIALS AND EXPERIMENTAL PLAN

7.2.1. Materials

Virgin Asphalt Binders

Unlike in previous stages of the research a virgin binder was used for artificial aging and consecutive rejuvenation. Such choice was in order to allow evaluating the ability of rejuvenators to restore the properties and micro-texture of the aged binder to a level of virgin binder. This would not be possible using extracted RAP binder since the original source binder for it was not available.

Two types of asphalt binders from the Materials Reference Library of the Strategic Highway Research Program (SHRP) were chosen to provide variations in crude source, chemical compositions, physical and mechanical properties, as indicated in Table 7-1 and Table 7-2.
Table 7-1. Crude Source, Chemical Composition, and Elemental Analysis of Asphalt Binders [1]

<table>
<thead>
<tr>
<th>Component</th>
<th>AAD binder (PG 58-28)</th>
<th>ABD binder (PG 58-10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturates</td>
<td>8.6 %</td>
<td>10.4 %</td>
</tr>
<tr>
<td>Aromatics</td>
<td>25.1 %</td>
<td>28.4 %</td>
</tr>
<tr>
<td>Resins</td>
<td>41.3 %</td>
<td>52.7 %</td>
</tr>
<tr>
<td>Asphaltenes</td>
<td>23.9 %</td>
<td>10.2 %</td>
</tr>
<tr>
<td>Elemental analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon</td>
<td>81.6 %</td>
<td>86.8 %</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>10.8 %</td>
<td>10.7 %</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.9 %</td>
<td>1.2 %</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.8 %</td>
<td>1.2 %</td>
</tr>
<tr>
<td>Sulfur</td>
<td>6.9 %</td>
<td>1.6 %</td>
</tr>
<tr>
<td>Vanadium</td>
<td>310 ppm</td>
<td>62 ppm</td>
</tr>
<tr>
<td>Nickel</td>
<td>145 ppm</td>
<td>123 ppm</td>
</tr>
<tr>
<td>Iron</td>
<td>13 ppm</td>
<td>54 ppm</td>
</tr>
<tr>
<td>Wax content</td>
<td>1.94 %</td>
<td>0.81 %</td>
</tr>
</tbody>
</table>

Table 7-2. Classification and Viscoelastic Properties of Asphalt Binders [1]

<table>
<thead>
<tr>
<th>Aging state</th>
<th>Property</th>
<th>AAD binder (PG 58-28)</th>
<th>ABD binder (PG 58-10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unaged</td>
<td>Viscosity @ 135 ℃</td>
<td>309 cSt</td>
<td>241 cSt</td>
</tr>
<tr>
<td></td>
<td>Viscosity @ 60 ℃</td>
<td>1055 poise</td>
<td>2112 poise</td>
</tr>
<tr>
<td></td>
<td>Penetration @25 ℃</td>
<td>135 ×0.1 mm</td>
<td>47 ×0.1 mm</td>
</tr>
<tr>
<td></td>
<td>Softening Point</td>
<td>48 ℃</td>
<td>120 ℃</td>
</tr>
<tr>
<td></td>
<td>G*/sinδ @ 58 ℃</td>
<td>1.47 kPa</td>
<td>2.69 kPa</td>
</tr>
<tr>
<td>RTFO Residue</td>
<td>Mass change</td>
<td>-0.81%</td>
<td>-0.12%</td>
</tr>
<tr>
<td></td>
<td>G*/sinδ @ 58 ℃</td>
<td>4.29 kPa</td>
<td>4.74 kPa</td>
</tr>
<tr>
<td>PAV residue</td>
<td>G*·sinδ @ 20 ℃</td>
<td>2.8 MPa</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>G*·sinδ @ 30 ℃</td>
<td>n/a</td>
<td>4.1 MPa</td>
</tr>
<tr>
<td></td>
<td>Stiffness @ -10 ℃</td>
<td>83 MPa</td>
<td>279 MPa</td>
</tr>
<tr>
<td></td>
<td>m-value @ -10 ℃</td>
<td>0.38</td>
<td>0.28 MPa</td>
</tr>
</tbody>
</table>

Rejuvenators

Two generic rejuvenators, Aromatic Extract and Waste Vegetable Oil, were used in this stage. These products were chosen based on their good performance in the complete characterization
study (Section 5) and to represent both petroleum and bio-based sources. 12 % dose by binder mass was used. Complete description of their properties can be found in Section 5.2.3.

7.2.2. Experimental Plan

The original testing plan consisted of DSR, BBR, AFM microscopic characterization and SARA separation for the virgin, aged, Aromatic Extract and WV Oil rejuvenated samples for both AAD and ABD binders in order to compare the effectiveness of rejuvenators between these two binders. However, some preliminary measurements run into the following technical challenges:

- WV Oil rejuvenated AAD sample was too soft to complete DSR successfully in the temperature range of 40-80 °C, and the BBR test at -18 °C for this sample also failed.
- The above reason together with concerns of experiment cost enforced the decision to conduct SARA separation only for the virgin, aged, and Aromatic Extract rejuvenated samples for both binders.
- Microscopic morphologies of virgin, aged, and rejuvenated samples were obtained successfully with intermittent-contact mode AFM. However, preliminary measurements of micromechanical properties on AAD-based samples run into technical challenges such as tip contamination, excessive deformation under a relatively small compressive force and complicated tip-sample interaction due to the dominant "bee-structures" on the sample surfaces (as later shown in Figure 7-2). WV Oil rejuvenated ABD sample was too compliant under a compressive force that was used for other ABD-based binders. Therefore, micromechanical property measurements were only carried out for virgin, aged, and Aromatic Extract rejuvenated ABD samples.

Based on these consideration the final implemented testing matrix is shown in Table 7-3. The test methods were described in detail in Section 3.
Table 7-3. Test Matrix for Rheological, Chemical, Morphological, and Micromechanical Characterization

<table>
<thead>
<tr>
<th>Test method</th>
<th>Analysis</th>
<th>ABD binder</th>
<th>AAD binder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Virgin</td>
<td>Aged</td>
</tr>
<tr>
<td>DSR</td>
<td>master curve stiffness and m-value</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>BBR</td>
<td>stiffness and m-value</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>AFM</td>
<td>morphology</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>AFM intermittent-contact mode</td>
<td>mechanical properties</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>SARA</td>
<td>chemical composition</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

7.3. RHEOLOGY

7.3.1. Properties at Intermediate and High Temperatures

The rheological properties of the virgin, aged, and rejuvenated asphalt binders at intermediate and high temperatures obtained from DSR are shown in Figure 7-1. Virgin ABD is stiffer yet more viscous than virgin AAD as shown in the master curves, which supports the results in SHRP report (Table 7-1) [1]. For both binders, aging resulted in an increase of the complex modulus and a decrease of the phase angle, which comforms with the well-known aging effect [145, 146]. The addition of the rejuvenators into the aged samples decreased the complex modulus and increased the phase angle to different extents depending on both the binders’ crude sources and the rejuvenating agent in use.

The rejuvenating effect of Aromatic extract was different from that of WV oil as can be seen in Figure 7-1 for ABD-based samples. Adding 12 wt% of Aromatic extract into the aged ABD binder restored the complex modulus to the level of the virgin ABD and the phase angle in between the virgin and aged samples. The same dose of WV oil softened the binder well below the level of the virgin binder, indicating that it was more effective than Aromatic extract in reducing the complex modulus of aged ABD sample. The phase angle of the WV oil rejuvenated sample, however, remained relatively frequency-independent, especially at higher frequencies.
The rejuvenating efficiency of Aromatic extract to the two binders (AAD and ABD) in terms of restoring their rheological properties was similar. The complex modulus master curves for the rejuvenated binders almost overlapped with their source virgin binders. Values of the phase angle for the rejuvenated binders fell in between the virgin and aged samples. Visible differences included aging and rejuvenation resulted in more significant shift of phase angle for AAD-based samples than ABD-based binders at lower frequencies (corresponding to higher temperature). This can be attributed to the rheological differences of the two binders from different crude sources.

Figure 7-1. Complex Shear Modulus (a) and Phase Angle (b) Master Curves of Virgin, Aged, and Rejuvenated Asphalt Binders AAD and ABD at a Reference Temperature of 40 °C.
7.3.2. Properties at Low Temperature

Bending Beam Rheometer (BBR) tests were performed in order to characterize the low temperature cracking potential (i.e., the creep stiffness and creep rate (m-value)). To increase the resistance to cracking, a low stiffness to reduce thermal stress and a high m-value is desirable to rapidly disperse the accumulated stress. A single test temperature of -18 °C was chosen in this study to allow direct comparison of all samples in the same conditions. For each sample, two repetitive tests were conducted, and the average values of creep stiffness and creep rate are reported and the results are reported in Table 7-4.

Because of its original low grade, the virgin ABD binder (PG -10 °C) is much stiffer and has lower m-value compared to AAD (PG -28 °C).

As expected, aging increased stiffness while reducing m-value for both binders and the introduction of the rejuvenators reversed this trend. Consistently to the observations at intermediate and high temperature, WV oil was more efficient in softening the binder compared to Aromatic extract. It produced a binder that was significantly softer than the virgin ABD and in fact would pass the Superpave requirement for PG -28 °C (Superpave grade is 10 °C lower than the test temperature). Aromatic extract softened the aged ABD binder to a level below that of the original virgin ABD, while the rejuvenating effect for aged AAD binder was less significant with a stiffness slightly higher and a m-value lower than those of the virgin binder. This is somewhat different from the observations at intermediate and high temperatures where the effect of Aromatic extract was qualitatively similar for both types of binders. The dependence of the rejuvenating effect of Aromatic Extract on binder type and test temperature is probably related to the chemical variations between their crude sources.
Table 7-4. Bending Beam Rheometer Test Results at -18 °C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ABD binder</th>
<th>AAD binder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin</td>
<td>Aged</td>
<td>Aged+ Aromatic Extract</td>
</tr>
<tr>
<td>Stiffness (MPa)</td>
<td>760</td>
<td>839</td>
</tr>
<tr>
<td>m-value</td>
<td>0.205</td>
<td>0.159</td>
</tr>
</tbody>
</table>

### 7.4. MICROSCOPIC MORPHOLOGY AND MECHANICAL PROPERTIES USING AFM

DSR and BBR tests indicated that the rejuvenators were capable of restoring the rheological properties of the aged binders close to the level of their source virgin binders. In order to better understand the rejuvenating mechanism, microscopic morphology and mechanical properties characterization using AFM was carried out.

#### 7.4.1. Microscopic Morphology

Microstructures of the virgin, aged, and rejuvenated AAD and ABD samples are shown in Figure 7-2. The two virgin binders have completely different morphologies: virgin ABD shows flake-like domains (with an average size of less than 2 µm in diameter) spreading over a smooth matrix; whereas elliptical "bee-structures" (with major and minor axes of ten and a few microns, respectively) dominate the surface of the virgin AAD. The appearance of the "bee-structures" has recently been attributed to the interaction between crystallizing waxes and the remaining non-wax asphalt components [147]. The morphological difference between the two binders can be related to their chemical compositions difference as showed in Table 7-1 and noted by Allen et al. [148] and the complicated molecular interactions among the various chemical components.

Upon aging, the size of the flake-like structures in ABD decreased while the quantity increased, and it appeared the large-sized domains in the virgin binder were replaced by smaller ones after aging. Not much morphological changes can be found in the aged AAD sample compared to its source binder.

Introduction of the Aromatic extract into the aged ABD binder produced "bee-structures", a similar effect as Pauli observed for the wax-doped binder samples [147]. The Aromatic extract is a petroleum-derived rejuvenating agent, and its chemistry is close to that of the maltene fractions in asphalt binders. Therefore, the mechanism responsible for the formation of the "bee-structures" might occur during the rejuvenation process. The Aromatic extract rejuvenated AAD sample...
exhibited finer-sized "bee-structures" and the amplitude of the undulated "bee-structures" was smaller than that of the virgin and aged ones. The introduction of the WV oil into the aged binders (both AAD and ABD) did not modify their morphologies much, as compared to either of the aged samples.

In summary, the virgin binders showed different microstructures because of their chemical composition difference; aging and rejuvenation led to some morphological changes as compared to their source virgin binders. However, the rejuvenated blends did not always reproduce the original microstructures exhibited by the virgin binders, which agrees with Nahar’s observation [84]. The development of asphalt binders’ microstructures depends on the binders’ chemistry and the complicated molecular interactions among the different chemical components and any additives [147]. Therefore, it is difficult to make direct correlation between the rheological and the microstructural properties for the asphalt binders studied here. Microscopic mechanical properties of ABD based binders were measured using Peak Force Tapping QNM mode to further explore the chemo-physical mechanism responsible for the rejuvenation process.
Figure 7-2. Topographic Images of Virgin, Aged, Aromatic Extract, and WV Oil Rejuvenated (from top to bottom) ABD (left, 20×20 μm²) and AAD (right, 40×40 μm²). The Color Scales Range Over 10 nm and 60 nm for ABD and AAD Based Samples, Respectively.
7.4.2. Microscopic Mechanical Properties

Results of the micromechanical properties for virgin, aged, and Aromatic Extract rejuvenated ABD samples are shown in Figure 7-3. The grayscales for each of the properties were set to be the same for easy visual comparison among the different samples. Maps of the different mechanical properties (adhesion, dissipation, and DMT modulus) for the virgin, aged and rejuvenated samples obtained from QNM mode consist of the same patterns as those from AFM tapping mode, indicating that morphology characterization for these samples is repeatable although the sample preparation was different, namely the amount of binder used. The flake-like domains in virgin and aged samples showed a smaller adhesion, dissipation and DMT modulus as compared to its surroundings, the matrix area. Since the area fraction of the flake-like domain is rather small (as can be seen in the histogram in Figure 7-4) only averaged values for their mechanical properties are reported. The "bee-structures" in the rejuvenated binder possessed a smaller adhesion and dissipation, yet a larger modulus value than the surrounding matrix domain, and the mechanical properties of both the "bee-structures" and the matrix phase are reported.

Figure 7-4 provides the histograms of the adhesion, dissipation and DMT modulus map of the virgin, aged and Aromatic extract rejuvenated ABD samples. Aging decreased the adhesion by about 10 % (16 nN and 14.5 nN for virgin and aged ABD, respectively). The introduction of the Aromatic extract brought the adhesion force on the matrix area back to the level of the virgin binder while the "bee-structures" showed a relatively low adhesion. Upon aging, the dissipated energy also decreased slightly whereas the rejuvenated samples had a similar value of dissipation to that of the virgin binder. In Figure 7-4(c), DMT modulus of the rejuvenated ABD was smaller than both the virgin and aged ones, as could be expected. It is foreseen that aging stiffens asphalt binders (as proved by DSR measurement); however, the PFT QNM measurement showed that the aged ABD had a smaller modulus compared to the virgin one, and repetitive measurements did not produce the expected trend. This is probably because DMT contact mechanics that is embedded into the PFT QNM mode failed to fully describe the complicated tip-binder interactive forces [149]. A blunt tip and JKR (Johnson, Kendall, Roberts [150]) contact mechanics model are recommended for more accurate microscopic modulus measurements.

Although changes in micromechanical properties among the virgin, aged, and rejuvenated sample were less significant, the trend is generally consistent with the DSR results. For instance, the decrease of the complex viscosity after aging and its recovery upon adding the Aromatic Extract agree with the changes in the dissipated energy from the microscale measurement. This suggests that the Aromatic Extract was well blended and relatively compatible with the aged ABD binder and the rejuvenation process occurred both at both the macro and micro scales. In addition,
micromechanical property measurements using AFM is more capable of evaluating the rejuvenation effect than merely morphological characterization.
Figure 7-3. Maps of Height, Adhesion, Dissipation, and DMT Modulus (from left to right) of Virgin (top), Aged (middle), and Aromatic Extract-Rejuvenated (bottom) ABD Samples
Figure 7-4. Histogram of Adhesion Force (a), Dissipated Energy (b), and DMT Modulus (c) of Virgin, Aged and Aromatic Extract Rejuvenated ABD.
7.5. CHEMICAL ANALYSIS

SARA separation was conducted in order to explore how the binder chemistry contributes to its overall mechanical properties and the rejuvenation mechanism. Changes in SARA fractions among virgin, aged and rejuvenated ABD binder were significant, as shown in Figure 7-5. After aging, the saturate and resin contents did not vary much while the aromatic fraction decreased from 28 % to 10 %, which led to an overall increase of the asphaltene component by about 12 %. Adding the Aromatic Extract introduced more saturates and aromatics which consequently lowered the fractions of resins and asphaltenes comparing to the aged sample. Similar to ABD sample, aging increased the asphaltenes and decreased the aromatics contents for AAD sample. The addition of the Aromatic Extract increased saturates and aromatics content whereas the asphaltene fraction did not decrease much as compared to the aged AAD sample. Preliminary measurements using diffusion-ordered two-dimensional nuclear magnetic resonance spectroscopy were also conducted on the asphaltene fractions separated from the virgin, aged, and Aromatic Extract rejuvenated ABD samples and the results indicated that the aggregation behavior and the molecular size of the asphaltenes from the three samples did not vary much. This means that the asphaltenes fractions are rather stable during the aging and rejuvenating processes. Therefore, it can be derived that changes in the chemical composition among the unaged, aged, and rejuvenated binders are responsible for the stiffening effect of aging and the softening effect resulted from the rejuvenating agents. This agrees with Roberts et al.’s [41] suggestion that adding the light bituminous fractions such as resins or aromatics helps restoring the mechanical properties for RAP binders.

![Figure 7-5. SARA Fractionation of the Virgin, Aged, and Aromatic Extract Rejuvenated ABD(a) and AAD(b)](image-url)
7.6. SECTION SUMMARY AND CONCLUSIONS

With the great interest of increasing the RAP content to produce more sustainable asphalt pavements, various rejuvenating agents have been added in order to restore the rheological and mechanical properties of the aged RAP materials for service-life extension of the pavements. In order to better understand the rejuvenation mechanisms, two distinct rejuvenating agents were added into two binders from different crudes sources. Rheological properties at intermediate and high temperatures were measured using DSR, and BBR test was conducted for low temperature measurements. Microscopic morphological and mechanical properties were tested using AFM. Changes in the chemical compositions of virgin, aged, and rejuvenated binder samples were determined using SARA fractionation. From the above tests, the following conclusions can be drawn:

12) The addition of the rejuvenators into the aged binder samples restored the rheological properties at intermediate and high temperature range as well as the low temperature, as measured by both DSR and BBR.

13) The rejuvenating effect depends on both the rejuvenator and the binder crude source. WV oil was more effective than Aromatic extract for restoring the rheological properties of ABD-based binders. On the other hand, the rejuvenating effect of Aromatic extract for the two binders from different crude sources was related to the temperature at which their rheology was measured.

14) Changes in the mechanical properties of virgin, aged, and Aromatic extract rejuvenated ABD binder samples obtained from AFM were generally consistent with the DSR results in terms of the rejuvenating effect, indicating that the rejuvenation process occurred at both the macro- and micro scales.

15) AFM-based mechanical property characterization is more suitable for investigating the rejuvenating effect than merely morphological observation.

16) Evaluation of the results from the different characterization techniques points out that changes in the chemical compositions were responsible for the improvement of mechanical properties with the addition of the rejuvenators.
8. FINITE ELEMENT MODELING OF REJUVENATOR DIFFUSION

Significant hindrance to successful recycling of high Reclaimed Asphalt Pavement (RAP) content mixes is the lack of confidence which stems from an absence of understanding of the rejuvenation and diffusion process that is supposed to occur when a rejuvenator is added to an aged asphalt mix. This section presents finite element simulation of rejuvenator diffusion into an aged asphalt binder film. 100% RAP mixture modified with five rejuvenators at three different temperatures for three rejuvenator doses was simulated. The final viscosity for complete diffusion and the required time to reach this state was determined. The results showed significant differences in the softening potential of different rejuvenators and helped in the estimation of temperature range to reach homogeneous rejuvenator concentration within the binder film before the production process is completed.

8.1. DIFFUSION IN PRACTICE

In conventional HMA production process the RAP is mixed together with virgin aggregates, and fresh asphalt or rejuvenator. A critical aspect of the use of rejuvenators is the diffusion of the different products into aged RAP binder. It is expected that during the short mixing time the aged asphalt attains necessary viscosity so that RAP and virgin aggregates receive a homogeneous film thickness. At the same time sufficient diffusion of the rejuvenator is required in the aged asphalt to restore its properties to the required level. The diffusion is a function of temperature, viscosity, mixing, transportation and storage time, and it may continue in the pavement during the service period. Therefore, until equilibrium is reached, the outer layer of the asphalt film may have relatively lower viscosity which can lead to increased probability of developing permanent deformations. The rejuvenator diffusion process is more thoroughly described in the Literature Review (Section 2.5.3).

The in-plant addition of rejuvenator involves three main interaction mechanisms between the aged binder and rejuvenator – dispersion, diffusion and mechanical mixing. Dispersion is the phenomenon of distribution of the rejuvenator on the RAP, diffusion occurs from the intermingling of the rejuvenator with the RAP binder, and mechanical mixing is caused by the friction between aggregate particles. At a drum plant the rejuvenator is usually added after drum heating and there is mechanical interaction between mix aggregates in the silo/elevator and during transportation. At a batch plant the rejuvenator would be introduced before the pugmill and therefore there would be even more contact between the mix aggregates when the RAP undergoes the mixing process in the pugmill. The dispersion and mechanical mixing are therefore defined by the technology and
equipment at the specific plant and would be unrealistic to simulate. The simulation study reported in this paper concerns the diffusion process only.

8.2. OBJECTIVE
The goal of the study was to develop a simulation process of the diffusion of rejuvenators into the aged RAP binder in order determine the softening efficiency, optimum mixing time and temperature range.

8.3. METHODS
The diffusion process was simulated with the help of finite element (FE) modeling, analysis and simulation using COMSOL "Multiphysics" software. The analysis was conducted with heat transfer module. The specific tasks of the modeling included:

- Evaluate the softening performance of five different rejuvenators at three different doses on the aged RAP binder.
- Compare the time of "equilibrium" (end of diffusion) after adding a predefined dose of each of them.
- Evaluate the changes in equilibrium time and softening performance at different temperatures within the common mixing and compaction range.

Five different rejuvenators and aged RAP binder were utilized in this study. The rejuvenators included refined tallow, paraffinic base oil, waste vegetable grease, waste vegetable oil, as well as a softer asphalt binder. The required parameters for diffusion simulation were tested or obtained from manufacturers of the products.

8.4. THEORETICAL BASIS FOR DIFFUSION SIMULATION
The diffusion process has been modeled using Stoke-Einstein’s equation (Equation (8-1)) and Fick’s Law (Equation (8-2)), on the basis of the fact that their applicability have been proven by several researchers in the past (for example, [151, 152]). The model was validated with the use of closely controlled laboratory experiment and is discussed in paper by Mallick et al. [153].
\[
D = \frac{K_B T}{6\pi \mu(R)} \quad (8-1)
\]

where,
D – rate of diffusion (m²/s)
R – mean molecular radius
μ – dynamic viscosity (Pa·s)
\(K_B T\) – internal heat energy
\(K_B\) – Boltzmann’s constant (1.3807 \cdot 10^{-23} \text{ J/K})
T – absolute temperature (K)

\[
J = -D \frac{\sigma c}{\sigma x} \quad (8-2)
\]

where,
J – diffusion flux (mol/m²·s)
D – diffusion coefficient
C – concentration (mol/m³)
x – distance (m)

It is hypothesized that the diffusion of the rejuvenator changes the viscosity of the aged binder, and as the process continues, more and more of the aged binder is "rejuvenated" – which is reflected by the change (lowering) of viscosity, until equilibrium is attained. The mixing of two materials of different viscosities to produce a mix with a specific viscosity was modeled by Equation (8-3).

\[
ln\mu_{mix} = c_1 \cdot ln\mu_1 + ln\mu_2 + c_1 \cdot c_2 \cdot G_{12} \quad (8-3)
\]

Index 1 and 2 denote two different liquids or binder and \(c_1\) and \(c_2\) denote volume, mass or molar fraction of liquid/binders 1 and 2. The parameter \(G_{12}\) considers the effect of the intermolecular interaction between different sets of binders – this parameter has not been considered in the analysis.

The diffusion process was modeled using finite element simulation. The following are the sequence of steps used by the FE software calculation and result expression.
1) Run the diffusion process for time interval of $\Delta t$ seconds; readjust the viscosity of the layers, based on the concentration of the rejuvenator in the layers at $\Delta t$, according to Equation (8-3) (mixing model); run the diffusion process for another $\Delta t$ seconds; repeat for the entire time $t_{\text{end}}$ that is allowed for mixing. The selection for the $\Delta t$ seconds was made on the basis of two things: 1) how fast the diffusion is occurring; 2) what is the smallest time that can be considered without having excessive computation time.

2) The concentration of the rejuvenator and the viscosity of the resultant binder at each $\Delta t$ time intervals throughout the thickness of the RAP binder were determined.

3) The total time of the simulation $t_{\text{end}}$ was chosen in order to reach homogeneous concentration (and viscosity) throughout the binder film thickness. This balance must be maintained at the aggregate and binder interface for least $t_1 \cdot 10$ intervals which shows that further changes in concentration will not occur.

4) Time of reaching homogeneous distribution of the rejuvenator in the entire film is reported as $t_{\text{balance}}$. It is calculated as the viscosity at time $t_{\text{end}}$ minus 1%.

### 8.5. PARAMETERS USED FOR MODELING AND SIMULATION

The formulation of the diffusion problem with respect to asphalt mix recycling in plant recycling is demonstrated in Figure 8-1. The simulation was run assuming 100 % RAP recycling with the use of rejuvenator; there is no virgin binder or aggregates.

![Figure 8-1. Aggregate, Binder and Rejuvenator Interface](image)

### 8.6. PLANT MIXING PROCESS AND TEMPERATURE

The asphalt mixture production in the plant involves two main characteristics - temperature and time of heating. The rejuvenator diffusion into the aged RAP binder film strongly depends on both of these factors. In a drum plant the rejuvenator is usually added after the RAP has been heated in
the drum to the required temperature as illustrated in Figure 2-2. The RAP temperature at this point was obtained from field data and in this case it was 145 °C. After addition of the rejuvenator the material is transported by elevator to the storage silo and hauled to the construction site. Through the first phase of this process the temperature remains relatively stable, therefore simulations were performed to determine the required time at this constant temperature for the rejuvenator to have maximum efficiency (to reach balance within the binder film).

To analyze the effect of temperature on the diffusion time, diffusion at two more temperatures (120 °C and 95 °C) was simulated. Different temperature may be used based on local circumstances (weather, RAP condition, binder grade, etc.) or the mix (for example, when some warm mix technology is utilized).

**Viscosity of Rejuvenators and Binders**

A range of rejuvenators were tested for kinematic viscosity using capillary tube viscometers at two different temperatures – 95 °C and 145 °C. Bitumen was extracted from RAP and tested for penetration at 25 °C and kinematic viscosity at 135 °C. The penetration data was converted to viscosity using the procedure by Texas DOT [154]. Log-log viscosity versus log temperature regression was used to express the viscosity of rejuvenators and binder at the required temperate range that is typically used for production and compaction of asphalt. The density of the products (listed in Table 8-2 and Table 8-3) that was used to calculate the dynamic viscosity as presented in Table 8-1.

**Table 8-1. Viscosity of Rejuvenators and Bitumen**

<table>
<thead>
<tr>
<th>Product</th>
<th>60°C</th>
<th>95°C</th>
<th>120°C</th>
<th>135°C</th>
<th>145°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extracted RAP binder</td>
<td>344.71*</td>
<td>14.92</td>
<td>4.12</td>
<td>2.31*</td>
<td>1.65</td>
</tr>
<tr>
<td>Virgin AC-20 binder**</td>
<td>198.44*</td>
<td>3.50</td>
<td>0.78</td>
<td>0.40*</td>
<td>0.28</td>
</tr>
<tr>
<td>Refined Tallow</td>
<td>0.0277</td>
<td>0.0055*</td>
<td>0.0033</td>
<td>0.0027</td>
<td>0.0025*</td>
</tr>
<tr>
<td>Paraffinic base oil</td>
<td>0.0529</td>
<td>0.0054*</td>
<td>0.0029</td>
<td>0.0023</td>
<td>0.0021*</td>
</tr>
<tr>
<td>VW Grease</td>
<td>0.0438</td>
<td>0.0085*</td>
<td>0.0049</td>
<td>0.0040</td>
<td>0.0035*</td>
</tr>
<tr>
<td>VW Oil</td>
<td>0.4326</td>
<td>0.0092*</td>
<td>0.0058</td>
<td>0.0048</td>
<td>0.0043*</td>
</tr>
</tbody>
</table>

*Test temperatures
**Viscosity obtained from source [155]
**Rejuvenator Parameters**

Film thickness, volume and concentration of the rejuvenators are required for FE calculation. The concentration depends on molecular weight, while the film thickness and volume depends on rejuvenator dose.

The molecular weight of the materials was obtained using Gel Permeation Chromatography (GPC) technique and in some cases from the information provided from producers of the rejuvenators.

The film thickness of the rejuvenators was calculated according to Equation (8-4) [40], where the surface area factor was calculated for the mixture that was used for the experimental study of this research. The rejuvenator mass (Equation (8-5)) in the mixture is required to calculate volume and a 2500 g sample that was used in experimental study was utilized for this purpose. The specific gravity of the rejuvenators was provided by the producers of the products. The calculation of concentration (Equation (8-8)) requires the number of moles for each rejuvenator (Equation (8-7)).

The calculations of required parameters were performed for three different doses of rejuvenators – 1 %, 2 %, and 3 % by the weight of mixture. The sequence of results for all the rejuvenators at 1 % dose are summarized in Table 8-2.

\[
FT_{rejuvenator} = \frac{b}{100 - b} \cdot \frac{1}{\rho_b} \cdot \frac{1}{SAF}
\]  

where,

- \(FT\) – film thickness, mm
- \(b\) – rejuvenator content, %
- \(\rho_b\) – specific gravity
- \(SAF\) – surface area factor, m²/kg (10.35 m²/kg was used).

\[
Mass\ of\ rejuvenator = rejuvenator\ dosage \times sample\ mass
\]

\[
Volume\ of\ rejuvenator = \frac{Mass}{Density}
\]

\[
Number\ of\ moles = \frac{Mass\ or\ rejuvenator}{Molecular\ weight}
\]

\[
Concentration = \frac{Number\ of\ moles}{Volume}
\]
Table 8-2. Rejuvenator Parameters

<table>
<thead>
<tr>
<th>Product description</th>
<th>Specific gravity</th>
<th>Dose, %</th>
<th>Film thickness, μm</th>
<th>Mass in 2500g sample, g</th>
<th>Molecular weight, g/mole</th>
<th>Volume, m³</th>
<th>Number of moles, mole</th>
<th>Concentration, mol/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refined Tallow</td>
<td>0.90*</td>
<td>1.0</td>
<td>1.14</td>
<td>25</td>
<td>283*</td>
<td>2.8E-05</td>
<td>8.9E-02</td>
<td>3186</td>
</tr>
<tr>
<td>Paraffinic Base Oil</td>
<td>0.88*</td>
<td>1.0</td>
<td>1.16</td>
<td>25</td>
<td>395*</td>
<td>2.8E-05</td>
<td>6.3E-02</td>
<td>2228</td>
</tr>
<tr>
<td>WV Grease</td>
<td>0.92</td>
<td>1.0</td>
<td>1.11</td>
<td>25</td>
<td>771</td>
<td>2.7E-05</td>
<td>3.2E-02</td>
<td>1193</td>
</tr>
<tr>
<td>WV Oil</td>
<td>0.92</td>
<td>1.0</td>
<td>1.11</td>
<td>25</td>
<td>2442</td>
<td>2.7E-05</td>
<td>1.0E-02</td>
<td>377</td>
</tr>
<tr>
<td>Nustar PG 64-22</td>
<td>1.02*</td>
<td>1.0</td>
<td>1.00</td>
<td>25</td>
<td>730</td>
<td>2.5E-05</td>
<td>3.2E-02</td>
<td>1320</td>
</tr>
</tbody>
</table>

*Provided by the producer material data sheets

8.7. BINDER PARAMETERS

The parameters of the aged RAP bitumen that were used in the simulation are provided in Table 8-3. A film thickness (9 μm) was considered on the basis of the recommendations found in literature for dense graded mixes of 9-10 μm, in terms of VMA, [156, 157, 158]. The molecular radius was obtained from Karlsson and Isacsson [151].

Table 8-3. Parameters of the Aged Binder

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.02</td>
</tr>
<tr>
<td>Film thickness</td>
<td>9.00 μm</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>877.2 g/mole</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.0 W/m·K</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1006 J/kg·K</td>
</tr>
<tr>
<td>Molecular radius</td>
<td>3e-10</td>
</tr>
</tbody>
</table>

8.8. SIMULATION RESULTS

The change in viscosity at the aggregate and bitumen interface is illustrated in Figure 8-2. For the first few seconds the rejuvenator has not reached the bitumen and aggregate interface and the viscosity is constant; in the next phase through diffusion process the rejuvenator softens the bitumen; at around 205 to 215 seconds the viscosity is found to be stable for 10 seconds which suggests that no further softening is possible with increased time or temperature. A tolerance of 1 % is deducted from the end viscosity and the time to reach this viscosity level is defined as the time to reach homogeneous rejuvenator concentration through the film. The illustration shows this process for 1 % WV grease rejuvenator at a temperature of 145 °C.
In the diffusion process the rejuvenator penetrates in the bitumen film gradually reducing the viscosity starting from the outer layer of the binder film and continuing throughout the film thickness until equilibrium is reached. If the process is interrupted by, for example reducing the temperature, the equilibrium will not be reached. The viscosity of the film will remain lower at the surface of the film and higher at the interface of bitumen and aggregate. This is potentially dangerous situation and may cause permanent deformations to the pavement. The viscosity through the rejuvenator and bitumen film for a simulation of 145 °C at 20 seconds is illustrated in Figure 8-3. The negative thickness represents rejuvenator film while the positive is the binder. It is clear that this time interval is too short for WV Oil rejuvenator to reach homogeneous distribution.

Figure 8-2. The Viscosity at Different Times for 1 % WV Grease
The changes of aged binder viscosity from adding different doses of rejuvenators at 145 °C are illustrated in Figure 8-4. It is evident that the refined tallow and paraffinic base oil has the highest softening performance, while the WV oil and virgin binder has the lowest. The difference is significant and refined tallow can be up to four times more efficient than addition of virgin asphalt. Potentially such approach can be used to determine the dose of rejuvenator to reach target viscosity, for this purpose viscosity of virgin AC-20 binder is illustrated in the figure.

These results, however, are not in good agreement with the binder viscosity testing results as can be inferred from Table 4-2 and Table 5-2. Although the properties of RAP binder used for this simulation were not determined from the same binder used for determining the viscosity in these tables, it can nevertheless be assumed that the softening efficiency and the ranking of products should be similar to those test results. However, the measured kinematic viscosity is in all cases lower than demonstrated in Figure 8-4. The relative viscosity between these products is also different than calculated here. Thus further work is necessary to optimize the simulation algorithm.
The time to reach the viscosity illustrated in Figure 8-4 can be very different when using different rejuvenators. Figure 8-5 shows minimum period of time that is required to reach balanced viscosity at entire film thickness for three different rejuvenator doses. It is evident that the time to reach equilibrium depends on the type of rejuvenator. By changing the dose of rejuvenator the relative comparison between the different rejuvenators also changes. This is due to the fact that the weight of parameters that influence the viscosity changes as described by mixing model (Equation (8-3)). While the concentration and viscosity remains constant, the volume and mass of the samples changes. For example the concentration of WV Oil is significantly lower compared to the other samples, which causes increase in the required time to reach equilibrium.

In absolute numbers the required time at this temperature seems to be sufficient to reach homogeneous rejuvenator distribution within the binder film. This is somewhat contradictory to the reports in literature about "black rock" effect and suggests that some other mechanisms are involved in this process. Perhaps two staged rejuvenation as reported by Huang et al. [52] would simulate the process more realistically.

Figure 8-4. Viscosity at Different Doses at 145 °C
Figure 8-5. Required Time to Reach Equilibrium at Different Rejuvenator Doses

Figure 8-6 illustrates the required time to reach balance at different temperatures for 1% paraffinic base oil. The increase in time is significant and there is a large chance that the diffusion process will not be finalized before construction if lower than recommended temperature is chosen. This extension of time is caused by the viscosity increase of both – the binder and the rejuvenators.

Figure 8-6. Time of Equilibrium at Different Temperatures for 1% Paraffinic Base Oil
8.9. SECTION CONCLUSIONS

1) The softening level of the aged binder depends on the parameters of rejuvenators which include, but is not limited to viscosity. Refined tallow was up to four times more effective than virgin binder.

2) The dose of the rejuvenator changes the time to reach equilibrium in the binder. According to the simulation total diffusion time at 145 °C is sufficient for reaching homogeneous rejuvenator distribution in practical applications, which does not comply with multiple studies demonstrating "black rock" effect. Simulation of staged diffusion may give more realistic results.

3) If the diffusion process has not been completed before opening to traffic because of insufficient time or low temperature, the outer layer of the film will have lower viscosity which can lead to lower stiffness and instability under traffic.

4) The testing of penetration after addition of rejuvenators and the mechanical tests of asphalt mixture confirm that rejuvenators are much more effective in improving the performance of aged binder compared to addition of softer binder. However, in general the simulation results poorly correlate with the bitumen testing data. Possible cause for this might be the fact that diffusion is only one of the processes taking place. The others include mechanical mixing and homogeneous dispersion of the rejuvenator. Further refining of the calculation algorithm is necessary to give more realistic results.
9. ENVIRONMENTAL ANALYSIS

Most life cycle studies clearly indicate that use of high content RAP reduce the emissions [159]. For hot mix pavements, the main two main processes that are responsible for GHG emissions and energy use are binder refining and asphalt mixture production [160, 161]. RAP use reduces the binder consumption and thus proportionally decreases the environmental effect. For example, the European Commission sponsored project Re-Road [162] investigated the life cycle benefits from using Warm Mix Asphalt (WMA) versus recycling and demonstrated that even at relatively low RAP rate of 15 % the recycling benefits are higher than those achieved by reducing temperature from 165 °C to 130 °C.

9.1. OBJECTIVE

The objective of this stage was to compare the environmental effects of producing 100 % RAP mixtures versus conventional pavements.

9.2. EMISSIONS FROM ASPHALT PRODUCTION

Several simple calculations were performed to estimate the changes in energy use and emissions for production of totally recycled mixture versus a virgin mixture. According to "Re-Road" project [162] 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 100 % RAP production technologies also claim that emissions are similar to traditional asphalt plants [9, 14, 17]. Therefore the energy use and emissions from different processes that are summarized in Table 9-1 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 % rejuvenator 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 rejuvenator.
Table 9-1. Energy Use for Material Production, Laying and Transportation

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy use</th>
<th>Source</th>
<th>Emissions</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand and gravel production</td>
<td>5.8 MJ/t</td>
<td>[163]</td>
<td>10 CO₂eq</td>
<td>[160]</td>
</tr>
<tr>
<td>Crushed stone production</td>
<td>54 MJ/t</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAP processing</td>
<td>16.5 MJ/t</td>
<td></td>
<td>4 CO₂eq</td>
<td>[164]</td>
</tr>
<tr>
<td>Bitumen and rejuvenator(^b) production</td>
<td>1749 MJ/t</td>
<td>[165]</td>
<td>285 CO₂eq</td>
<td>[160]</td>
</tr>
<tr>
<td>Hot mix asphalt production</td>
<td>275 MJ/t</td>
<td>[160]</td>
<td>22 CO₂eq</td>
<td></td>
</tr>
<tr>
<td>Laying</td>
<td>9 MJ/t</td>
<td></td>
<td>0.6 CO₂eq</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td>0.9 MJ/t-km</td>
<td></td>
<td>0.06 CO₂eq</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)in Europe: oil extraction1090 MJ/t + bitumen production 510 MJ/t + pipeline transport 49 MJ/t + storage 100 MJ/t

\(^b\)rejuvenator production assumed equal to bitumen production

9.3. EFFECT OF TRANSPORTATION DISTANCE

Transportation is of particular importance to the environmental benefits and costs of recycling. To illustrate the effects of haul distance on energy use a 100 % RAP mixture was compared to a typical virgin mixture. The emissions (Table 9-1) for the production of constituent materials of virgin mix, processing of milled RAP and production of rejuvenator for RAP mixtures were considered constant. Transportation difference is the only variable. The results in Figure 9-1 illustrate that for up to 200 km difference in hauling distance the use of 100 % RAP mixture produces less emissions than using virgin materials. For example, if the asphalt plant and material sources would be located next to each other, it would still produce less emissions to haul RAP from a 190 km distant milling site. A similar calculation with the values from Table 9-1 was performed for energy use and the results in Figure 9-2 show that the initial energy use of 100 % RAP mix would be 100 MJ smaller than that of virgin materials. This would be equal to increase of 110 km in transportation distance.

The average hauling distance of RAP in the US from site to plant is 20 km, while for virgin aggregates it is 70 km [166]. In such case the use of 100 % RAP versus virgin mix would allow to save 156 MJ and 15 kg CO₂eq per ton of mix. This is particularly relevant in light of the facts that specifications are getting tighter, sources of good quality aggregates are not abundant, and opening of new quarries is becoming increasingly difficult due to environmental regulations [167].
9.4. CRADLE-TO-GATE EMISSION ANALYSIS

A comprehensive view 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. The durability 100 % RAP pavement probably is the largest unknown in such calculation and can have a large impact on the conclusions of life cycle effects compared to conventional pavement. Research by Waymen et al. [162] suggests that reduction of durability of pavement from 20 to 14 years would increase the global warming potential by 13 %. Lee et al. [159] concludes that at 30 % RAP rate the pavement the service life has to be 80 to 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 calculations.

The emission data from Table 9-1 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 Figure 9-3 demonstrate that 18 kg of CO₂ equivalent and 20% energy per ton of paved mixture can be saved by producing asphalt from 100% reclaimed material.

![Figure 9-3. Emissions and Energy Use per Ton of Paved Asphalt](image-url)
9.5. SECTION SUMMARY

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 energy use of 20% can be achieved by switching to 100% RAP asphalt, mostly due to embedded energy for production of constituent materials. Along with this 18 kg CO$_2$eq emissions per ton of paved mixture can be saved. With respect to transportation distance, hauling of materials from 100 km distant site for 100% RAP production would still generate less emissions than production of virgin mix at materials quarry. These environmental effects and implementation of innovative production process would greatly benefit the agencies that have applied certification systems for sustainable construction practices (LEED, Greenroads, etc.).
10. ECONOMIC ANALYSIS

The cost of binder has been increasing constantly since 1990 and has tripled during the last decade as illustrated in Figure 10-1. The RAP price compared to that is very low ranging from 15 to 30 USD [33] 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. However, the savings must be quantified to account for additional expenses related to RAP processing, testing, and use of rejuvenator. Switching to 100 % recycling would also require significant investments for modification of production technology that must be put into the equation.

![Figure 10-1. Binder Price Index [168]](image)

10.1. OBJECTIVE

The objective of this research stage is to compare the costs for production of 100 % RAP mixture with those of conventional asphalt and to perform an analysis of the expected break even time for the required investment in plant technology to allow production of 100 % RAP mixtures.
10.2. REJUVENATOR COSTS

The approximate price per liter of all the rejuvenators that were used in the study\(^2\) in the US are included in Table 10-1. For reference, the price of virgin binder is also included. To compare the rejuvenator cost per ton of produced asphalt mixture, the rejuvenator dose needs to be optimized to deliver the required performance. In the dose optimization study in Section 6 it was established that rejuvenator content that reaches the penetration of virgin binder (78 ×0.1 mm) also satisfies the Superpave PG requirements. Therefore the required dose was calculated according to the relationship developed in the dose study for penetration (Equation (6-1)) by using the penetration testing data from dose study (Section 6) and screening study (Section 4). The mixture binder content was assumed 5% for calculations.

The rejuvenator costs per ton of asphalt mixture range from 3.29 to 15.13 USD. It is clear that the cost of waste products is the lowest, with all of them estimated below 4 USD per ton of produced asphalt mixture and at least 1.5 USD lower than the next cheapest product. The Aromatic Extract proves to be the most expensive both because of relatively higher price point and the high required dose.

\(^2\) WEO bottoms and WEO+FT wax are not included in the table since they would require unrealistically high dose to provide equal penetration to virgin binder (42.1% and 53.3% respectively)
Table 10-1. Rejuvenator Prices in the US and Costs per Ton of Asphalt Mixture

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Engineered or generic</th>
<th>Source</th>
<th>Refined or Waste</th>
<th>Price per liter, USD</th>
<th>Rejuvenator dose, % from binder mass*</th>
<th>Specific Gravity</th>
<th>Cost per tonne of asphalt mix, USD**</th>
</tr>
</thead>
<tbody>
<tr>
<td>WV Oil</td>
<td>Generic</td>
<td>Organic</td>
<td>Waste</td>
<td>0.58</td>
<td>10.7</td>
<td>0.92</td>
<td>3.37</td>
</tr>
<tr>
<td>WV Grease</td>
<td>Generic</td>
<td>Organic</td>
<td>Waste</td>
<td>0.73</td>
<td>8.3</td>
<td>0.92</td>
<td>3.29</td>
</tr>
<tr>
<td>Distilled tall oil</td>
<td>Generic</td>
<td>Organic</td>
<td>Refined</td>
<td>1.59</td>
<td>11.1</td>
<td>0.95</td>
<td>9.29</td>
</tr>
<tr>
<td>Waste engine oil</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Waste</td>
<td>0.46</td>
<td>14.1</td>
<td>0.87</td>
<td>3.73</td>
</tr>
<tr>
<td>Aromatic extract</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>1.26</td>
<td>20.9</td>
<td>0.87</td>
<td>15.13</td>
</tr>
<tr>
<td>Paraffinic base oil</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>0.97</td>
<td>16.7</td>
<td>0.87</td>
<td>9.31</td>
</tr>
<tr>
<td>Refined tallow</td>
<td>Generic</td>
<td>Organic</td>
<td>Refined</td>
<td>1.34</td>
<td>8.7</td>
<td>0.89</td>
<td>6.55</td>
</tr>
<tr>
<td>Organic oil</td>
<td>Engineered</td>
<td>Organic</td>
<td>Refined</td>
<td>1.57</td>
<td>10.1</td>
<td>0.95</td>
<td>8.35</td>
</tr>
<tr>
<td>Napthenic flux oil</td>
<td>Engineered</td>
<td>Petroleum</td>
<td>Refined</td>
<td>1.00</td>
<td>25.1</td>
<td>2.38</td>
<td>5.27</td>
</tr>
<tr>
<td>Virgin PG64-22</td>
<td>Generic</td>
<td>Petroleum</td>
<td>Refined</td>
<td>0.62</td>
<td>-</td>
<td>1.03</td>
<td>-</td>
</tr>
</tbody>
</table>

*dose calculated to reach penetration of 78 ×0.1 mm (virgin binder)

**assuming 5.0 % binder content

10.3. SAVINGS FROM SWITCHING TO 100% RAP PRODUCTION

A simple calculation was performed to assess the materials related costs for production of mixtures with increased RAP dose. The assumptions for costs that were used for calculation are listed in Table 10-2 and include all major positions that are expected to change with increased RAP use. However, these expenses may vary depending on 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 10-2. Rural areas, on the other hand may have shortage of RAP and asphalt producers will need to purchase it. The operational expenses that are likely to remain constant with the change of RAP content (e.g. staff wages, rent) were not included in the calculation.
Table 10-2. Material Related Costs

<table>
<thead>
<tr>
<th>Expense position</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>$19.80/t</td>
</tr>
<tr>
<td>Binder</td>
<td>$704.00/t</td>
</tr>
<tr>
<td>Rejuvenator*</td>
<td>$1.30/l</td>
</tr>
<tr>
<td>RAP purchasing</td>
<td>$11.00/t</td>
</tr>
<tr>
<td>RAP Disposal</td>
<td>$5.50/t</td>
</tr>
<tr>
<td>RAP Processing</td>
<td>$3.30/t</td>
</tr>
<tr>
<td>Burner Fuel</td>
<td>$3.47/t</td>
</tr>
<tr>
<td>Pollution Control</td>
<td>$2.75/t@100%RAP</td>
</tr>
</tbody>
</table>

*Rejuvenator price was assumed at the higher end as can be seen from Table 10-1

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% + rejuvenator 0.6%) was used for calculations.

Some additional costs associated with production of 100% RAP mixture will rise for characterizing the RAP, determining its binder properties and conducting performance-related tests (discussed in section 2.6.3). The test methods and the minimum binder testing frequency of high RAP mixes are proposed by NCHRP Report 752 and were summarized in Table 2-6. The mixture performance-related testing frequency was not defined by the report and is assumed equal to that of binder performance grading. The expenses obtained from commercial testing facility are summarized in Table 10-3 and the calculation based on the proposed testing frequency shows 1.48 USD expenses per ton of produced asphalt. Other testing expenses (e.g. aggregate and mixture volumetric properties) are assumed equal to conventional mixtures and therefore are not included in the calculation.
Table 10-3. Testing Expenses

<table>
<thead>
<tr>
<th>Property</th>
<th>Test frequency</th>
<th>Cost per sample, USD</th>
<th>Cost per tonne of asphalt, USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP binder content</td>
<td>1 per 900 t</td>
<td>200.00</td>
<td>0.22</td>
</tr>
<tr>
<td>Recovered aggregate gradation</td>
<td>1 per 900 t</td>
<td>75.00</td>
<td>0.08</td>
</tr>
<tr>
<td>Recovered aggregate bulk specific gravity</td>
<td>1 per 2700 t</td>
<td>150.00</td>
<td>0.06</td>
</tr>
<tr>
<td>RAP binder recovery</td>
<td>1 per 4500 t</td>
<td>325.00</td>
<td>0.07</td>
</tr>
<tr>
<td>Performance grading (PG)</td>
<td></td>
<td>950.00</td>
<td>0.21</td>
</tr>
<tr>
<td>Hamburg rut depth</td>
<td></td>
<td>700.00</td>
<td>0.14</td>
</tr>
<tr>
<td>Semi-circular bend test (low temperature cracking)</td>
<td></td>
<td>2,000.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Energy ratio (top down cracking)</td>
<td></td>
<td>1,500.00</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1.48</strong></td>
<td></td>
</tr>
</tbody>
</table>

Figure 10-2 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 availability of RAP, the costs of per ton of 100 % RAP mixture would be reduced between 32 to 48 USD or 50 to 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.

![Figure 10-2. Material Related Costs of Hot Mix Recycling](image-url)
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 [12].
- A representative from "BAB Belag", who owns Ammann 100 % RAP capable plant in Switzerland, indicates savings of approximately 11 USD for every 10 % increase in RAP content.
- Smart PAVE system [14] claims 30 % or higher savings in production related costs compared to HMA produced with primarily virgin aggregates.

10.4. 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 ton of mix.

The average production rate of a plant located in the US in 2011 was 95,000 tonnes per year [6]. Reaching the country average might be a high target for a new technology and therefore a calculation at 30,000 tonne per year rate was performed as well. Three different investment levels (1, 2, and 5 million USD) and profit margins ranging from USD 5 to 40 per tonne of mix were used for calculation of time to break even and the results are illustrated in Figure 10-3. The profit per tonne 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 tonne of produced mixture (see Figure 10-2). 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/yr. production rate.
10.5. SECTION CONCLUSIONS

In recent years the industry focus has been placed on increasing the amount of RAP in hot 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 recycling. Switching to 100 % RAP production would enable material related cost savings of 50 to 70 % compared to virgin mixture. Price reduction of USD 20 per ton of asphalt compared to virgin mixes would still provide the contractor a profit of at least 12 USD per ton of produced 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.
11. SUMMARY AND CONCLUSIONS

The use of rejuvenators and production of 100% reclaimed hot-mix asphalt was investigated in this doctorate research and a short summary of the study is presented in Video 11-1.

At least ten technologies allowing production of 100% recycled hot-mix asphalt are readily available and with good RAP management practices can provide cost effective production while reducing environmental impact of asphalt industry. Use of rejuvenators is the key for production of very high RAP content mixtures. Eleven different products were screened and six of them were used for thorough evaluation of performance-related properties of extracted RAP binder and 100% RAP mixture. It was found that rejuvenator dose and diffusion into RAP binder are critical aspects of successful rejuvenation. Therefore, a methodology was developed for optimization of rejuvenator dose to ensure correspondence of RAP binder to the required performance grade and finite element modelling was utilized to simulate rejuvenator diffusion. Finally, the effect of two select rejuvenators on SHRP binders was investigated by characterizing the chemical composition, rheology, morphology and micromechanical effects.

Video 11-1. Summary of the Dissertation (click to play or access at http://youtu.be/y-rYvdGiEbY)
Each section of the thesis provides a summary and detailed conclusions for the respective research stage which can be briefly described as follows:

- Chapter 2. Ten technologies readily available for production of 100% RAP mixtures were identified and five are described in detail. Conventional techniques for application of such mixtures can be used. The historically recorded performance of 100% RAP mixtures, potential distresses, proposed mix design guidelines, along with best practices of material supply chain management were presented.

- Chapter 4. In the rejuvenator screening study, nine products were evaluated for their ability to reduce binder viscosity and improve low temperature cracking resistance. The products that performed the best at this stage are organic oil, refined tallow, aromatic extract and distilled tall oil, while paraffinic base oil, waste engine oil, naphthenic flux oil, WEO+FT wax, and WEO bottoms failed to improve the RAP binder/mixture performance in at least one of the tests.

- Chapter 5. The complete characterization study demonstrated that at 12% dose rejuvenators provided the required rutting resistance of 100% RAP mix and most of six tested products significantly improved the cracking resistance of both mixture and binder. Workability was improved compared to RAP but remained lower than that of virgin mixture. Generally at the tested dose, organic products outperformed the petroleum additives in most performance-related properties.

- Chapter 6. Rejuvenator type and dose in aged RAP binder can be optimized to satisfy the PG requirements of source binder. With increasing rejuvenator dose, high and low PG temperature reduces linearly and intermediate $G^* \cdot \sin\delta$ parameter is also expected to decrease linearly until the Superpave threshold of maximum 5,000 kPa. A methodology was developed to optimize the rejuvenator dose.

- Chapter 6. Penetration increases exponentially with increased rejuvenator dose. For the combinations of six rejuvenators and one binder used in the study, optimization of dose to reach penetration of virgin binder also ensured correspondence to the performance grade of the same virgin binder. Penetration and high PG temperature were found to predict the mixture rutting with a reasonable precision and therefore can be used for initial screening of products and optimization of dose.

- Chapter 7. The rheological properties of aged-rejuvenated SHRP binders were in between those of source virgin and aged binders and this was qualitatively consistent with micromechanical and morphological analysis of these binders as determined with AFM.
Chapter 8. FE modeling of rejuvenator diffusion confirmed that the diffusion speed is a function of time, temperature, viscosity and molecular weight. However, the results poorly correlated with mechanical test results and further refining of the calculation algorithm is necessary.

Chapter 9. The production of 100 % RAP mixtures in the presented case of cradle to gate analysis of asphalt application would allow reduction of energy demand by 20 % and emissions by 35 % compared to virgin mixture.

Chapter 10. Economic calculations of the material related expenses showed reduction of 50-70% compared to virgin mixtures. As an example, a reduction of asphalt mixture price by as much as 20 USD would allow to break even an investment in plant technology of 1 million dollars in three years at a conservative production rate of 30,000 tons per year.

11.1. FURTHER RESEARCH

Any future research activities will be published along with the results of this study online at http://zaumanis.com. It was shown in this research that rejuvenators can ensure the required binder grade, but further studies are necessary to develop methods for evaluating compatibility of rejuvenators with a specific binder and to determine the diffusion speed and the amount of "activated" RAP binder for blending with virgin materials. Comparison of performance of optimally designed 100 % RAP mixtures with a conventional asphalt would provide further confidence. Finally, full scale trials with pavement monitoring would allow to conclusively demonstrate the potential of 100 % recycling. If successful, the government agencies should permit routine application of 100 % recycled hot-mix asphalt on public roads on equal terms with conventional asphalt by specifying the application, quality control and mix design principles.
REFERENCES


References


[74] K. Burke and S. A. Hesp, "Penetration testing of waste engine oil residue modified asphalt cements," in 1st Conference of Transportation Research Group of India (CTRG), Bengalore, India, 7th to 10th December, 2011.


References


References


