HOT MIX ASPHALT RECYCLING AT HIGH PERCENTAGES: PRACTICE OF OPTIMIZATION AND USE OF REJUVENATORS IN SERBIA AND CZECH REPUBLIC

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Abstract: Asphalt recycling, whether hot, warm, or cold, has proven to be the most sustainable, efficient, and readily applicable technology for a wide range of paving applications. In response to this, numerous technical specifications and standards have been developed in recent years to facilitate the incorporation of reclaimed asphalt (RA) into new asphalt mixtures, in some cases even removing limits on the allowable recycling content. In Europe, Italy and Serbia are pioneers in this field, as their regulations define minimum RA contents for new asphalt production and mandate the use of rejuvenators. This paper investigates commonly applied protocols for rejuvenator optimization and presents two successful case studies from the Czech Republic and Serbia, where asphalt mixtures containing 50% and 40% RA, respectively, were produced using a vegetal-based rejuvenator. The results indicate that, in addition to bitumen-scale testing, whether conventional or advanced, a minimum set of mixture-scale performance tests is essential to ensure the satisfactory in-situ performance of asphalt mixtures with high RA contents.

Keywords: *Asphalt recycling, Reclaimed Asphalt (RA), Optimization, Case studies, Bio rejuvenator.*

RECIKLAŽA VRUĆIH ASFALTNIH MEŠAVINA SA VISOKIM SADRŽAJEM RECIKLIRANOG ASFALTA: PRAKSA OPTIMIZACIJE I PRIMENE REJUVENATORA U SRBIJI I ČEŠKOJ REPUBLICI

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Rezime: Reciklaža asfalta, bilo da je po vrućem, toplom ili hladnom postupku, pokazala se kao najodrživija, najefikasnija i lako primenljiva tehnologija za širok spektar primena u izgradnji i rehabilitaciji kolovoza. Kao odgovor na to, poslednjih godina razvijene su brojne tehničke specifikacije i standardi radi omogućavanja ugradnje recikliranog asfalta (RA) u nove asfaltne mešavine, pri čemu su u pojedinim slučajevima čak ukinuta ograničenja u pogledu dozvoljenog procenta recikliranog asfalta. U Evropi su Italija i Srbija pioniri u ovoj oblasti, jer njihova regulativa definiše minimalni udeo RA u proizvodnji novih asfaltnih mešavina i propisuje obaveznu primenu rejuvenatora. Ovaj rad istražuje najčešće primenjivane protokole za optimizaciju doziranja rejuvenatora i prikazuje dve uspešne studije slučaja iz Češke Republike i Srbije, u kojima su proizvedene asfaltne mešavine sa 50% i 40% RA, primenom rejuvenatora na bazi biljnih sirovina. Rezultati ukazuju da je, pored ispitivanja na nivou bitumena – bilo konvencionalnih ili naprednih – neophodan minimalni obim ispitivanja performansi na nivou asfaltne mešavine kako bi se obezbedilo zadovoljavajuće ponašanje kolovoza u eksploataciji pri visokim udelima RA.

Ključne reči: *Reciklaža asfalta, Reciklirani asfalt (RA), Optimizacija, Studije slučaja, Bio rejuvenator.*

1. INTRODUCTION

Producing based on Life Cycle Assessment (LCA) studies, asphalt recycling is the most effective technology for sustainable asphalt pavement materials and reducing its carbon footprint. Accordingly, increasing the proportion of Reclaimed Asphalt (RA) in new asphalt mixtures is a key measure within most national carbon reduction action plans. Accordingly, some countries, such as Italy and Serbia, have recently removed dosage limitations from their national regulations and instead require a minimum content level [1-2]. However, the incorporation of high RA contents could create several technical challenges due to asphalt plant limitations and mixture performance. As far as asphalt plants are concerned, the new amendments in old system and even double drum plants resolved the hardware to maximize the RA content in new asphalt production [3]. However, the quality of the produced recycled asphalt and its in-situ performance requires more attention including a comprehensive mix design, the use of proper type and dosage of recycling agent, and the use of performance indicators, all of which are essential parameters for achieving durable and performant recycled asphalt. Among the mentioned items, the correct choice of recycling agent is probably the most important

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factor particularly for high RA content mixture [4]. This becomes especially critical for mixtures with high RAP contents (≥30%), in which the amount of fresh bitumen is significantly reduced. Under such conditions, the use of a softer virgin binder alone is generally insufficient to meet binder and mixture performance requirements [5]. Consequently, the use of asphalt recycling agents is essential to restore the properties of the highly oxidized RA binder and to ensure the long-term durability of recycled asphalt mixtures. A wide range of recycling agent formulations derived from different sources has been introduced to the asphalt pavement industry, including waste vegetable oil, waste vegetable grease, organic oils,distilled tall oil, aromatic extracts, and waste engine oil [6].
Despite their diverse chemical compositions, these materials can facilitate asphalt recycling to varying degrees and are therefore collectively referred to as asphalt recycling agents. However, the mechanism by which these agents interact with the aged asphalt binder differs significantly. According to EAPA and the literature, recycling agents are commonly classified as fluxing agents (softeners) or rejuvenators. According to EAPA [7], an asphalt recycling agent is “a family of products used in the manufacturing of asphalt mixes containing reclaimed asphalt to act on the aged bituminous binder and help to meet the requirements/specifications of binders and asphalt mixes,” noting that the term “rejuvenator” is often used for a subset of these products. This classification is even highlighted in the harmonized European terminology standards EN 12597: 2024 [8]. Fluxing agents primarily influence the physical and rheological properties of the binder, whereas rejuvenators are capable of partially restoring the chemical composition of aged bitumen, thereby bringing it closer to its original, unaged state. These differing mechanisms have been extensively investigated, with one of the most comprehensive descriptions provided by the Building and Road Research Center (BRRC), which identified three distinct modes of chemical interaction between recycling agents and aged binders [9]. In addition to the selection of recycling agents, the optimization of their dosage remains a significant challenge for asphalt mixture design. Several dosage design charts and procedures have been proposed, predominantly based on binder-scale testing. Among these, the RILEM protocol [10] and the more recent German guideline (H Rejuv WA; 2021) [11] are the most widely applied. While the German guideline offers a more comprehensive framework by incorporating mixture-scale verification, studies have reported a tendency toward higher recommended dosages at the binder-scale compared to the RILEM protocol. Given that asphalt mixtures are the final structural product subjected to traffic loading and environmental conditions, mixture-scale performance verification is widely regarded as essential. Against this background, the objective of this paper is to present laboratory results from a recycled asphalt mixture containing 50% RAP and a bio-based rejuvenator.

2. Material

In the first section of this article, in which rejuvenator optimization methods is investigated, a 50/70 penetration grade bitumen binder was used. However, depending on the specific project requirements, different binders were considered for the introduced projects. Accordingly, a 50/70 paving grade bitumen was used for the case study in the Czech Republic and a 45/80-65 SBS polymer-modified bitumen (PmB) was used for the project constructed in Serbia. The properties of the bitumens are reported in the Results and Analysis section as part of the obtained test results.

The rejuvenator used in this study, was a bio rejuvenator formulated in a mixture of vegetal derivatives. The mechnism of action and its preformance, which shown effective both on physical and chemical properties of aged bitumen have been presented via several research works [12]. Some of the given properties of the rejuvenator are summarized in Table 1.

Table 1: *Some of the properties given of the rejuvenator*

Property	Unit	Value/aspect
Colour	-	Black
Viscosity @25°C	cP	750 - 950
Flash point	°C	≥ 215
Density @25°C	g/cm3	0.90-1.00

3. Methods

3.1. German guidelines on the use of Rejuvenator

Considering the objectives of this paper, the first section of the analysis focuses on optimization methods for rejuvenators. For this purpose, the German protocol and the new Serbian specifications were compared and evaluated using a typical 50/70 paving grade bitumen. Following the German guideline (H Rejuv WA, 2022), the applied testing methods included BTSV in accordance with EN 17643, conducted before and after short-term aging using the Rolling Thin Film Oven Test (RTFOT) according to EN 12607-1, as well as long-term aging using the Pressure Aging Vessel (PAV) in accordance with EN 14769. Figure 1 shows the testing procedure. As illustrated, the first step is dedicated to the virgin state (Stufe B0), the short-term aged state (Stufe B1.1), and the long-term aged state (Stufe B1.2). Subsequently, three different rejuvenator dosages (Stufe 2a–Stufe 2c) are added to the long-term aged bitumen, and the optimum dosage is determined accordingly. Thereafter, the rejuvenated bitumen is aged and compared with the virgin bitumen to validate the selected dosage. In addition to DSR analysis, the selected rejuvenator dosage is then controlled via Bending Beam Rheometer (BBR) following European standard EN 14771. The test confirms the dosage especially for the cold climate pavements.

The selected dosage of the rejuvenator shall be validated via mix-scale tests including low-temperature properties following EN 12697-46, resistance to Fatigue following EN 12697-24, and resistance to permanent deformation based on EN 12697-22. The mixture prescribed to be produced in the mixture analysis shall be an 8 mm dense-graded asphalt concrete containing 50% of RAP to be compared with the totally virgin mixture. As far as the RAP material is concerned it shall be noted that the RAP was produced artificially following the TU Braunschweig mixture aging method [13]. For this purpose, after 4 hours of short-term aging at 135°C, the aged mixture was maintained in the oven for 96 h at 80 °C.

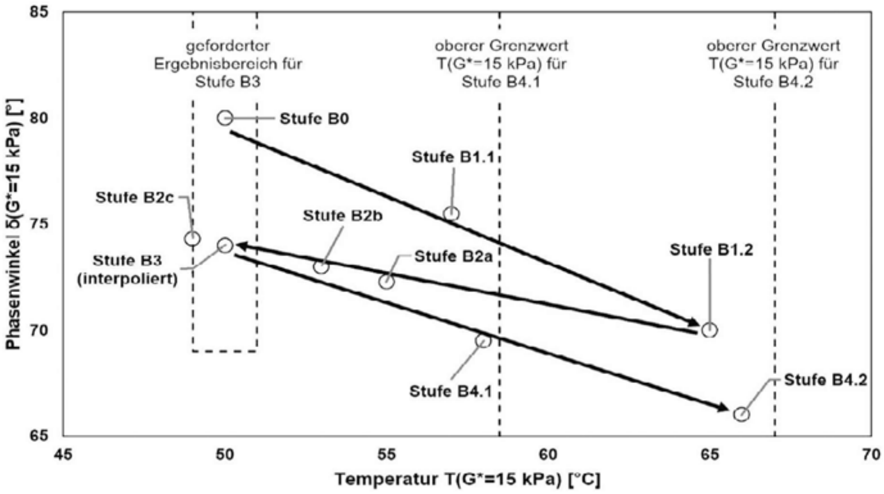

Figure 1: *Rejuvenator dosage optimization procedure according to H Rejuv WA; 2022*

3.2. Serbian Guidlines

According to the new Serbian technical specifications on the use of reclaimed asphalt, the determination of the type and grade of the virgin binder, as well as the optimization of the rejuvenator dosage, requires the extraction of the aged binder. The extracted binder shall be tested for penetration in accordance with SRPS EN 1426, softening point according to SRPS EN 1427, Fraass breaking point in accordance with SRPS EN 12593, complex shear modulus and phase angle following SRPS EN 14770, and elastic recovery (for the PmB cases) at 25 °C in accordance with SRPS EN 13398. After defining the optimum rejuvenator dosage, it shall be verified through comprehensive mixture-scale testing. The resulting asphalt mixture must comply with the technical requirements specified for the respective pavement layer type.

4. Results and analysis
4.1. Rejuvenator dosage optimization: binder-scale tests

Table 2 summarizes the results obtained in accordance with the German guidelines. As an initial dosage, 5.5% rejuvenator, based on the additive's technical data sheet (TDS), was selected, after which the analysis was extended to higher dosages until properties comparable to the reference (virgin) bitumen were achieved. As indicated by the DSR rheological results, a rejuvenator content of 7% enabled the recovery of the aged bitumen to a condition equivalent to the virgin state. The selected dosage was subsequently evaluated through low-temperature analysis using the Bending Beam Rheometer (BBR). When compared with the reference bitumen, the addition of 7% rejuvenator resulted in lower stiffness, indicating that this dosage may be excessive. In this case, the final verification of the dosage shall be completed via mixture scale tests as the final product will be

the asphalt pavement under the service. A complete mixture test pan has been anticipated in this specifications.
In the next step, in accordance with the new Serbian specifications, the same asphalt binder grade was evaluated using conventional testing methods, applying 5% and 7% dosages of the same rejuvenator. Although the binders originated from different sources, the use of identical binder grades and rejuvenator dosages in both approaches allowed for a meaningful interpretation of the results. the reference binder.

Table 2: *Binder-scale tests' results according to H Rejuv WA; 2022 – Bitumen source I*

Test Step*	**Material Bitumen 50/70 Source I**	**Test parameter**			
		T °C (G* = 15 kPa)	**Phase angle**	**T °C (S = 300 MPa)**	**T °C (m = 0,3)**
B0	Virgin state	49	82.1	-16.5	-18.7
B1.1.	Short-term aged	54.5	80.0	-	-
B1.2.	Long-term aged	65	75.6	-14.3	-13.9
B2a	Long-term aged + 5.5 % Rej.	52	79.9	-	-
B2b/c	Long-term aged + 7.0 % Rej.	49	79.0	-23.1	-22.3
B3	**7.0 % is selected**				
B4.1.	Short-term aged B 2b/c*	52.5	76.7	-	-
B4.1.	Long-term aged B 2b/c*	65.5	73.5	-19.3	-15.4
*According to H Rejuv WA; 2022. See figure 1					

In the next step, the same asphalt binder grade was investigated in accordance with the testing methods specified in the new Serbian technical specifications. As the temperature and detailed parameters for the Dynamic Shear Rheometer (DSR) analysis were not defined, the shown values are at 30 °C. As summarized in Table 3, the addition of 5% rejuvenator was insufficient to restore the required performance indicators, whereas an 7% dosage resulted in lower complex shear modulus results. At the same time, the addition of 7% rejuvenator resulted in an identical softening point and a relatively similar penetration value compared to the reference bitumen.Considering the overall test outcomes, it can be inferred that, similarly to the findings obtained using the German guidelines, a rejuvenator dosage of approximately 7% yields binder properties comparable to those of the reference bitumen.
Furthermore, a comparison of binder properties before and after aging indicates that the rejuvenated binder exhibits lower aging susceptibility than the reference bitumen, as reflected by reduced stiffness after aging. Based on these results, it can be concluded that an optimum rejuvenator dosage of approximately 7%, or slightly lower, is technically appropriate according to both optimization protocols applied.

Table 3: *Binder-scale tests' results according to Serbian technical specifications*

Test Step*	**Material Bitumen 50/70 Source II**	**Test parameter**				
		Penetration (dmm)	**Softening point (°C)**	**Complex Shear modulus @ 30°C* (Pa)**	**Phase angle @ 30°C* δ (°)**	**High PG**
B0	Virgin state	55.5	51.7	410070	68.48	71.5
B1.1.	Short-term aged	35.2	57.8	939410	60.90	77.9
B1.2.	Long-term aged	19.3	67.4	2387100	50.76	88.3
B2a	Long-term aged + 5.0 % Rej.	46.6	54.3	539360	61.14	76.4
B2b/c	Long-term aged + 7.0 % Rej.	54.1	52.7	272800	64.15	70.4
B3	7.0 % is selected					
B4.1.	Short-term aged B 2b/c	33.6	54.9	335910	61.11	76.7
B4.1.	Long-term aged B 2b/c	22.1	67.7	1486100	49.86	87.9
*According to H Rejuv WA; 2022. See figure 1 **The Serbian specification it does not determine the test temperature; the temperature was the choice of authors						

4.2. Dosage control: Mixture-scale test

As discussed earlier, both the German guidelines and the Serbian technical specifications require confirmation of the mixture dosage after it has been estimated through binder-scale tests. In this study, volumetric properties, water sensitivity, and low-temperature cracking resistance were investigated, as these parameters are identified as critical in both specifications. For this purpose, in accordance with the German guidelines, the investigated mixtures contained 50% artificially produced reclaimed asphalt, prepared following the TU Braunschweig protocol. Table 4 summarizes the some of the volumetric properties of the tested and reference mixture.

Table 4: *The volumetric measured values*

Test parameter	Unit	Virgin mix	Test mix (50% RAP+7.0%Rej.)
Added bitumen 50/70	%	5.8	3.33
Bitumen from the RAP	%	0.0	2.32
Rejuvenator	%	0.0	0.15
Bulk density asphalt	g/cm^3	2.578	2.576
Prism specimens air void	%	2.0	1.7

Water sensitivity was evaluated using 50 Marshall hammer–compacted specimens and quantified through the indirect tensile strength ratio (ITSR) in accordance with EN 12697-12. The results yielded average ITSR values of 98% for the virgin mixture and 96% for the RAP mixture. Both values exceeded the minimum requirement specified in both German and Serbian technical standards (80%), indicating a high resistance to moisture damage. The Low-temperature performance was assessed using prismatic specimens extracted from roller-compacted slabs and tested using the Thermal Stress Restrained Specimen Test (TSRST) in accordance with EN 12697-46. The corresponding test results are presented in Figure 2.

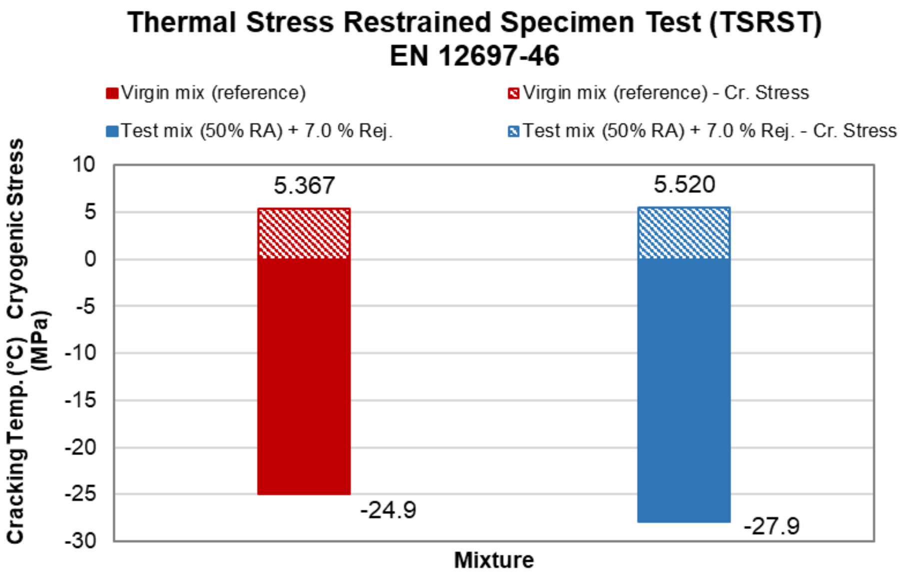

Figure 2: *Mix-scale low-temperature properties by means of TSRST*

Based on the obtained values, the recycled asphalt mixture exhibited superior low-temperature cracking resistance compared to the reference mixture and comparable water sensitivity, with both mixtures satisfying the requirements of the relevant technical specifications. This behavior could stem from the high rejuvenator dosage, as the same trend that was also observed in the binder-scale analysis.

The inconsistency between the dosages determined at the binder and mixture scales can be attributed to two main factors: (i) differences in the aging levels achieved through laboratory binder aging and mixture aging simulations, and (ii) the absence of short-term aging of the recycled mixture (containing 50% RAP) prior to specimen compaction. At the binder scale, the bitumen is subjected to both RTFOT and PAV aging, which is more severe than the mixture aging applied during artificial RAP production in an oven at 80 °C (TU Braunschweig method). According to AASHTO R 30-2 (2015), asphalt mixtures should be conditioned either for 2 h at the compaction temperature or for 4 h at 135 ± 3 °C prior to compaction. The limitations of optimizing rejuvenator dosage solely based on binder-scale tests have been widely reported in the literature [14], consistently indicating a tendency toward excessive dosages. Consequently, confirmation through mixture-scale testing is recommended [15]. This does not restrict the use of rejuvenators but highlights the need to apply reduced dosages when optimization is based exclusively on binder-scale evaluations.

4.3. Dosage validation: binder extraction

To correlate binder- and mixture-scale results and to validate the selected dosage, binders extracted from the virgin reference and recycled mixtures were tested. Summarized in Table 5, the results confirm that the selected dosage was excessive and higher than necessary to restore the aged binder, consistent with the mixture-scale findings. The high rejuvenator dosage may adversely affect other properties, such as permanent deformation resistance. It should be noted that the reclaimed asphalt was artificially produced rather than field-aged; therefore, the observed differences are expected to be less significant when using in situ aged RA.

Table 5: *Dosage validation via extracted binder analysis*

Extracted Binder	Test parameter			
	T at G*= 15 kPa (°C)	phase angle at G*=15 kPa	T at S = 300 MPa (°C)	T at m = 0.3 (°C)
Virgin mix (reference)	50.8	77.3	-26.4	-24.4
Test mix (50% RA) + 7.0 % Rej.	45.8	77.8	-29	-31

5. Case studies
5.1. Service road in Serbia

In response to the new technical regulations in Serbia, the introduced rejuvenator was investigated and successfully applied in the paving of a road within the warehouse area. The paving was carried out smoothly without any rolling or compaction issues, which could be in some cases with high RAP content happens. The recycled asphalt mixture shown in Figure 3 was produced, placed, and compacted under field conditions, demonstrating satisfactory workability and performance. The production was carried out using a parallel drum system, with the reclaimed asphalt heated to 110°C. A summary of the produced recycled mixture and the corresponding pavement structure is presented as follows:

- Location: Service road within the warehouse area of a private company on the outskirts of Belgrade.
- Construction date: April 2025
- Type of road: Local access Rd.
- Type of mixture: BNS (dense-graded asphalt concrete) 22 mm
- Type of layer: Base course
- Reclaimed Asphalt quantity: 40%
- Aged bitumen content of RA: 4.9%
- Paving bitumen: PEN 45/80-65
- RAP quantity in the mix: 40%
- Rejuvenator: A bio-based rejuvenator (details provided in the section material)
- Dosage: 5% (on the weight of the aged binder)

Figure 3: *The mixture containing 40% RA with rejuvenator during laying*

Prior to asphalt production, the mixture was optimized and investigated. The first phase of the analysis focused on the characterization of the aged binder and the optimization of the rejuvenator dosage. For this purpose, three different rejuvenator dosages were evaluated, and the properties of the rejuvenated binders were compared with those of the reference bitumen using conventional testing methods predominantly adopted in Serbia. Table 6 summarizes some of the obtained results. According to the results, it can be seen that the addition of 5% rejuvenator corresponds to the reference bitumen properties. Nevertheless, this value was controlled via mixture-scale tests, before and after prodution.

Table 6: *Rejuvenator dosage estimation based on binder tests*

Bitumen sample	Penetration (dmm)	Softening point (°C)
Virgin ref. Bitumen 50/70	55.5	51.7
Aged Bitumen RA extracted	28	60.2
Aged Bitumen + 3% Rejuvenator	40	57.6
Aged Bitumen + 5% Rejuvenator	53	53.4
Aged Bitumen + 7% Rejuvenator	74	50.5

During the installation of the pavement, the loose mixture was collected from the job site, reheated, and recompacted for analysis. For this purpose, the reheated material was compacted by applying 50 blows of a Marshall hammer on each side. Table 7 summarizes the obtained results for the reference and test mixture containing 40% RA. According to the results, the introduction of the rejuvenator led to a lower air void content while maintaining nearly the same density. From a mechanical point of view, although the Marshall stability decreased, the flow number slightly increased. These findings can be attributed to the reduced stiffness (or rigidity) of the mixture due to the addition of the rejuvenator. Ultimately, this reduction in stiffness enhances the cracking resistance of the pavement.

Table 7: *Mixture-scale test results*

Test parameter	Unit	Reference mix 40% RA – No rejuvenator	Test mix 40% RA – 5% rejuvenator	Specification limits
Density (SSD)	kg/m^3	2415	2449	–
Maximum Theoretical Density (Gmm)	kg/m3	2580	2574	–
Air voids	%	6.4	4.9	5.0 – 9.0
Air voids in mineral aggregates	%	15.9	14.5	–
Bitumen content	%	4.0	4.0	–
Marshall Stability	kN	16.6	13.3	Min 8.0
Marshall Flow	mm	2.7	4.0	–

In addition to the mixture-scale tests conducted to verify the accuracy of the rejuvenator dosage and confirm the positive performance of the rejuvenator in reducing the rigidity of the mixture, the bitumen from both mixtures was extracted and tested. As shown by the results presented in Table 8, comparing the extracted bitumen of the mix without rejuvenator (No. 3) with RA extracted bitumen (No.2 1), the incorporation of added virgin bitumen into the mixture improved the softening point and penetration values compared to those of the aged bitumen. However, comparing the results with reference values (no.1), it is clear that the bitumen is stiffer. In turn, comparing the obtained results for the extracted bitumen form the rejuvenated mix (no. 4) with RA extracted bitumen and reference bitumen (no.1) shows that the mixture containing 5% rejuvenator was able to restore these properties to levels close to those of the virgin bitumen. Taken together, these results, along with the mixture-scale test outcomes, validate the selected rejuvenator dosage in the mix design.

Table 8: *Rejuvenator dosage estimation based on binder tests*

no.	Extracted Bitumen sample	Penetration (dmm)	Softening point (°C)
1	Virgin 50/70 bitumen (reference values)	55.5	51.7

2	Aged Bitumen of RA	28	60.2
3	Bitumen of 40% RA mix	34.2	54.8
4	Bitumen of 40% RA + 5% Rej. mix	53.9	50.8

5.2. Surface course in Czech Republic

Among the parameters defining the sustainability of asphalt pavements, durability is one of the most critical, if not the most important. Durability directly influences the frequency of maintenance interventions and the consumption of raw materials throughout the service life of the infrastructure. In the context of asphalt recycling, durability has always been a primary concern; consequently, mixture designers assess and control durability through various laboratory testing methods. From a technical perspective, for mixtures containing high recycled asphalt (RA) contents, one of the key functions of the rejuvenator is to reactivate the aged binder and enhance the adhesive properties of the blended binder, thereby improving resistance to moisture/freeze and thaw damage and temperature-induced aging cycles. The rejuvenator introduced in this study was used in the production of a recycled asphalt mixture nine years ago and was subsequently investigated by Brno University of Technology. The project considered a control section consisting of RAP without the rejuvenator to serve as a baseline. This allowed for a direct performance comparison with the rejuvenated counterpart material, effectively isolating the impact of the rejuvenator. The project described below represents a successful case of asphalt recycling, as the material remains in good condition after nine years of service.

- Location: Siřem, Blšany, close to 2218 Rd.
- Construction date: 2017
- Type of road: Local access Rd.
- Type of mixture and layer: AC 11 mm - Surface course
- Paving bitumen: PEN 50/70
- RAP quantity in the mix: 50%
- Aged bitumen penetration and softening point: 25 dmm - 60°C
- Rejuvenator: A bio-based rejuvenator (details provided in the section material)
- Dosage:4.0% (on the weight of the aged binder)

Table 9 summarizes some of the post-prodcution results. For this purpose, the loose mixture collected from the job site, reheated and recompacted in the lab.

Table 9: Post production test results

Test	Standard	Unit	Recycled mix: 50% RA + Rej.	50% RA	Specification limits
Binder content	–	%	5.50	5.30	–
Penetration	EN 1426	dmm	41	25	30 – 55
Softening point	EN 1427	°C	54	60	48 – 60
Air voids	EN 12697-8	%	3.1	5.2	2.0 – 6.0*
2-point bending stiffness modulus	EN 12697-26	MPa	9440	10606	7000**
Low-temp. cracking failure temp.	EN 12697-46	°C	-19.4	-17.9	–
* According to the new specs, the range is 2-6% **It is not declared within specs. This value is mostly used in the Czech technical road specifications					

According to the results, although the rejuvenator dosage corresponded to the minimum level recommended in the technical data sheet (TDS), it was sufficient to restore the binder properties, reduce mixture stiffness, and enhance low-temperature cracking resistance. However, both binder penetration results and mixture stiffness measurements suggest that a slightly higher rejuvenator dosage would result the optimum level. Nevertheless, based on the most recent monitoring in 2025, the pavement was found in good structural and surface condition, as shown in Figure 4.

Figure 4: The mixture containing 50% RA with rejuvenator during laying

Conclusion

In response to the growing awareness on enhancing the sustainability of asphalt pavements and reducing their carbon footprint, increasing the recycling rate of asphalt mixtures has proven as the most efficient solution. From a technical perspective, however, high levels of recycling are challenging because the limited amount of virgin binder in such mixtures restricts the feasibility of using softer binders. Moreover, in certain cases, severely-aged-reclaimed asphalt containing highly hardened bitumen cannot be sufficiently reactivated or blended with the added virgin binder to ensure the required technical performance. This paper investigated the applicability of the German technical guideline for optimizing asphalt rejuvenator dosage compared with recently issues Serbian technical specifications. In addition, the paper presents two projects where high contents of RA and a bio rejuvenator was used producing new asphalt mixtures under various conditions.
Based on the experimental results and in line with findings reported in the literature, the following highlights can be drawn:

- The rejuvenator dosage determined using binder-scale verification in accordance with the German guideline was higher than the dosage required when assessed using mixture-scale testing.
- Both conventional binder characterization methods (penetration, softening point, and viscosity) and dynamic shear rheometer (DSR) analysis yielded consistent results for binder-scale rejuvenator dosage optimization. However, in both approaches, the optimized dosages exceeded those determined from mixture-scale tests. This difference is attributed to:

  (i) differences in aging severity between artificially aged binders (RTFOT and PAV) and RA binders produced during artificial RA manufacturing (in this case TU Braunschweig),
  (ii) and (ii) the absence of short-term aging of recycled mixtures during specimen preparation for mixture-scale testing.

- In addition to the presented successful project in Serbia, the technically good condition of the nine-year-old trial section in the Czech Republic indicates that the investigated rejuvenator performs effectively in recycled asphalt mixtures with high RA content. No rutting or cracking, nor surface degradation, was observed during pavement condition monitoring conducted by pavement experts.

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