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Impact of bio-based rejuvenator on bitumen and asphalt mix performance - laboratory and field evaluation

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Abstract

The transformation of Europe’s economy into a more sustainable one constitutes a key part of the current strategy of the European Commission. Within the paving sector, the re-use of reclaimed asphalt (RA) offers a perfect case to fulfill this goal. At present, the additional focus to both environmental as well as economic advantages of RA re-use demands further optimization in terms of higher percentages of re-use and/or in enabling multiple recycling of RA in the future. A major obstacle to the durable re-use of RA is the advanced ageing state of the binder in RA. Hence, it is recognised that rejuvenators may be needed to regenerate the old binder. Therefore, BRRC initiated the research program Re-RACE (Rejuvenation of Reclaimed Asphalt in a Circular Economy) to investigate the impact of rejuvenators on the performance of both bitumen as well as asphalt mixtures containing RA. In this context, a collaboration between a supplier of a bio-renewable rejuvenator, an asphalt producer and BRRC facilitated the set-up of full-scale test sections comprising an AC14 base course (70% RA) with and without the use of rejuvenator. The realization of latter test sections was closely monitored allowing for the follow-up of the production process, the laying and compaction stage, and finally the sampling of all constituents and bulk materials. After construction, additional test specimens were taken by coring. This enabled to investigate the true effect of the rejuvenator by characterizing the binder by both empirical as well as rheological testing. In parallel, the performance of the asphalt mixtures was studied while evaluating compactibility, water sensitivity, the resistance to rutting and the fatigue behavior. As rejuvenators are added differently during real production as compared to the laboratory practice, special attention was paid at all times to validate laboratory results on the basis of field experience.

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1. INTRODUCTION AND SCOPE

In March 2019, the European Commission adopted a comprehensive report on the implementation of the Circular Economy Action Plan. The report sketches out future challenges to shaping our economy and paving the way towards climate-neutral and sustainable products [1]. A commission Staff Working Document on the implementation of the Circular Economy Action Plan was published comprising 54 actions [2]. The plan identified five priority sectors, among them the construction and demolition sector.

In the field of asphalt paving, the re-use of reclaimed asphalt (RA) offers a perfect case to fulfil this goal and is probably the most common application of re-use in industry. The re-use of RA was initiated by the petroleum crisis in the early ’70 and is therefore nowadays a common practice in many countries over the world as it offers substantial environmental, technological as well as financial benefits to all stakeholders involved. Recycling percentages of RA in the range of 50% are already routinely applied in asphalt base layers in some European countries [3,4,5]. At present, the interest in RA re-use continues to grow and therefore demands further optimisation in terms of higher percentages of re-use, very aged asphalt and/or in enabling multiple recycling of RA in the near future while maintaining durability [6].

One of the major obstacles to the durable re-use of RA is the advanced ageing state of the bitumen in RA. Ageing affects the bitumen properties through a number of mechanisms, one of the most important of which is chemical oxidation [7,8,9,10]. It results not only in an increase in stiffness but also in embrittlement and therefore makes aged bitumen more prone to fatigue and/or low temperature cracking and more resistant to healing. Latter phenomena directly impacting the mechanical performance finally limit the re-use of RA.

In order to mitigate the negative effect of aged bitumen present in RA on the performance of asphalt mixture comprising (high) percentage of RA, it is recognised that rejuvenators may be needed to regenerate or restore the lost properties of the aged binder [11,12,13]. Although rejuvenators were already marketed in the US in the late 60’s, no practical experience with such additives was gained in Belgium for a long time. Therefore, BRRC initiated in 2017 the research program Re-RACE (Rejuvenation of Reclaimed Asphalt in a Circular Economy) to investigate the impact of rejuvenators on the performance of both bitumen as well as asphalt mixtures containing RA.

In this context, a close collaboration between a supplier of a bio-based rejuvenator, an asphalt producer and BRRC facilitated the set-up of full-scale test sections. The field study focused on an AC14 base course containing 70% of RA with and without the use of a rejuvenator and compared with a standard AC14 base with 50% RA. The scope of the study was not only to acquire practical experience with the addition of rejuvenators, but also to determine the effect of the additive to restore the lost properties of the aged bitumen in RA and to evaluate their impact on the performance of the corresponding asphalt mixtures. Therefore, the realisation of the test sections was closely monitored, allowing for the follow-up of the production process, the laying and compaction stage, and finally the sampling of all constituents and bulk materials. After construction, additional test specimens were taken by coring. The sampling of constituents also allowed for investigating how to carry out a representative initial type testing study (ITT) while applying rejuvenators in the laboratory. The results of this study are discussed at large by Tanghe et al. in a separate contribution [14].

In this paper, a series of tests were performed to thoroughly investigate the effect of the rejuvenator by characterising the bituminous binder by both empirical as well as rheological testing. Moreover, the performance of the asphalt mixtures comprising RA with or without the use of rejuvenator was studied while evaluating compactibility, water sensitivity and the resistance to rutting. As the rejuvenator was added differently during the plant production as compared to the laboratory practice, special attention was paid at all times to validate laboratory results on the basis of field experience [14].

2. MATERIALS AND METHODS

2.1 Selection of AC14 base course variants

As already mentioned in the introduction, the focus of the field trials was a comparative study including three variants of an AC14 base course. In consultation with all parties, three variants were selected for the study as summarised in Table 1: an AC14 base mixture with 50% RA corresponding to the daily practice for this type of application, and two AC14 base mixtures comprising a very high rate of 70% RA (+ 20% as compared to current practice) with and without the use of a rejuvenator. The AC14 base mixture with 50% RA complies with the tender specifications in the Flemish region (SB250 v3.1) for heavily trafficked roads [15] and is more specifically known as an APO-B mix: asphalt mixture for base course as defined in EN 13108-1 based on the fundamental approach (only making use of performance characteristics).

Table 1. Overview of the AC14 base variants

# section	AC14 base course variant	Layer thickness	Length section / quantity produced
1	AC14 base + 50% RA	6 cm	300 m / 250 tons
2	AC14 base + 70% RA (reference section)	6 cm	260 m / 220 tons
3	AC14 base + 70% RA + rejuvenator	6 cm	360 m / 300 tons

2.2 Characterisation of RA

The RA used in this study originated from a single stockpile and was sieved to obtain a 0/14 mm grading. The nature of the aggregate was a mixture of both porphyry and limestone. The RA complied both with EN 13108-8 as well as the highest specifications with respect to homogeneity (classification HE or H+) of the tender specifications SB250 v3.1. (Chapter 3 § 7.1.1.1.B.4) [15]. The bitumen content after extraction according to EN 12697-3 and the empirical properties of the recovered binder are summarised in Table 2. It can be noted that the aged binder properties of the RA used, is representative for the current average values observed in Belgium, although not especially hard.

Table 2. Overview of the aged binder properties of the RA

# section	Binder content (m-%)	Penetration value at 25°C, x 0.1 mm (EN 1426)	R&B temperature, °C (EN 1427)
RA	4.76	21	62.8

2.3 Mixture composition of AC14 base variants

In this study, an AC14 base mixture comprising 70% RA without rejuvenating agent was selected as reference mixture. Table 3 lists its composition, including the use of a virgin paving grade bitumen 50/70. Latter bitumen was characterised by a penetration value of 60 x 0.1 mm and a softening point temperature of 50.4°C. The targeted binder grade of the final AC14 base + 70% RA mixture was corresponding to a 35/50 paving grade bitumen.

Table 3. Mixture composition of AC14 base course variants

Fraction	Amount (m-%)	
	AC14 base + 50% RA	AC14 base + 70% RA
Course aggregate > 2 mm	58.9	59.1
Sand aggregate (2 mm – 0.063 mm)	32.9	32.9
Fines (< 0.063 mm)	8.2	8.0
Total (aggregates)	100	100
Total binder in AC14 base mixture	4.21	4.21
Binder originating from RA	2.28	3.33
Virgin bitumen (50/70) added	1.93	0.88*

* In case of the mixture with rejuvenator, it contributed to the final binder by 3.5% of RA binder = 0.11% in final AC14 base mixture.

2.4 Selection of rejuvenating agent

In this study, a bio-based rejuvenating performance additive was used. It is a liquid additive that will, with its specific amphipathic chemical structure, disperse the highly polar fractions of bitumen, therefore limiting the agglomeration of asphaltenes. Oxidation phenomenon being irreversible, with low dosage, it does not affect the relative asphaltene/maltene balance, but act more in the inter-mobility of asphaltenes into the bitumen matrix, which usually affects low and intermediate temperature behaviour. The aim of the effect is to restore the lost properties of aged binder at low and intermediate temperature, while still maintaining the benefit at high temperature and ensuring a durable effect over time. This rejuvenator has been already evaluated in numerous research projects [16,17,18,19] and has shown that a 5% dosage per weight of aged binder would restore, on average, the binder properties by two grades. Table 4 presents the main properties of the rejuvenator.

Table 4. Typical properties of the rejuvenator

Flash point	Viscosity at 60 °C	Cloud point	Density
> 280 °C	22 mPas	< 25 °C	0.927 g/cm^3

Given the binder content and properties of the RA used (see Table 2), a dosage of 3.5 % per weight of RA binder was defined. This dosage was determined to restore the penetration value to a 35/50 paving grade bitumen while still maintaining the minimal R&B temperature. As the rejuvenator is part of the final binder content, in the AC14 base mixture with 70% RA in combination with the rejuvenator, the final quantity of rejuvenator was 70%*4.76%*3.5%= 0.11%, or 1.1 kg per ton of final AC14 base mixture and the quantity required for the virgin binder was adjusted to 4.21 % - 70%*4.76%*(1+3.5%) = 0.77% nominal per weight of total AC14 base 70% RA mixture (= 7.7 kg/ton of mix).

3. TEST RESULTS AND DISCUSSION

3.1 Asphalt mix production

The asphalt production was carried out from 7 until 11 September 2017 at Matériaux de Vaulx (Stadsbader nv) in Vaulx-Lez-Tournai. The rainy weather conditions were quite unfavourable for the season with rather low temperatures (10 - 15°C) and a chilly wind. The paving job site was located at the asphalt plant and was integrated as a part of the construction of a new covered (in order to limit the water content) storage area for aggregates of about 5000 m^2. The asphalt mix plant was a batch plant (Ammann Euro-S-300 H) equipped with a parallel drying drum facilitating the introduction of RA at high rates. A production rate of about 115 ton/h was set at a target mixture temperature of 170°C.

An optimal dosage of 3.4 % by mass of the aged binder was applied in order to achieve a target penetration of a 35/50 binder class. Taking into account its density this corresponds to 1.17l/ton produced asphalt mixture comprising 70% RA. Although multiple ways of adding a rejuvenating agent during real production have been reported and discussed in literature [20,21] for the purpose of these field trials, the additive was spread through a spreading bar with nozzles, in a homogeneous way onto the cold RA on the conveyer belt transporting RA to the parallel drum (Figure 1). This was made possible due to the high flash point of the rejuvenator. In this way the rejuvenating agent is directly made in contact with the aged binder and given sufficient time to diffuse into and homogenize throughout the RA.

Figure 1: Addition of the rejuvenating agent by spraying onto RA on the conveyer belt

During the production, asphalt bulk samples of all AC14 base variants and RA (untreated as well as treated by the rejuvenating agent) were collected at several locations for further analysis in terms of quality control as well as for advanced testing on binder and asphalt mix level (see below). Additionally, all dry constituents were sampled in sufficient quantities to carry out a profound laboratory test program in a next phase [14].

3.2 Laying and compactibility on site

The field compaction was monitored by a follow up of the number of roller passes (a roller pass is considered as a pass of both wheels of the tandem roller compactor) and the evolution of the temperature of the AC14 base variants. Latter measurements were carried out while using a temperature probe which was inserted within the asphalt layer. The record of the temperature in function of time facilitated calculating the time window for compaction (lower T limit set at T = 90°C). Additionally, the temperature of the bulk mixtures was also determined in the truck while unloading using a penetration thermometer. The results of the temperature measurements are summarised in Table 5.

Table 5. Overview of temperature measurement during laying and compaction

AC14 base variant	# trucks	Average T (°C) in the truck	Time before T < 90°C (min.)	# roller passes before T < 90°C
AC14 base + 50% RA	7	170.2 ± 7.4	29.5	4
AC14 base + 70% RA (reference section)	6	168.1 ± 7.6	40.8	4
AC14 base + 70% RA + rejuvenator	6	168.1 ± 7.9	43.8	5

Based on the obtained results, the following conclusions can be put forward:

- The temperatures of all the produced asphalt AC14 base variants were very constant and in line with the target production temperatures;
- For all AC14 base variants sufficient time is available for compaction taking into account a critical temperature of 90°C.

Shortly after construction, six test specimens of 400 cm^2 (∅ 220 mm) and of 78 cm^2 (∅ 100 mm) were obtained from the test sections by coring as carried out by the asphalt producer, allowing for the determination of the resistance to permanent deformation (rutting) and the water sensitivity in a next step.

3.3 Binder testing

During the plant production, samples were collected for further extraction and binder recovery. This enabled characterising the binder and evaluate the potential effect of high RA content of 70% in mixture as compared to the standard 50% RA mixture and the effect of the rejuvenator. All the binders were characterised with penetration value at 25 °C, as the consistency at ambient temperature, and softening point temperature, as the consistency at high temperature. More fundamental characterisation was also performed using Dynamic Shear Rheometer (DSR) according to EN 14770. Additionally, chemical characterisation was conducted with Fourier Transform InfraRed (FTIR) in Attenuated Total Reflectance (ATR) mode. This enables to identify functional groups and track the level of oxidation through carbonyl and sulfoxide absorption peaks or to detect the presence of the rejuvenator.

3.3.1 Effect of rejuvenator on the RA during production

During the production of the asphalt mixtures at the asphalt plant samples were collected at different points of the production line, from RA stockpile, after the RA parallel drying drum and then on the final AC14 base mixture variants. Figure 2 and Table 6 displays the results with empirical properties. Whilst the RA binder was not excessively hard, after being through the drum, its softening point temperature increased by 3°C. With the use of the rejuvenator, after being processed through the drying drum, the effect is still visible with a softening point temperature remaining 5°C lower as compared to the RA (59°C ↔ 64°C). In the hypothesis that the rejuvenator would disappear (thermal degradation and/or emissions) during the drying process, the binder properties should have been similar to the RA after the drying drum. Furthermore, these data points can be compared with the binder in the final AC14 base mixtures. In the case of no rejuvenator, the properties came back closely to the initial RA as a result of the blend with a fresh 50/70 paving grade bitumen. Whilst, the mixture with the rejuvenator did not see much difference as compared to the RA treated with rejuvenator after the drying drum.

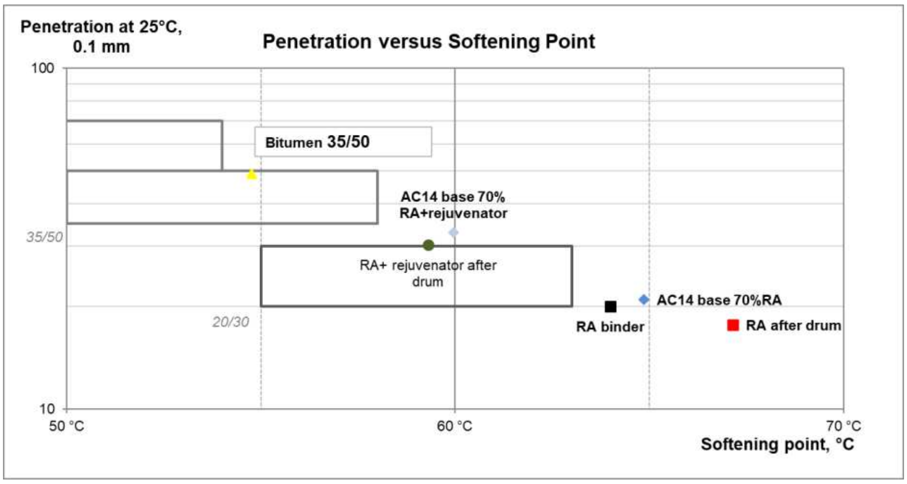

Figure 2: Binder properties along manufacturing process

Table 6. Binder properties along manufacturing process

Binder	Penetration value at 25°C, 0.1 mm (EN 1426)	R&B temperature (°C) (EN 1427)	Penetration index
RA	20	64.0	-0.18
RA after drying drum	18	67.2	0.12
RA + rejuvenator after drying drum	30	59.4	-0.23
Fresh 35/50 bitumen	49	54.8	-0.13
35/50 bitumen after RTFOT	25	62.2	-0.08
AC14 base 70% RA	21	65.0	0.06
AC14 base 70% RA + rejuvenator	33	60.0	0.06

Additionally, FTIR provided further information to track the presence of the rejuvenator [22] and the level of oxidation. Figure 3 displays the spectrum around the carbonyl groups, between 1600 and 1800 cm^{-1}, of the RA, RA after the drying drum and treated RA after drum as compared with 35/50 and 50/70 paving grade bitumen. For the RA, a clear peak around 1695 cm^{-1} is visible as part of carbonyl group, which was not present in original binder. This peak is still present for all binders as collected after the drying drum, and even showing a slight increase in intensity due to the additional oxidation during the drying process. Latter observation is in good agreement with the changes in empirical properties as discussed above (see Table 6). In the case of the treated RA, an absorption peak is also visible around 1740 cm^{-1} as a typical footprint of the rejuvenator. This confirmed that the rejuvenator was still present after being through the drying drum and did not deteriorate. Such an approach can be used in terms of quality control to confirm the presence and dosage of the rejuvenator.

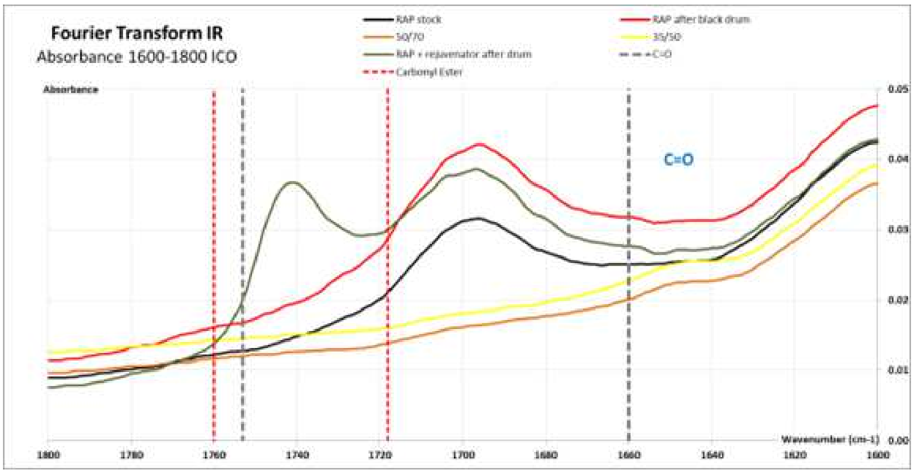

Figure 3: FTIR for binder sample collected during mixing process

3.3.2 Comparison of empirical binder properties for the three AC14 base variants

Figure 4 displays the empirical properties of the binder from the three AC14 base variants. It includes as well data set from a 35/50 paving grade bitumen as the targeted binder grade, including after short-term ageing by the RTFOT method in the laboratory. Normally after short-term aging, bitumen properties harden by one paving grade. In the case of the 35/50 bitumen, the ageing impact was slightly more pronounced. The AC14 base standard mixture with 50% RA comprising a 50/70 bitumen was almost like a 20/30 penetration grade and close to the 35/50 after RTFOT. In the case of the AC14 base mixture with 70% RA and no rejuvenator present, despite the use of softer pen-grade 50/70, the properties can't be restored to the extent of the targeted 35/50 paving grade bitumen. With the AC14 base variant with 70% RA and rejuvenator, the effect was clearly visible, with properties between a 20/30 and 35/50 penetration grade bitumen and even showing less aging as compared with the 35/50 paving grade bitumen.

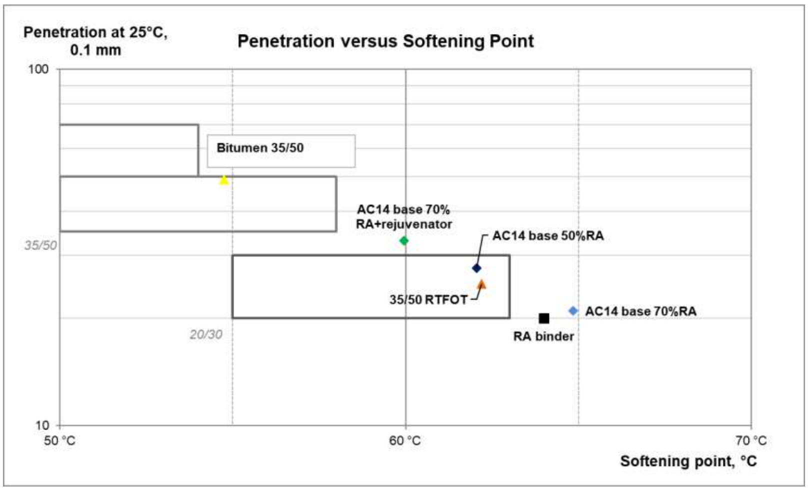

Figure 4: Empirical properties of binder properties from the three mixtures

3.3.3 Advanced rheological testing

In addition to the empirical tests, more fundamental evaluation was carried out using DSR measurements. Latter tests were carried out on each binder recovered from the three AC14 base mixtures in a temperature range between -20 °C and 90 °C at 10 rad/s on a 10 mm plate and 2.5 mm gap. Figure 5 displays the results of the determination of complex shear modulus |G*| as function of temperature. The binder from the AC14 base 70% RA variant was overlapping the RA binder curve, meaning it was not possible to recover the lost binder properties, which is line with the empirical properties as listed up in Table 6. The binder from the AC14 base 70% RA with the rejuvenator was almost overlapping the standard AC14 base variant with 50% RA, even characterized by slightly lower |G*|-values.

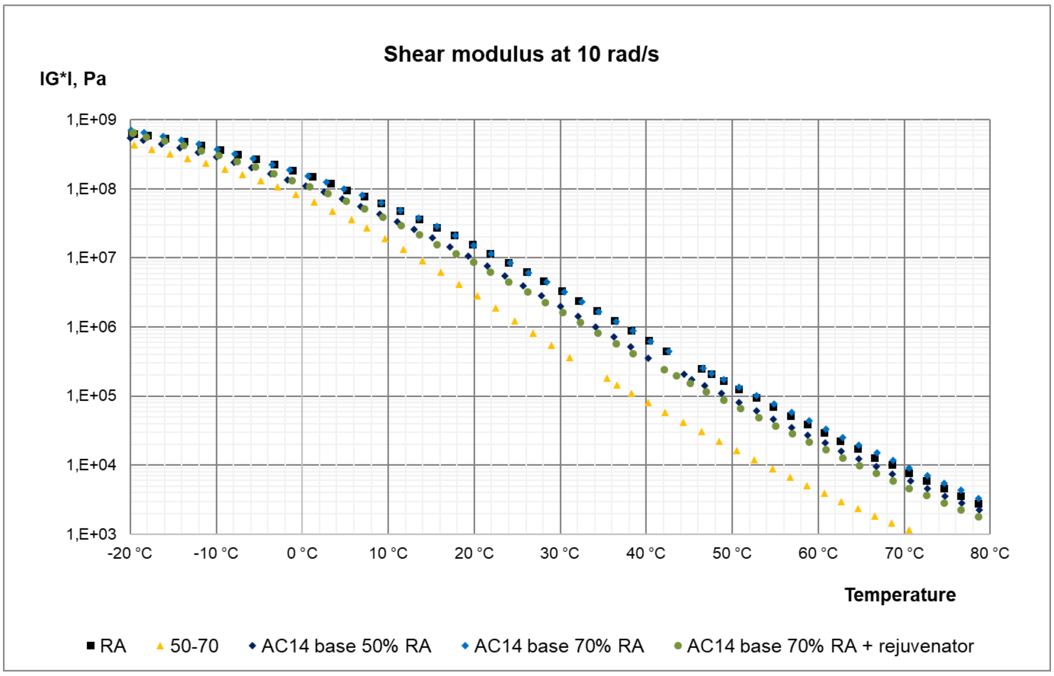

Figure 5: DSR measurements for the recovered binders

3.4 Asphalt mix testing

3.4.1 Compactibility

The impact of the recycling rate and the use of a rejuvenator on the compactibility of the AC14 base variants was assessed by investigating the evolution of the geometric bulk density during gyratory compaction according to EN 12697-31 of bulk materials sampled during plant production. Gyratory compaction was not only carried out for the measurement of the air void content at 60 gyrations for which criteria are set in the tender specifications SB250 v3.1 [15] within the framework of the ITT-study, but also for the fabrication of test specimens to be used in a next step for the determination of the stiffness (up to 60 gyrations) and water sensitivity (up to 25 gyrations). Moreover, for comparison with the field, gyratory compaction curves were also derived up to 200 gyrations. An overview of all results is provided in Table 7.

Table 7. Overview of the geometric air void content for AC14 base variants following gyratory compaction

	AC14 base + 50% RA (section 1)	AC14 base + 70% RA (section 2 - reference)	AC14 base + 70% RA + rejuvenator (section 3)
Test samples for water sensitivity measurement at 25 gyrations (n = 4)	8.2% ± 0.1%	7.0% ± 0.2%	7.9% ± 0.2%
% air voids at 60 gyrations (n = 4)	5.5% ± 0.3%	5.0% ± 0.4%	5.1% ± 0.5%
Test samples for stiffness measurement at 60 gyrations (n = 3)	6.2% ± 0.5%	6.5% ± 0.5%	6.6% ± 0.5%
Comparison with field compaction at 200 gyrations (n = 2)	3.8% ± 0.6%	3.3% ± 0.4%	3.9% ± 0.4%

Examination of the results summarized in Table 7 leads to the following conclusions:

- All AC14 base variants meet the criterion of minimal 5% and maximum 10% air voids as set out in the tender specifications SB250 v3.1;
- Generally, all AC14 base variants are characterized by very similar geometric air void contents for a given gyratory compaction level (ranging from 25 up to 200 gyrations). Therefore, it is quite tough to demonstrate any effect of the use of a rejuvenator in this case study;
- Only while comparing air voids at 25 gyrations a significant difference between the values corresponding to the sections with and without the use of a rejuvenator was observed. However, contrary to the expectations a somewhat higher air void content in case of a rejuvenator was determined: 7.9% ± 0.2% as compared to 7.0% ± 0.2%. However, no logical explanation could be provided, except for a possible impact of the intrinsic variability of the RA used.

3.4.2 Stiffness

The impact of the recycling rate and the use of a rejuvenator on the stiffness of the AC14 base variants was determined according to EN 12697-26 Annex C. This test method allows for the measurement of the stiffness modulus using an indirect tensile test (IT-CY) applied to cylindrical specimens with a diameter of 100 mm. Latter specimens were fabricated by gyratory compaction according to EN 12697-31 (# 60 gyrations) at the laboratory facilities available at the asphalt plant shortly after the sampling of bulk materials during production. In this way, the spread in air voids was limited, contrary to cored samples which reflect also variations in field compaction. The stiffness was measured at three temperatures: 5°C, 15°C and 25°C. The results (average of three test specimens) are illustrated in Figure 6.

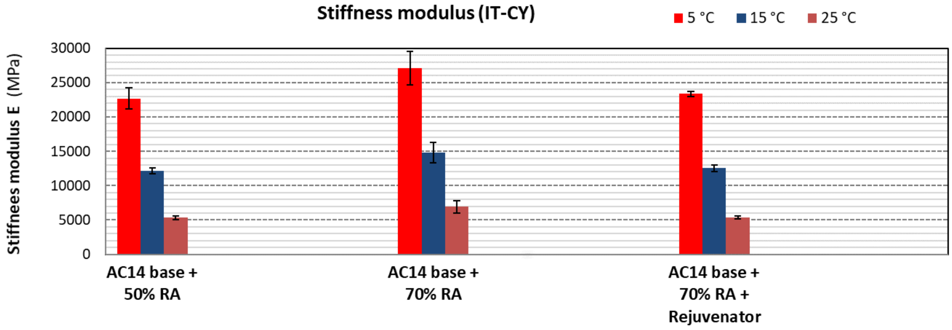

Figure 6: Stiffness modulus (IT-CY) of AC14 base variants at 5, 15 and 25°C

Based on the results visualized in Figure 6, the following conclusions can be put forward:

- As expected, the stiffness decreases as the temperature rises: about a factor 2 every 10°C;
- As anticipated, the increased recycling rate of 70% RA as compared to 50% is reflected in an higher stiffness modulus at all temperatures;
- The use of rejuvenator causes a drop in stiffness modulus. In this study, a dosage of 3.4 m-% to the aged binder reduces the stiffness for an AC14 base mixture with 70% RA back to the level of an AC14 base mixture with 50% RA and therefore 'compensates' for the stiffening effect of adding 20% more RA. Latter observation is in good agreement with the empirical properties and DSR-measurements of the recovered binders as discussed previously (§ 3.3), demonstrating the 'softening' effect attributed to the presence of the rejuvenator.

3.4.3 Resistance to rutting

The resistance to rutting was assessed by the wheel tracking test according to NBN EN 12697-22 while using the 'large size device'. The tests were performed in duple at a temperature of 50°C and the proportional rut depth PiLD (%) was measured up to 30,000 cycles. Test specimens were obtained from the road by coring six test specimens of 400 cm^2 (∅ 220 mm, thickness 50 mm) from each section the day following the construction. The cores were sawn to rectangular samples which are subsequently fixed in the testing molds (three core per test specimen) using plaster of Paris. Moreover, the resistance to permanent deformation was also evaluated for the AC14 base + 70% RA reference mixture of which the test specimens were prepared in the laboratory while making use of the same constituents sampled during the production at the asphalt plant. In latter case, the rejuvenator was added in the laboratory mixer at the moment the preheated RA is added to the mixture. Latter protocol is part of the development of a representative ITT-procedure when using RA in combination with rejuvenators and is described in detail elsewhere [14]. The results are illustrated in Figure 7.

Based on the results visualized in Figure 7, the following conclusions can be put forward:

- Taking into account the test results obtained while using cores from the field, no difference was observed between the AC14 base + 70% RA variants with or without the addition of rejuvenator. Therefore, no further risk related to permanent deformation was identified or could be associated with the use of rejuvenator;
- While comparing the results for the AC14 base + 70% RA reference mixture, one can observe that the test specimens acquired from test sections are showing a higher sensitivity for rutting as compared to laboratory prepared test samples. Latter phenomenon was largely attributed to the higher air void content of the cores gained from the field;
- The AC14 base + 70% RA reference mixture is meeting the criterion set out in the tender specifications SB250 v. 3.1 [15] for the highest traffic class with respect to rutting resistance (PiLD < 5%).

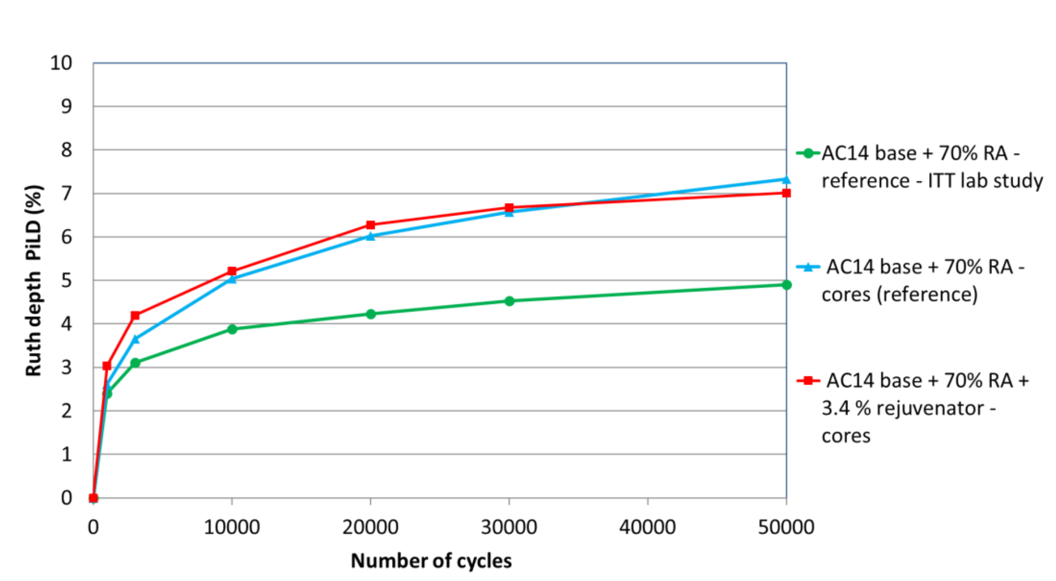

Figure 7: Results of the wheel tracking tests for all AC14 base variants

3.4.4 Water sensitivity

The water sensitivity of the AC14 base asphalt mixtures was evaluated by indirect tensile strength (ITS) measurements carried out before and after conditioning in water, using the test method EN 12697-12 in combination with EN 12697-23. The indirect tensile tests were performed at 15°C as required in EN 13108-20 (type testing of bituminous mixtures). Routinely, air voids of the test specimens were calculated according to NBN EN 12697-8 following the determination of the maximum density according to NBN EN 12697-5 except for test specimens of bulk material. Test specimens were obtained either by coring in situ or fabricated by gyratory compaction (# 25 gyrations) while using both plant produced bulk material as well as AC14 base asphalt mixtures produced in the laboratory (starting from the dry constituents sampled at the asphalt plant). An overview of the test results for water sensitivity is given in Table 8.

Table 8. Results of the water sensitivity tests for AC14 base variants

AC14 base variant	origin test specimen	Before conditioning		After conditioning		*ITS-Ratio (%)*
		ITS (MPa)	*Air voids (%)*	*ITS (MPa)*	*Air voids (%)*	
AC14 base + 50% RA (section 1)	Plant bulk material	2.7 ± 0.3	8.2 ± 0.1*	2.6 ± 0.1	8.2 ± 0.1*	97 ± 6
	Field cores	2.4 ± 0.2	6.4 ± 0.5	1.9 ± 0.2	6.6 ± 0.8	80 ± 8
AC14 base + 70% RA (section 2 - reference)	Plant bulk material	3.5 ± 0.5	6.7 ± 0.5*	3.5 ± 0.1	6.7 ± 0.5*	100 ± 8
	Field cores	2.8 ± 0.1	5.0 ± 0.2	2.0 ± 0.2	5.4 ± 0.3	72 ± 3
	Lab ITT study	3.4 ± 0.1	4.3 ± 0.3	2.9 ± 0.1	4.3 ± 0.8	87 ± 2
AC14 base + 70% RA + rejuvenator (section 3)	Plant bulk material	2.5 ± 0.4	8.0 ± 0.2*	2.3 ± 0.3	8.0 ± 0.2*	93 ± 11
	Field cores	1.9 ± 0.2	6.8 ± 1.0	1.2 ± 0.2	6.7 ± 0.8	64 ± 7
	Lab ITT study	2.8 ± 0.1	4.5 ± 0.3	2.4 ± 0.3	4.3 ± 0.5	87 ± 7

* Air void content (geometric) as determined from gyratory compaction curve at 25 gyrations.

Examination of the results summarized in Table 8 leads to the following conclusions:

- Generally, AC14 base variants are characterized by a very high ITS-ratio and are therefore characterized by a low or even no water sensitivity taking into account the spread on the ITS-R values; all ITS-R values meet the criterion of 70% as stated in the tender specifications SB250 v3.1 (Flemish region).
- The lowest ITS-R values (for all AC14 base variants) were determined in the case of field core test specimens. In latter cases, the more elevated air void content of the test specimens may explain the increased water sensitivity.
- Taking into account the precision of the test method, no significant differences in ITS-R values could be attributed to the use of a rejuvenator independent the origin of the test specimens. Therefore, no negative or positive effect of the use of a rejuvenator was identified;
- As anticipated, the increase of the RA recycling rate from 50% up to 70% results in a higher ITS-value of the unconditioned samples: e.g. 2.7 MPa → 3.5 MPa (bulk material). However, the addition of a rejuvenator reduces the ITS-values, approximately back to the level of the AC14 base + 50% RA variant: e.g. 3.5 MPa → 2.5 MPa (bulk material). This phenomenon is in good agreement with the results previously obtained with respect to the stiffness measurements.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

In this paper, the results of a field study comprising full-scale test sections of AC14 base mixtures with high RA recycling rates in combination with a bio-based rejuvenator are discussed. The impact of the use of a rejuvenator was evaluated both on a binder level as well as on the performance of the asphalt mixtures. Based on the results acquired, the following conclusions can be drawn:

- The sampling of materials and subsequent recovery of binders at different locations during the plant production process did not show any thermal deterioration of the rejuvenator. FTIR measurements enabled to detect the rejuvenator at all times offering excellent perspectives with respect to quality control. In addition, the positive effect on the physical properties of the treated binder remained.
- When comparing the AC14 base 70% RA with the standard AC14 base 50% RA mixture or even with a laboratory short-term aged paving grade bitumen 35/50, it was not possible to restore the lost binder properties at intermediate or high temperature. On the contrary, the AC14 70 % RA with rejuvenator was able to restore binder properties to the same (and even higher) level as compared with the standard AC14 base 50 % RA mixture as based on empirical characteristics. It was therefore confirmed that the use of the rejuvenator enabled increasing the RA content in the AC14 base asphalt mixture. Latter findings were also confirmed by the results of rheological measurements using DSR methodology.
- The impact of the use of the rejuvenator observed at binder level was also confirmed by measuring the stiffness of the corresponding AC14 base asphalt mixtures. The use of the rejuvenator reduced the stiffness of mixture containing up to 70% RA back to the level of the standard AC14 base mixture comprising 50% of RA.
- While carrying out other performance related tests on the AC14 base 70% RA mixtures with and without rejuvenator, it was generally very tough to demonstrate any difference taking into account the precision of the test methods (except for stiffness measurements) in this study. No negative or positive effect on the resistance to rutting or water sensitivity could be observed. Moreover, the interpretation of test results while making use of field cores was hampered by elevated air void content arising from variations during in situ compaction.

At the time this paper was drafted, the test programme with respect to the fatigue behaviour is still ongoing. Latter tests are scheduled within the framework of the corresponding ITT-study of the AC14 base variants carried out in the laboratory while making use of the sampled dry constituents during the plant production. It is anticipated that the use of a rejuvenator will affect in a positive way the healing behaviour and therefore the fatigue life of AC14 base mixtures with high rates of RA.

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