1 Determining optimum rejuvenator addition location in asphalt 2 production plant

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14 Abstract

15 Rejuvenator is an oil that can be added during asphalt production to restore Reclaimed Asphalt
 16 Pavement (RAP) binder. Ten potential locations for rejuvenator addition in asphalt plant were
 17 ranked in terms of pavement performance, plant operation, and environmental safety. A full scale
 18 production was performed to compare rejuvenator addition to cold RAP on conveyor belt versus
 19 addition to hot RAP in mixer (video <https://youtu.be/LYBq93e8BG0>). Mixture test results
 20 indicated that spraying of rejuvenator onto cold RAP facilitates rejuvenator diffusion in RAP
 21 binder resulting in improved asphalt fatigue and crack propagation resistance. Both addition
 22 locations generated equal organic carbon emissions from asphalt plant.

23 **Key words:** *asphalt recycling; RAP; rejuvenators; emissions; environment; production; partial*
 24 *blending; black rock; pavement; road*

25 **Declarations of interest:** none

26 Highlights

- 27 – Rejuvenator addition on RAP conveyor belt, dryer outlet or in mixer is recommended
- 28 – Early rejuvenator addition might be advantageous for mixture performance
- 29 – Rejuvenator addition before and after RAP dryer produce the same emissions

Graphical abstract

1. Introduction

The use of Reclaimed Asphalt Pavement (RAP) in production of new hot mixtures is continuing to increase because of economic and environmental benefits. However, the increase in RAP use to a large extent owes to the fact that producers are choosing to put low RAP rates in more mixtures and to a lesser extent to increased RAP rate in a given mix design. To further raise the re-use of reclaimed asphalt, a higher RAP rate needs to be used in mixtures. This can only be achieved by rejuvenating the aged asphalt binder film. Use of softer binder grade has historically been the most popular approach, but it has several drawbacks: (1) at high RAP rate the effect of using softer bitumen becomes less evident [1,2] and (2) changing between the RAP sources and using various RAP rates in mix design would mean that multiple soft binder grades (and corresponding number of bitumen tanks) are necessary. This is difficult to ensure.

Rejuvenators are oils that are aimed at restoring the mechanical performance of the RAP for another asphalt pavement service period. Contrary to when softer binders are used, they provide flexibility to switch between different types and contents of RAP and can rejuvenate binder at up to 100% RAP content [3–5]. Their use, however, also imposes new challenges. Control of RAP

homogeneity, ensuring optimum rejuvenator dosage, homogeneous distribution of rejuvenator, good diffusion of rejuvenator into the RAP binder film, and good blending of virgin with RAP binder are five key parameters for ensuring the expected pavement performance. Only two of the five parameters, control of RAP homogeneity and determination of optimum rejuvenator dose, partially depend on the work in the mix design laboratory. At the same time all five depend on the practices in asphalt plant and cannot be accurately reproduced in laboratory. Diffusion of rejuvenator into RAP binder film is of particular importance because this “activates” the RAP binder and makes it available for blending with virgin materials to form a homogeneous binder film on RAP and virgin aggregates. It is, however, recognized that not all of RAP binder is activated and part of it behaves as “black rock” thus reducing the effective binder content in the mixture [6,7]. This in turn can lead to low temperature and fatigue cracking: risks that are already associated with the use of RAP due to its high stiffness. Many researchers have proposed methods to determine the proportion of “active” RAP binder [8–10]. However, virtually no studies have focused on practical means for increasing the RAP binder activation. A preliminary work by the authors [11] evaluated effect of rejuvenator addition location in asphalt plant on the properties of extracted binder and the results demonstrated that rejuvenator effectiveness for binder rejuvenation is not lost regardless of its addition location. However, the standard binder extraction procedure inherently blends rejuvenator and all of RAP binder together thus evaluation of rejuvenator diffusion is not possible.

This research then aims to evaluate means for maximizing the “active” RAP binder by comparing various locations for rejuvenator addition in asphalt plant. The different options are compared with respect to pavement quality, efficiency of rejuvenator addition (homogeneous distribution, residence time, diffusion, loss of rejuvenator), process stability, practicality,

environmental effects (emissions, leaching), operator and plant safety. A summary of the study can be viewed in Video 1.

Video 1: Research summary (<https://youtu.be/LYBq93e8BG0>)

1.1 Disclaimer

The study will consider only batch asphalt plant types, but at the same time similar analysis can be applied to analysis of continuous type asphalt plants. For all reasoning it is assumed that liquid non-flammable rejuvenators are considered. If other conditions are used, then a thorough evaluation, including a risk assessment and hazard identification according to European ATEX directives: (1) equipment directive 2014/34/EU and (2) user/workplace directive 1999/92/EC, and/or locally applicable standards must be carried out.

1.2. Objective

The objective of the study is to compare different locations for rejuvenator addition in a batch asphalt plant and offer recommendation for optimum location based on analytical assessment and full-scale production test results.

2. Materials and methods

2.1 Analytical comparison of rejuvenator addition points

An analytical analysis of a batch asphalt plant was carried out to identify potential rejuvenator addition locations. This was performed by listing benefits and drawbacks for each of the locations in terms of environmental aspects, operator and plant safety, pavement quality, technological process and economic reasons. The goal of this analysis was to identify the most promising locations for evaluation in a practical full-scale experiment.

2.2 Materials

After analytical comparison, two rejuvenator addition locations were selected for comparison in a full scale experiment. Only RAP and rejuvenator were used for evaluation of mixture properties without any other virgin materials. Such approach was chosen to minimize the number of variables and achieve the objective of the study.

RAP with maximum aggregate size of 22mm (Table 1) was characterized before production. It had a binder content of 3.9% and penetration of 20 0.1mm.

Table 1. Particle size distribution of RAP

Sieve, mm	0.063	0.125	0.250	0.500	1.0	2.0	4.0	5.6	8.0	11.2	16.0	22.4
Amount passing, %	7.40	11.70	19.20	27.70	35.90	48.30	62.90	71.30	82.50	90.20	97.10	100.00

A rejuvenator based on distilled tall oil was used in the experiment. It is a byproduct of Kraft manufacturing process. The additive is classified as non-hazardous and has a flash point above 280°C making it safe for use in the RAP dryer. Viscosity at 20°C is 100mm²/s thus liquid additive dosing systems can be used. Based on earlier experience of the authors, 5% rejuvenator content from binder mass was chosen for the experiment [12].

2.3 Production plant

Rejuvenator diffusion depends on plant parameters, most notably residence time on RAP binder and temperature. For this reason description of the conditions in the production plant is provided. Ammann “Uniglobe 200” plant with “RAH 100” RAP dryer was used for the production. It was described by Zaumanis et al. [13]. The RAP heating and drying system has two stages: a static combustion chamber and a rotating RAP dryer where hot air is circulated. The static combustion chamber has a diameter of approx. 2.5 meters and a length of approx. 5 meters and is equipped with a 14 MW dual fuel burner (natural gas or heating oil “EL”). The rotating RAP dryer has a diameter of approx. 2.5 meters and a length of approx. 7 meters; it has a maximum RAP throughput capacity of approximately 160 t/h. The RAP material residence time in the RAP dryer is from one up to several minutes depending on RAP material, RAP feed rate, RAP moisture and dryer revolutions (can be varied according to requirements). This indirect heating principle allows heating RAP without direct contact with the flame, to a conventional hot-mix asphalt production temperature of 160°C (used in this experiment). The RAP dryer is located on a tower to ensure gravity-driven material discharge to the storage unit and mixer. Exhaust gases from either the virgin aggregate (VA) dryer and/or the RAP dryer are combined upstream of bag filter. In the bag filter, the exhaust gas is cleaned from coarse and fine dust before it is released to the atmosphere through the plant's exhaust gas chimney.

2.4 Binder tests

The RAP binder was extracted according to EN 12697-1 using toluene and recovered according to EN 12697-3. Penetration was determined according to EN 1426.

2.5 Mixture tests

The focus of the study is on mixture tests that would allow highlight the differences in rejuvenator effectiveness depending on its addition location. Two criteria were used to select the particular test methods used in the experiment: (1) testing of properties that are traditionally considered unfavorable for high RAP mixtures – fatigue and cracking and (2) sensitivity of the test method to binder content and stiffness allowing to capture the effects of binder activation. Stiffness, fatigue and Semi-Circular Bend (SCB) test fulfil these requirements and were therefore used in this study. These tests were used as indicators of rejuvenator effectiveness at each addition location and not for prediction of the long-term cracking performance. Long-term performance evaluation would require aging of the mixtures but was not in the scope of this paper.

In order to highlight the differences between the rejuvenator addition locations, every effort was made to minimize rejuvenator diffusion after production. This was done for two reasons:

- 1) It was important to keep the conditions the same for all the samples because for practical purposes it is not possible to produce and test all the samples simultaneously. The diffusion that occurs while some samples are sitting in laboratory while other are being tested would jeopardize this objective.
- 2) Although it is true that the rejuvenator diffusion will continue during the service life of the pavement, it must be ensured that the pavement has the required properties already when it is opened to the traffic. It is possible that the asphalt plant is at an immediate vicinity of the paving site and thus rejuvenator diffusion between the production and opening to the traffic is relatively short. For this reason no aging was performed on the asphalt samples.

In order to minimize the rejuvenator diffusion that is not related to the production process, following collection of asphalt samples from the asphalt plant, they were kept in an environmental chamber at +4°C until ready for heating and compaction. To keep the sample preparation time short, the mixture was pre-heated in a microwave oven for 10 minutes followed by heating in an oven at 150°C for 1h until a homogeneous temperature was reached throughout the mixture. The total time that the samples were exposed to high temperature, including production, sampling, re-heating in laboratory and compaction, was about two hours. This is approximately similar time to a real-world situation when the jobsite would be near to the asphalt plant.

Mixture samples were prepared using gyratory compactor with 150mm diameter molds according to EN12697-31 by targeting 4% air voids. The samples were then cut to the required height but no closer than 15mm from the surface to avoid inhomogeneity. After determining volumetric properties, the prepared samples were again placed into the environmental chamber at +4°C until ready for conditioning and testing.

2.6 Stiffness and fatigue

Stiffness (EN 12697-26) followed by fatigue test (EN 12697-24) on the same specimens was performed using dynamic indirect tensile test on cylindrical shaped specimens of 60mm in height and 150mm in diameter. Stiffness tests were performed by applying a sinusoidal load at frequencies of 0.1, 1 and 10 Hz at temperatures of -10, 10 and 20°C. The load level at each frequency and temperature was chosen to induce horizontal strains in the specimen in the range between 0.05 and 0.10‰. Four specimens were tested at each temperature and frequency. These results were then used to create master-curves using the principle of time-temperature superposition to shift data at multiple temperatures and frequencies to a reference temperature.

This allows to view the stiffness data without temperature as a variable. A sigmoidal model was used [14], with the shift factors calculated following the Williams-Landel-Ferry [15] relation: $\log a_T = (-C_1(T - T_{ref})) / (C_2 + (T - T_{ref}))$, where a_T is a factor for shifting complex modulus at certain temperature T to a reference temperature T_{ref} (20°C in this study); C_1 and C_2 are material constants obtained by least squares regression.

Fatigue test was performed at 10°C by applying a sinusoidal repeated loading at 10Hz frequency. Failure criterion (N_{f50}) of 50% loss of initial stiffness modulus was used. Strain levels were chosen to induce failure of the specimens at three distinct levels ($\sim 10^5$, $\sim 10^{5.5}$, $\sim 10^6$). This allows calculating another failure criterion – the strain at 1 million cycles (ϵ_6).

2.7 Crack propagation

Semi Circular Bend (SCB) test at 25°C was used to determine crack propagation. According to the experience of the authors and literature [16,17] the SCB test at 25°C is highly sensitive to RAP proportion, binder grade and binder content while according to the experience of the authors, when performing it at 0°C (according to EN 12697-44) the test is not sensitive to the binder content or viscosity [18]. These are the properties that are important to evaluate the RAP binder “activation” in this research. To prepare an SCB sample the 150mm diameter gyratory samples were trimmed to 50mm in height and cut in half. A notch of 15mm in length and 3.5mm in width was then sawed in the horizontal part to control crack initiation. Four samples per mix were tested. During testing the specimen was positioned in three point testing frame and a load was applied at a monotonic rate of 50 mm/min along the vertical axes. Load and frame displacement were measured during the test.

Results were expressed in terms of the Flexibility Index (FI) calculated according to AASHTO TP 124-16. A typical test result is illustrated in Figure 1. First, fracture energy was calculated:

$G_f = W_f / \text{Area}_{\text{lig}} \times 10^6$, where G_f is fracture energy in N/m, W_f is work of fracture (the area under the load versus displacement curve) in Joules, Area_{lig} is ligament length in mm^2 multiplied by t , and t is specimen thickness in mm. FI was then calculated: $FI = G_f / |m| \times A$, where FI is flexibility index, m is the post peak slope at the inflection point of the load-displacement curve in kN/mm, and A is 0.01.

Figure 1. Typical SCB test result

2.8 Emissions

Plant exhaust gas emission measurements were carried out with two instruments:

- Multi Gas Analyzer (MGA) “MRU MGA5” was used for measuring various gas components, including exhaust gas temperature (T_{gas}).
- Flame Ionization Detector (FID) “SICK FID 3006” was used for measuring Total Organic Carbon (TOC), or Volatile Organic Compounds counted on carbon atoms (VOC- C_1).

The sensors of both emissions testing instruments were installed in the clean gas stack downstream of the plant's main bag filter and upstream of the exhaust gas chimney as illustrated in Figure 2. Since only concentration measurements and no air flow measurements were carried out, the sensors were placed in the inlet duct to the chimney, downstream of the main blower. All emission data was recorded with a mobile NI (National Instruments) LabVIEW SignalExpress data acquisition system using a sampling rate of 1 data point per second for each signal (s^{-1}).

Figure 2. Location and positioning of MGA and FID emission testing instruments / sensors and emission data recording hardware

3. Analytical comparison of rejuvenator addition locations

The potential rejuvenator addition locations in asphalt plant can be categorized in three groups:

1. Upstream of RAP dryer drum
2. Downstream of RAP dryer drum
3. Bitumen

Within each of these groups there are several options resulting in at least ten potential locations for rejuvenation addition as summarized in Figure 3. The factors that have to be taken into

account when choosing the optimum location include environmental aspects (emissions, leaching or rejuvenators into the ground), operator and plant safety, pavement quality (even rejuvenator distribution, residence time, temperature, diffusion, loss of rejuvenator), technological (process stability, practicability) and economic reasons. Based on Boesiger et al. [19] a summary of benefits and drawbacks for each addition location is provided in Table 2. The number of each addition location in Table 2 corresponds to the visualization in Figure 3. It must be noted that these are analytical considerations based on the authors' experience and can change depending on plant type, setup and experience of operation.

Figure 3. Rejuvenator addition locations (Source: Ammann)

1 *Table 2. Benefits and drawbacks of each rejuvenator addition location*

Addition location	Benefit	Drawback
Upstream of RAP dryer		
1. RAP shredder belt	Long rejuvenator exposure on RAP binder Potentially lower RAP heating temperature due to lower RAP binder viscosity (reduced emissions, energy consumption, increased plant capacity)	Inhomogeneous rejuvenator distribution Rejuvenator drainage Stockpile stickiness Potential worker exposure to rejuvenator Rejuvenator evaporation in RAP dryer Possibly increased exhaust gas emissions due to rejuvenator presence
2. RAP storage	Long rejuvenator exposure on RAP binder Potentially lower RAP heating temperature due to lower RAP binder viscosity (reduced emissions, energy consumption, increased plant capacity)	Inhomogeneous rejuvenator distribution Rejuvenator drainage Stockpile stickiness Potential worker exposure to rejuvenator Rejuvenator evaporation in RAP dryer Possibly increased exhaust gas emissions due to rejuvenator presence
3. RAP conveyor belt	Long rejuvenator exposure on RAP binder Potentially lower RAP heating temperature due to lower RAP binder viscosity (reduced emissions, energy consumption, increased plant capacity) Precise dosage based on RAP feed rate	Possibly inhomogeneous rejuvenator distribution Potential worker exposure to rejuvenator Rejuvenator evaporation in RAP dryer Possibly increased exhaust gas emissions due to rejuvenator presence
4. RAP dryer inlet chute	Long rejuvenator exposure on RAP binder Potentially lower RAP heating temperature (reduced emissions, energy consumption, increased plant capacity) Precise dosage based on RAP feed rate	Possibly inhomogeneous rejuvenator distribution Potential worker exposure to rejuvenator Rejuvenator evaporation in RAP dryer Very short interaction of rejuvenator and binder before heating likely resulting in high volatilization of rejuvenator and increased exhaust gas emissions due to rejuvenator presence
Downstream of RAP dryer		
5. RAP dryer outlet chute	Precise dosage based on RAP feed rate Rejuvenator not exposed to RAP dryer (potentially lower emissions, safety)	Shorter exposure time compared to “upstream of RAP dryer” options Possibly inhomogeneous rejuvenator distribution
6. RAP scale	Rejuvenator not exposed to RAP dryer (potentially lower emissions, safety)	Shorter exposure time to RAP binder compared to “upstream of RAP dryer” options Inhomogeneous rejuvenator distribution
7. RAP chute	Rejuvenator not exposed to RAP dryer (potentially lower emissions, safety)	Shorter exposure time to RAP binder compared to “upstream of RAP dryer” options Inhomogeneous rejuvenator distribution
8. Mixer	Rejuvenator not exposed to RAP dryer (potentially lower emissions, safety) Simple plant integration Most precise rejuvenator dosing Most homogeneous rejuvenator distribution	Shorter exposure time compared to “upstream of RAP dryer” options Shortest rejuvenator exposure time to RAP binder
Fresh bitumen		
9. Bitumen line/scale	Precise rejuvenator dosing Simple plant integration	No direct contact of rejuvenator with RAP binder
10. Separate bitumen tank	Precise rejuvenator dosing	No direct contact of rejuvenator with RAP binder No flexibility to change rejuvenators/dosages depending on RAP rate and properties Separate bitumen tank necessary

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In order to compare the different options for rejuvenator addition some parameters in Table 2 should be given a priority over others:

- 1) The rejuvenator application should be **safe for the environment and workers**.

Depending on the type of rejuvenator used this could filter out options No. 1 (RAP shredder belt), No. 2 (RAP storage) and No. 4 (RAP dryer inlet chute).

- 2) **Direct contact of rejuvenator and RAP binder** is preferred rather than pre-blending of rejuvenator with bitumen. This allows rejuvenator diffusion into RAP binder to soften it and maximize blending with virgin bitumen and aggregates. This preference screens out options No. 9 (bitumen line/scale) and No. 10 (separate bitumen tank).

- 3) Finally, **precise rejuvenator dosage control and homogeneous distribution of rejuvenator on RAP binder** are necessary for ensuring best pavement performance.

These requirements screen out options No. 6 (RAP scale) and No. 7 (RAP chute) as well as the options deemed unacceptable previously (No. 1 and No. 2).

Finally three options of rejuvenator addition remain: **No. 3 (RAP conveyor belt)**, **No. 5 (RAP dryer outlet chute)**, and **No. 8 (mixer)**. Addition location No. 3 is located upstream of RAP dryer and locations No. 5 and No. 8 are located downstream of RAP dryer. These three locations require further analysis.

3.1 Rejuvenator addition at the RAP conveyor belt (No. 3)

Rejuvenator is sprayed by means of nozzles installed on top of the belt, directly onto the RAP that is being transported by the conveyor belt from RAP cold feeders towards the RAP dryer.

The rejuvenator dosage rate can be adjusted by the RAP feed rate or mass (if a scale is installed on the belt). Covering of the RAP belt to protect from wind and rain might be necessary to limit rejuvenator loss and operator health and safety hazards.

3.1.1 Benefits

Addition of rejuvenator upstream of the dryer allows longer contact time with RAP binder thus increasing diffusion and consecutive RAP binder activation. This can be beneficial for ensuring more transfer of RAP binder between RAP and virgin aggregates to ensure homogeneous binder film thickness. The additional time (compared to addition in mixer) for which rejuvenator interacts with RAP bitumen can be important to increase the mobilization of RAP binder. Another potential benefit is that the viscosity of the hard RAP binder is reduced before heating in RAP dryer thus enabling lower heating temperatures. This is important mainly because at high RAP rate, emissions caused by heating of RAP are a dominant problem and even a small reduction in heating temperature can reduce the magnitude of these emissions. Additionally, this would reduce energy consumption and increase plant capacity.

3.1.2 Drawbacks

Since the RAP has to pass through the heating RAP dryer, only a rejuvenator with a high ignition point can be used. The specific minimum ignition temperature depends on the plant type. Even if not ignited, high temperature might cause chemical changes in rejuvenator composition. Another potential problem is loss of volatile fractions inside the hot RAP dryer and a consecutive increase in emissions and a reduction in rejuvenation efficiency. Finally, rejuvenator is only dosed on the surface of RAP. The material does mingle in the conveyor belt(s), in the RAP elevator, at the material transfer points (chutes) and in the RAP dryer, as well as later in the mixer. Nevertheless, a less homogeneous distribution may be achieved compared to addition in the mixer. This risk is higher for rejuvenators that require a small dosage rate.

3.2 Rejuvenator addition at the RAP dryer outlet chute (No. 5)

Rejuvenator is sprayed on the RAP material flow leaving the heating RAP dryer. The injection rate can be adapted to the RAP material flow rate.

3.2.1 Benefits

The risk of rejuvenator ignition or evaporation is significantly reduced compared to rejuvenator addition on RAP conveyor belt because of lower temperatures at the RAP dryer outlet as compared to flame inside the RAP dryer.

3.2.2 Drawbacks

Inhomogeneous distribution of rejuvenator can occur because of spraying. This risk is decreased, however, if RAP goes through the mixer afterwards.

3.3 Rejuvenator addition at the mixer (No. 8)

Rejuvenator is added in the mixer in a sequence to ensure direct blending with RAP before addition of any virgin materials. Dosage rate is calculated based on RAP mass.

3.3.1 Benefits

There is considerably more experience in addition of additives directly in the mixer and many plants have additive dosage systems pre-installed thus virtually eliminating need for modifications to the production plant. This option would also likely result in the most precise dosing due to known quantity of RAP in the mixer and will result in the most homogeneous distribution of rejuvenator because of mixing during the rejuvenator addition. It is possible to adjust the blending time of RAP and rejuvenator as necessary.

3.3.2 Drawbacks

Exposure time of RAP binder to rejuvenator is the shortest compared to previous options (seconds compared to minutes, depending on plant configuration). At the same time, the produced mixture is at an elevated temperature even post-production during storage, hauling, and paving. This time period is considerably longer compared to the time of rejuvenator residence directly on RAP binder, before addition of virgin binder and mineral aggregates. During this post-production time rejuvenator diffusion into the RAP binder film continues, although at a slower rate because of lower temperature and dilution in virgin binder. The diffusion will also

depend on the mix composition. For example, at a very high RAP rate it would matter less if the rejuvenator is added early during production process because the diffusion would continue during the post-production operations while for a lower RAP rate early rejuvenator addition would be of a higher importance because of rejuvenator dilution in virgin binder resulting in a slower diffusion rate.

4. Results of experimental production

As discussed in Section 3, three locations can be analytically considered best for rejuvenator addition. Two of them, No. 3 “RAP conveyor belt” and No. 8 “Mixer”, were compared in a practical experiment at an asphalt plant to evaluate the mixture rejuvenation effectiveness and emissions during production. The third option (No.5 “RAP dryer outlet chute”) can be reasonably assumed to provide similar mixture performance to option No.8 “Mixer”.

During the experiment the rejuvenator was added at two locations in the asphalt plant:

- 1) **On the RAP conveyor belt (No. 3 in Figure 3).** The experiment was run at RAP feed rate of between 145 and 175 t/h. Rejuvenator was sprayed on the RAP as illustrated in Figure 4 at 3% and 5% dosage from the RAP binder mass. For mixture performance testing only 5% dosage rate was used, while for emission testing both doses were tested. The spray rate was adjusted by constantly monitoring RAP flow rate of the conveyor belt based on pre-determined 3.9% RAP binder content.
- 2) **In the mixer (No. 8 in Figure 3).** Rejuvenator was added in the 3t capacity mixer by spraying it through additive addition system at 5% dosage from the RAP binder mass. The material was mixed for 120 seconds.

Figure 4. RAP dryer location in asphalt plant and rejuvenator spraying nozzles on cold RAP conveyor belt

4.1 Sampling

The samples differ by (1) rejuvenator application location (sprayed on cold RAP on conveyor belt or in mixer on hot RAP), (2) rejuvenator content (3) RAP rate. The sample abbreviation is chosen to reflect these three variables (an example):

All the different samples considered in the research are summarized in Table 3. Three mixture samples were collected for mechanical tests. In all cases the RAP passed through RAP dryer and hot material (around 160°C) was collected after discharge from the hot storage silos. Sampling was done immediately after mixing. The samples were always collected after the previous materials were cleared from the production system and the new setup had been running for multiple batches.

The emission measurements were performed in the inlet duct to the exhaust gas chimney and 5 different cases were tested (Table 3). Besides 5% rejuvenator dose, also 3% was used and besides 100% RAP feed rate, also 60% feed RAP rate was used. The time intervals during switching between the different production cases (transient phases) were excluded from the analysis.

Table 3. Test matrix and sample abbreviation

Abbreviation	Rejuvenator application location	Rejuvenator content	RAP rate	Testing
None-0-100	None	0%	100%	Mixture and emissions
Belt-5-100	RAP cold feed belt	5%	100%	Mixture and emissions
Mixer-5-100	Mixer	5%	100%	Mixture and emissions
Belt-3-100	RAP cold feed belt	3%	100%	Emissions
None-0-60	None	0%	60%	Emissions

4.2 Bitumen test results

As described earlier, the rejuvenator dosage of 5% from binder mass was calculated based on binder content of 3.9% that was determined before production. Test results of the produced asphalt, however, demonstrate 0.5% range in the actual binder content within the gathered samples. This can be attributed to the variability of reclaimed asphalt. Such range can be considered acceptable since many mix design specifications allow 0.5% binder content variability for virgin mixtures. Due to the fact that rejuvenator dosage was kept constant with respect to RAP flow rate (*Belt-5-100* sample) or RAP mass (*Mixer-5-100* sample) throughout the production process while the binder content of RAP varies, the rejuvenator content from binder mass also varies slightly. The total binder content consists of RAP binder and rejuvenator. Since the rejuvenator dosage and total binder content are known, the proportion of rejuvenator from RAP binder mass can be back-calculated. These results are summarized in Table 4. Penetration

test results indicate that the binder has been softened by the addition of rejuvenator in both cases to a similar level. This is despite the fact that rejuvenator dosage in the *Belt-5-100* sample is slightly higher compared to the *Mixer-5-100*. It might indicate some rejuvenator loss in the RAP dryer. However, an earlier study by the authors [11] indicated that rejuvenator is not lost in the dryer and since the differences in test results in Table 4 are relatively small, this it might simply be a sampling error or test variability.

Table 4. Bitumen empirical test results

Sample	Total binder content, %	Back-calculated RAP binder content, %	Back-calculated rejuvenator dosage, % from RAP binder mass	Penetration, 0.1 mm
None-0-100	4.4	4.4	0.0%	20
Belt-5-100	4.0	3.8	5.1%	30
Mixer-5-100	4.5	4.3	4.5%	33

4.3 Stiffness

Complex modulus master curves of the three samples are illustrated in Figure 5. Each data point is an average of four replicates. As expected due to no added rejuvenator the *None-0-100* sample has the highest G^* throughout the entire frequency range. Both rejuvenated samples are relatively close and the *Belt-5-100* has slightly higher complex modulus. Based on previous reported studies [20–23], complex modulus test results are highly sensitive to binder content. It is therefore possible that the difference in modulus between the *Belt-5-100* and the *Mixer-5-100* can be attributed to 0.5% binder content difference (Table 4). A significant difference between the samples in the low frequency (high temperature) and high frequency (low temperature) range can not be seen.

Figure 5. Complex modulus master curves (lines) and data points (markers) shifted to 20°C

4.4 Fatigue

Relationship between fatigue criteria $N_{f/50}$ and applied strain amplitude ϵ is demonstrated in

Figure 6. Wöhler type linear regression between decimal logarithms of $N_{f/50}$ and ϵ were used to obtain the necessary parameters for calculation of ϵ according to equation:

$\text{Log}(N_f) = a + (1/b) \times \text{Log}(\epsilon)$, where ϵ is the amplitude of tensile strain at cycle 100, N_f is the number of applications to failure, a is the ordinate of the fatigue line and $1/b$ is the slope. The calculated parameters of tested samples are indicated in Figure 6. Only the two samples representing final asphalt mixture were tested (*Belt-5-100* and *Mixer-5-100*). Due to the amount of available material, the number of replicates was smaller than the required nine.

Figure 5 demonstrates that the slope of the *Mixer-5-100* sample is flatter compared to *Belt-5-100* indicating shorter fatigue life. Higher number of samples should be tested to determine the statistical significance of the 40% difference in strain amplitude (95‰ versus 134‰). The authors are aware that the number of samples has an effect on the final results but Figure 6 is

used as an indication of the fatigue performance of the mixtures. Due to the relatively high R^2 values, it is possible that the overall trend would hold.

Figure 6. Fatigue diagram of Belt-5-100 and Mixer-5-100 samples showing failure criteria N_{f50} versus applied strain amplitude ϵ

4.5 Crack propagation

Flexibility index (FI) and fracture energy (G_f) results are summarized in Figure 7 and demonstrate that addition of rejuvenator has increased resistance to crack propagation regardless of the application location. The two addition locations demonstrate statistically insignificant differences (based on four samples) both in terms of FI and fracture energy. The load-displacement curves demonstrate that the characteristics of the maximum load and crack propagation dynamics of the rejuvenated mixtures are also similar. Both rejuvenator addition locations made the mixture less brittle as indicated by the roundness of the load-displacement diagram in Figure 7b in comparison to the sharp brittle failure of the non-rejuvenated mixture. The FI test is highly sensitive to binder content, which is one of the reasons the test was chosen for the study. From the authors' experience, testing AC8 type mixtures, 0.5% binder difference

that is evident in this study can lead to increase of FI by 3 to 5 and fracture energy increase by more than 600N/m. It is therefore likely that if *Belt-5-100* and *Mixer-5-100* samples would have the same binder content, the FI and fracture energy of *Belt-5-100* would be higher compared to the *Mixer-5-100*. In other words, early addition of rejuvenator has ensured similar active binder content of the *Belt-5-100* mixture compared to the *Mixer-5-100*, despite having lower actual binder content.

Overall FI of all the mixtures is relatively low compared to other studies [16], and indicate crack-prone mixture. However, optimization of mix design was out of the scope of the study and only relative comparison between the samples is important for reaching the research objective.

Figure 7. Flexibility index (a) and load-displacement curves (b)

4.6 Emission test results

Addition of rejuvenator upstream of RAP dryer holds a potential risk of its volatilization due to the exposure to the extreme temperature in the dryer. It was therefore determined during the experimental production if rejuvenator addition location or dosage affects the measured plant emissions and the results were compared to those of conventional asphalt production. Moreover, an increase in measured emissions would indicate loss of rejuvenator mass and therefore reduction in its effectiveness.

1 The experimental production was carried out in six windows by ensuring a sufficient time to
2 gather representative emissions measurements for each production case. In addition to the 100%
3 RAP mixtures that were used for testing of mixture properties, 60% RAP mixture (*None-0-60*)
4 was produced. The *None-0-60* mixture was chosen as the reference because it is within the
5 locally permitted RAP rate and thus provides a reasonable baseline. The mixture composition
6 and time of production windows according to the sequence of production are summarized in
7 Figure 8. The average temperature during the testing day was 23°C with no precipitation
8 ensuring favorable ambient conditions for the measurements.

9 The emission test results and production temperature are summarized in Figure 8 following the
10 sequence of production. First of all, it is important to recognize that heating temperature is a
11 significant contributor towards generating emissions. In order to minimize the variables, every
12 effort was placed to achieve constant temperature throughout the six production windows. It can
13 be seen in Figure 8 that this was achieved since RAP material temperatures are in a narrow 160
14 °C to 167 °C range for all evaluation windows. For this reason RAP material temperature
15 influence on TOC emissions can be assumed to be negligible and will not be considered in
16 further analysis.

Figure 8. Total organic carbon (bars on primary axes) and RAP temperature (rhombos on secondary axes) test results (average result of each measurement time window)

As mentioned earlier, the *None-0-60* mixture (60% RAP) is used as the TOC emission reference.

All other TOC emission values in Figure 8 are normalized relative to this reference. The following findings can be drawn by analyzing the TOC emissions in the figure:

- Two production windows of the *Belt-3-100* in the morning and evening were used to evaluate consistency of the measurements. It can be seen in Figure 8 that the two production windows resulted in virtually identical TOC emission indicating that a good measurement consistency throughout the day was achieved.
- The different windows with various contents of rejuvenator at 100% RAP rate can be used to evaluate the effect of rejuvenator on TOC emissions. It can be seen that compared to the 0% rejuvenator window (*None-0-100*), the TOC emissions at 3% and 5% rejuvenator windows vary slightly but, considering the test variability, they can be considered similar. Therefore, based on the limited production data in this experiment, no clear correlation between TOC emissions and rejuvenator addition rate can be stated.

3. Comparison of the *Belt-5-100* and the *Mixer-5-100* windows allows evaluating the effect of rejuvenator addition location on TOC emissions. It can be seen in Figure 8 that the emissions in both cases are identical, indicating that there is no difference in TOC emissions whether 5% rejuvenator is sprayed on the cold RAP on the belt or on the hot RAP directly into the mixer.

4. Since there is no significant effect of either rejuvenator addition location or rejuvenator content, the 100% RAP production windows can be compared to the reference 60% RAP window (*None-0-60*). On the average 100% RAP samples resulted in 33% higher TOC emissions compared to the 60% RAP window. Higher TOC emissions are a common and known effect when increasing the RAP rate. Generally the main contributors for this are: fumes from heating RAP bitumen, RAP material grading, RAP bitumen type and content, moisture content, fumes from fresh bitumen.

It must be noted that the above results and findings are based on and only valid for:

- The present one-day measurement campaign with a limited number – a total of six production and evaluation windows – during the test.
- The particular plant type, process and design.
- The plant operating conditions during the test.
- The material properties – and in particular the RAP material properties – during the test.
- The specific rejuvenator used during the test.

Results may vary significantly if one or more of the above mentioned parameters are changed.

5. Summary

In order to summarize analytical results of the ten rejuvenator addition locations (Section 3) and the experimental test results (Section 4), Table 5 was developed. Here the different rejuvenator

addition options are grouped in categories of environmental effect, plant operations and resulting asphalt mixture quality. Each of these categories has several parameters that are compared among the different options using an arbitrary four level system as summarized in the legend. If any of the parameters is rated unacceptable, this option is not evaluated further because rejuvenation addition is not advised at this location. As discussed in Section 3, addition of rejuvenator on RAP shredder belt (option No.1 in Figure 3) at RAP storage (No.2) or RAP inlet (No.4) present environmental hazards as well as rise concerns about the rejuvenation quality. Rejuvenator addition at the RAP scale (No.6), or RAP chute (No.7) will likely not ensure homogeneous rejuvenator distribution. Finally, rejuvenator addition at the bitumen line/scale (No.9) or in a separate bitumen tank (No.10) may not ensure sufficient rejuvenator diffusion into RAP binder, potentially resulting in inferior performance. This leaves rejuvenator addition options on RAP conveyor belt (No.3), RAP dryer outlet chute (No.5) and Mixer (No.8) as the best choices. It must be noted that depending on the plant setup, production conditions, and rejuvenator type the ranking may change. Further advances in production technology or experience will also affect the ranking and possibly allow considering some rejuvenator addition options that are rated unsuitable currently. Finally, the reader based on his experience and external requirements may apply different weights to the various categories which will affect the relative comparison of rejuvenator addition locations.

In the environment category application of rejuvenator in the mixer (No.8) provides somewhat less operational health and safety hazards compared to the other two options (No.3 and No.5), because rejuvenator is sprayed in an enclosed environment. The application on conveyor belt may be prone to negative effects from weather (wind, rain) thus exposing the workers to the product. This can be avoided by covering the conveyor belt and/or dosing point. The emissions, as concluded by this study do are not increased as a result of rejuvenator addition. For addition

upstream of RAP dryer, the rejuvenator has to be non-flammable and should not produce excess emissions due to the high temperature present in the RAP dryer.

In the plant operation category rejuvenator addition in mixer (No.8) receives the highest rating. This is because usually additive dosing system is already present in modern asphalt plants, thus the addition of rejuvenator does not require additional plant modification. For the other two options (No.3 and No.5), the integration of dosing system is relatively simple and well worth the effort if advantages in mix performance are found. In either case rejuvenator dosage can be changed flexibly based on RAP mass or flow rate.

In the quality category rejuvenator addition in mixer (No.8) is preferred because it ensures the highest accuracy due to known RAP weight in the mixer. Other options (No.3 and No.5) have to rely on flow rate or scale of cold feed belt which is not as accurate. This advantage, however, should not be over-valued because rejuvenator content is based on the RAP binder content, which is not consistent due to inherent RAP variability (also evident in the experimental part of this study). Therefore, the accuracy of rejuvenator addition depends not only on the technological processes during production but also on RAP management to ensure homogeneity and quality control procedures to provide representative binder content of selected binder stockpile. Homogeneous rejuvenator distribution is another concern and in this category the best results can be ensured in the mixer, while for other options a somewhat less homogeneous distribution is possible, especially if low rejuvenator dosage is used. Nevertheless, good distribution can be reasonably expected also when dosing the rejuvenator before mixer, because of agitation during the production process as well as eventually blending in the mixer. Finally, the test results of this study demonstrate that there might be an advantage to add rejuvenator on the RAP conveyor belt (No.3) to ensure higher fatigue and crack propagation resistance which

are the key pavement distress concerns when using high RAP rate. This option therefore receives the highest rating in the mix performance category because it allows the rejuvenator to come in contact with the RAP binder directly and interact with it for a longer time compared to the other two acceptable locations. Rejuvenator addition in mixer, however, has been proven as a successful ongoing practice in many asphalt plants and therefore receives rating “good performance”.

Table 5. Comparison of potential rejuvenator addition locations

	Environment		Operation		Quality		
	Operational health and safety hazards	Emissions	Ease of plant integration	Flexibility of rej. dosage	Accurate rej. dosage	Homogeneous rej. distribution	Rej. effectiveness/ mix performance
Addition location							
Rejuvenator added upstream of RAP dryer drum							
1. RAP crusher belt	✗	✗	—	—	✗	—	—
2. RAP storage (stockpiles)	✗	✗	—	—	✗	✗	—
3. RAP conveyor belt	↗	↗	↗	↗	↗	↗	↗
4. RAP dryer inlet chute	—	✗	—	—	—	—	—
Rejuvenator added downstream of RAP dryer drum							
5. RAP dryer outlet chute	↗	↗	↗	↗	↗	↗	—
6. RAP scale	—	—	—	—	—	✗	—
7. RAP chute	—	—	—	—	—	✗	—
8. Mixer	↗	↗	↗	↗	↗	↗	↗
Rejuvenator added in virgin bitumen							
9. Bitumen line/scale	—	—	—	—	—	—	✗
10. Separate bitumen tank	—	—	—	—	—	—	✗
Legend:	↗ no risk ↘ minimal risk → acceptable ✗ unacceptable — not evaluated		easiest simple acceptable not possible not evaluated		highest performance good performance acceptable performance unacceptable performance not evaluated		

6. Conclusions

With ever increasing reclaimed asphalt content in asphalt mixtures, rejuvenator use is becoming inevitable for ensuring the required pavement performance. This research evaluated the possible

rejuvenator addition locations in one type of asphalt plant in order to provide guidelines to benefits and drawbacks for each of them. Although the work is done for batch type asphalt plant, the rationale behind the analysis can be applied to any type of asphalt mixing plant. In total ten locations were identified and analyzed analytically and two most promising were chosen for further investigation. The results were compared in a practical experiment as summarized in a Video 1 (<https://youtu.be/LYBq93e8BG0>). RAP was heated to 160°C in counter flow heating RAP dryer and a rejuvenator was applied to cold RAP on feed belt and to hot RAP in mixer. Three asphalt mixture samples were gathered to evaluate the effect of rejuvenator addition location on binder properties and asphalt mixture mechanic performance. Emissions were measured during the production to determine the environmental effects of rejuvenator addition location and high RAP use in general. Based on the test results and analytical assessment, the following conclusions can be made:

- From the ten possible locations rejuvenator addition to reclaimed asphalt on conveyor belt, dryer outlet chute or plant mixer are recommended.
- Rejuvenator addition on cold RAP on conveyor belt provided the same crack propagation resistance as rejuvenator addition on hot RAP in mixer despite 0.5% lower binder content.
- Rejuvenator addition on cold RAP conveyor belt provided higher fatigue resistance compared to addition in hot mixer (the fatigue tests did not have enough repetitions to conform to standard).
- The samples for which rejuvenator was applied in mixer had lower complex modulus. This however, might be due to the 0.5% higher binder content compared to the samples where rejuvenator was sprayed on the reclaimed asphalt conveyor belt.

- Rejuvenator addition resulted in no significant TOC emission increase, irrespective of 3% or 5% rejuvenator addition compared to 0% rejuvenator addition.
- It made no difference to TOC emissions whether rejuvenator was sprayed on the conveyor belt on cold RAP or into the mixer on hot RAP.
- Increase in RAP rate also increased TOC emissions – a common and known effect.

The future work includes determining the long term diffusion of rejuvenator, including aging of the samples. Different asphalt plant configurations with lower RAP contents should also be tested and other rejuvenator types should be validated. Finally, a rejuvenator addition procedure in the laboratory should be established to simulate a given scenario in the asphalt plant.

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