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Incorporating the transverse profile of the wearing course into the control of the hot in-place recycling of asphalt concrete

Michalina Makowska¹, Eeva Huuskonen-Snicker², Pauli Alanaatu², Kalle Aromaa³, Abhishek Savarnya⁴, Terhi Pellinen¹, Animesh Das⁴

¹ Department of Civil Engineering, Aalto University, Espoo, Finland

² Destia Oy, Turuntie 207, 02740 Espoo, Finland

³ Anton Paar Nordic AB, Tekniikantie 14, FI- 02150 Espoo, Finland

⁴ Department of Civil Engineering, IIT Kanpur, Kanpur, India 208016

michalina.makowska@aalto.fi

Abstract. The hot in-place recycling (HIR) of asphalt concrete (AC) is one of the least CO_2 emissive reuse techniques. It allows for 100% reuse of material in-situ in the same application, at a reduced need for the material transport to and back from the construction site, as well as the reduced price in comparison with the fresh wearing course overlay. Finland uses the technique predominantly to fill wheel path ruts caused by the studded tire abrasion, to retain structural capacity and prevent hydroplaning. During the HIR process, the aged AC material is heated up in-situ, milled to the approximate depth of 40 mm, blended with fresh AC admixture and rejuvenator. However, the amount of the aged material and the amount of the aged bitumen that undergoes rejuvenation depends on the pavement transverse profile. The rut depth, width and shape determine the minimum volume of admixture necessary for refill during the process in order to retain the structural capacity, as well as the amount of the aged binder requiring rejuvenation. In favor of achieving homogenous rheological properties in the final product, the proportion between the aged binder and the fresh binder should be controlled, as it influences the required amount of rejuvenator. Therefore, the rut cross-sectional area and furthermore, the rut volume is one of the previously unrecognized or ignored major variables of the hot in-place recycling process in Finland that should be incorporated to the HIR process control. This article demonstrates the methodology of incorporating the transverse road profile measurements by 17 vehicle-mounted laser sensors into the calculation of required rejuvenator amounts. This can be done during the procurement preparation phase or during the paving work as a continuous in-situ process control. In the rheological optimization the apparent Newtonian viscosity concept and the rotational viscosity are utilized in the viscosity based blending equation, which then allows the use of oily rejuvenators. The method reduces the need for aged pavement sampling compared with the determination of the calibration curve between rejuvenator concentration and the rheological response. Additionally, the apparent Newtonian viscosity corrects the complex viscosity by the phase angle derived correction factor, opening a previously unexplored opportunity of targeting desired viscoelastic characteristics. The approach is less sensitive to the frequencies and temperatures at which the shear measurements are conducted. This makes proposed calculative method of the desired proportioning of the aged binder, the fresh binder and the rejuvenator a promising tool for the industry. The combined algorithm presented allows for: the discrimination of sites where HIR type maintenance of pavement in question would result in a substandard product; the choice of the most promising material combination of the admixture and rejuvenator, as well as for the adjustment of the admixture and rejuvenator amount in-place.



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1. Introduction

The hot in-place recycling (HIR) of asphalt concrete (AC) is one of the least CO_2 emissive reuse techniques [1] [2] [3]. It allows for 100% reuse of AC in-situ in the same application, at a reduced need for the material transport to and back from the construction site, as well as the reduced price in comparison with the fresh wearing course overlay [3]. Finland uses the technique predominantly to fill wheel path ruts caused by the studded tire abrasion.

During the HIR process, the aged AC material is heated up in-situ, hot milled to the depth of ca. 40 mm, blended with fresh AC admixture (typically with bitumen penetration grade 70/100, about 25 kg/m²) and rejuvenator (paving grade soft bitumen 650/900, up to 250 g/m²). As a result it is estimated that the final product contains approximately 70-80% aged AC, which makes it one of the highest AC reuse techniques available. Nevertheless, the past research reports suggest that pavements deterioration increases in the consecutive cycles of reuse [4] [5], and that especially for AC with stiff aged binder achieving good performance in the final product is troublesome. In addition to the previously discussed shift towards decreased viscous response due to the multiple recycling of bitumen [6], one of the simpler aspects that has been recognized now is the lack of optimization of rheological properties during HIR. The progressive increase of stiffness of binder in the final product due to that is preventable.

In favor of achieving homogenous rheological properties in the final product, the proportion between the aged binder and the fresh binder should be controlled, as it influences the required amount of rejuvenator. The rut depth, width and shape determine the minimum volume of admixture necessary for refill during the process in order to retain the structural capacity, as well as the amount of the aged binder requiring rejuvenation. A necessity to develop continuous in-situ control system for binder consistency optimization, based on the existing pavement transverse profile (TRP) is proposed.

The purpose of this study, funded by the Finnish Transport Agency, is to demonstrate how along the length of the road section the true variation in TRP can affect the ratio between the aged and fresh binder in the HIR, and as a result influence the required rejuvenator amount.

At this point the correction of the aggregate gradation during the HIR process is not considered. The HIR conducted correctly is protecting the gradation in-place [7] as the separation of aggregates is happening through the softening of the bitumen rather than the mechanical force (e.g. during cold planning [2]). Due to that and brevity, the focus of present paper is in linking the TRP to the optimization of the rheological characteristic of the binder after HIR.

2. Binder rheology

The data used to evaluate the blending rules presented below comprised characteristics of bitumen samples extracted and recovered from cores, straight run bitumen of various grades (viscosity and penetration) before and after aging, as well as oil based rejuvenators. More specific information about the bitumen samples and their rheological characteristics are provided elsewhere [8] [9] [10] [7].

Bitumen samples were measured with dynamic shear rheometer to establish complex modulus ($|G^*|$) and phase angle (δ) (MCR 302 device with a Peltier temperature control system, Anton Paar, Austria) in frequency sweeps 0,01-10 Hz (FS) for temperatures 0-90°C at 10°C increments, with additional FS at 25°C. The parallel plate geometry of diameter 8 and 25 mm, using 2 mm and 1 mm gap, was used respectively. The applied shear strains were 0.05 % with 8 mm plate and 1% with 25 mm plate and within the Linear Viscoelastic range assured by amplitude sweep measurements.

For rotational viscosity (η_{rot}) measurements, the same equipment, but using the cone-plate (CP) geometry of 50 mm diameter (cone truncation 0.1 mm, CP angle 1° [ISO 3219:1995]), was used for oil based rejuvenators and soft bitumen samples at shear rates of 0.01-100 [1/s] between temperatures of 20-70°C at 10°C intervals, with additional measurement at 25°C.

Penetration (Pen) for all the bitumen samples reported below was measured at 25°C according to standard SFS-EN 1426 typically on the 100 g size sample. The Pen of 25 1/10 mm is noted as 25Pen.

For the below calculations, rheological characteristics of three extracted and recovered bitumen (BEX) samples from field collected material were used to represent field aged material. One BEX of

(4)

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35Pen comes from a core collected from the road before the process. The two additional samples, 3R and 4R [8] [10], both are BEX of 25Pen from the reheated and scarified material in the HIR process, before addition of the admixture or rejuvenator. They differ by history [10] and $|G^*|$ to δ [8] relationship.

As reported previously, for BEX of Pen>32Pen the lower raveling and thermal cracking were observed [9]. Thus, two rheological targets for final product properties were considered, 40Pen (BEX from core from good performing area after the HIR process, 3FC in [8]) and 47Pen (rolling thin film oven aged 70/100 bitumen, similar to those found in freshly recovered AC). To represent the properties of fresh bitumen in admixture the characteristic of straight run bitumen 70/100 (79Pen) was used [7].

The currently used rejuvenator in the HIR process is soft bitumen penetration grade 650/900 (Penetration between 180-360 1/10 mm measured at 15°C according to EN 12591:2009 and [11]), but the motivation of this study is to switch towards a softer viscosity graded product of viscosity at 60°C between 1000-2000 mm²/s (V1500). The previous reports of using V1500 in the place of 650/900, without the amount adjustment due to the difference in the viscosity of those products, reported problems with bleeding and over softening [12].

The purpose of hereby work was to develop the rules of blending which could allow substitution of 650/900 with V1500, while preventing the over softening. Coincidentally, the rules apply as well to other low viscosity products which could be potentially used as rejuvenators. The bio-based low viscosity oil was used to demonstrate the applicability of the approach to this types of products as well.

2.1. Blending equations

Because of the complex structure of the asphalt binder it is very difficult to model the interaction. Several attempts have been made by different researchers to come up with the mixing rules and their review is provided elsewhere [13]. Nevertheless, the Finnish Asphalt Specifications (FAS) [11] allow the use of four blending equations:

$$\log(Pen25^{\circ}C_{blend}) = a * \log(Pen25^{\circ}C_{aged}) + b * \log(Pen25^{\circ}C_{fresh})$$
(1)

$$SP_{blend} = a * SP_{aged} + b * SP_{fresh}$$
⁽²⁾

$$\log|G_{blend}^*| = a * \log|G_{aged}^*| + b * \log|G_{fresh}^*|$$
(3)

 $loglog(visc_{blend}) = a * loglog(visc_{aged}) + b * loglog(visc_{fresh})$

where a+b =1, Pen25°C stands for penetration measured at 25°C [1/10 mm], SP stands for softening point [°C], $|G_x^*|$ stands for complex modulus of blend component, measured at 1,78 Hz and 30°C, or 1,59 Hz and 25°C [Pa], "visc" stands for viscosity (typically kinematic or dynamic) [units unspecified], "blend" superscript indicates the properties in the obtained mixture/blend, "aged" superscript indicates the properties of the aged binder, e.g. RAP, "fresh" superscript indicates the properties of the freshly added material, e.g. admixture.

However, not every equation is applicable for the use in blending of components such as penetration graded bitumen, viscosity graded bitumen and oils (see Table 1).

Table 1. The measurable rheological properties for type of subcomponent in bituminous binders in the con	text of
equations 1-4. The "x" means the property is applicable for the material, while "-" is not.	

Measurable property	Aged binder	Fresh binder	Soft bitumen as rejuvenator	Oil based rejuvenator
D				
Penetration at 25°C	Х	Х	-	-
Softening Point	Х	Х	Х	-
Complex shear modulus	Х	Х	Х	-
Viscosity	Х	Х	Х	X

Moreover, when the binary system of aged and fresh bitumen is considered, the ratios "a" and "b" are different when derived from viscosity (e.g. measured at 60 °C) and when derived from eq. 1. That issue is demonstrated in Figure 1. Additionally, it was pointed out that equations suggested for use in

(5)

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FAS [11] are not having a specified unit for viscosity. Both mPa•s and Pa•s are accepted viscosity units elsewhere in the specifications. When using mPa•s and Pa•s, the calculated ratio is different, due to the lower linearity of the temperature susceptibility upon the use of Pascal as a main unit.

Nevertheless, there is still diminished linearity in the temperature susceptibility curves for viscosity expressed in mPa•s, which is related to deviation from Newtonian behavior at lower temperatures and higher frequencies, when the $\delta < 90^{\circ}$ [14] (Figure 2). For that reason, the concept of apparent Newtonian viscosity (η_{VTS}) [15], which takes account the effects of non-linearity in the viscoelastic binders, was investigated as a plausible input into equation 4 (see section 2.2.).



Figure 1. The mass ratio of aged binder in the blend with fresh binder (79Pen) computed with equations 3 and 4 (using η_{VTS} and η^* as input) for two bitumen samples 25 Pen (3R and 4R) using G* and δ data measured at (a, b) f=0,01Hz and (c, d) f=10 Hz, compared against the result obtained using eq.1. T40 denotes target rheological blend characteristic in line with 40Pen binder extracted from cores and recovered, T47 - blend characteristic in line with 47Pen binder (laboratory aged 70/100).

2.2. Apparent Newtonian viscosity (η_{VTS})

The concept of η_{VTS} has been used to derive the viscosity applicable in eq. 4 from the $|G^*|$ and δ of binder. The Cox-Merz rule relates steady state viscosity, η , the complex viscosity, η^* , and the complex modulus G* of a fluid [16]. It's given as:

$$\eta^* = \frac{G^*}{\omega}$$

where η^* is the complex viscosity, G^* is the complex modulus and ω is the angular frequency in rad/sec. At higher temperatures, when δ approaches 90°, the η^* and the steady state viscosity are equal: $\eta = |\eta^*| = \frac{|G^*|}{\omega}$ (6)

The asphalt binders do not exhibit Newtonian behavior over the complete range of interest in pavement applications. Hence at low temperatures and high frequencies, correction factor is used to convert $|G^*|$ to steady state viscosity. Researchers compared standard rheological measurements to $|G^*|$ and proposed the form of correction factor obtaining the apparent Newtonian viscosity (η_{VTS}) or the viscosity from ASTM viscosity-temperature equation [mPa•s] [15] as:

$$\eta_{VTS} = \frac{|G^*|}{\omega} \left(\frac{1}{\sin\delta}\right)^{a_0 + a_1\omega + a_2\omega^2} \tag{7}$$

where $|G^*|$ is the measured shear modulus, δ is the measured phase angle, ω is the angular frequency used to measure $|G^*|$ and δ and a_0 , a_1 , a_2 are the fitting parameters, hereby used for non-modified bitumen 3.639216, 0.131373 and -0.000901, respectively [15] [7].



Figure 2. The temperature susceptibility curves of considered materials (25Pen, 40Pen, 47Pen and 79Pen bitumen) are presented by means of apparent Newtonian viscosity [mPa•s] and complex viscosity [Pa•s] at (a) 0.01 Hz ($\dot{\gamma} \rightarrow 0$) and (b) 10 Hz. The rotational viscosity at ($\dot{\gamma} \rightarrow 0$) in this case 0.1 1/s is plotted in (a) for V1500 bitumen and oil based rejuvenator. To demonstrate the deviation from the Cox-Merz rule at lower temperatures and higher frequencies in bitumen samples, the δ at loading frequencies (c) 0.01Hz and (d) 10 Hz is given.

2.3. Input into the calculations

The goal is to recover the viscous properties at the lowest loading frequencies (e.g. 0,005 rad/s [17]) and the lowest shear rates, due to the interesting aspect of recovering the ductile behavior for better low temperature performance. Based on the computations presented in Figure 1, and the above assumption the choice of optimization frequency of bitumen loading from the collected data was 0,01 Hz (0.06283 rad/s) as the lowest measured (not obtained through time-temperature superposition principle).

Both η^* [Pa•s or mPa•s] and η_{VTS} [mPa•s] work in an acceptable manner in eq. 4 when bituminous binders are considered. The problems emerge when η_{rot} needs to be considered as a third component in the blending equation. If the Pa•s is used as unit log-log η_{rot} becomes negative. Additionally, the rejuvenators used in this study are non-Newtonian liquids. Therefore the assumption was made that using viscosity measured at the lowest shear rates measurable ($\dot{\gamma} \rightarrow 0$) should be used in calculations.

As presented in Figure 2, the η^* of bitumen samples at low frequency and low shear rates has a tendency to be highest (e.g. 0.01 Hz vs. 10 Hz). At increased frequency of loading and increased shear rate the η^* is lower, resulting in the higher "a" as a result of the calculations in equation 4 (Figure 1). Using η^*_{10Hz} can lead to a risky assumption that the final product could contain bigger percent of aged AC, leading to decreased viscous response at low temperatures. However, by using frequency as one of the variables, the eq. (7) corrects the temperature susceptibility of η^* , producing overlapping lines.

Whether the shear rate is corrected for due to this transform, remains to be studied. Nevertheless, the "a" calculated using the η_{VTS} at 10 Hz gives similar result to those at 0.01 Hz, which is untrue if η^* is used as input. Additionally, in case of using measurements at higher frequencies as input in

(8)

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calculations, we still need to consider how to choose the viscosity of the rejuvenator measured by η_{rot} if we use η^* as an input. The use of η_{VTS} eliminates that issue.

Nevertheless, it has been experimentally confirmed, using five various rejuvenators, that using this approach of combining equation 4 and 7 for three components, i.e. aged bitumen, fresh bitumen and rejuvenator, we can obtain a blend of rheological characteristic within 10% by $|G^*|$ and under 3° by δ difference to the target binder across temperature range 0-90°C and frequencies 0.01-10 Hz, or within +/-2 1/10 mm as measured by Penetration ([7]).

The applicability of different frequencies is still under investigation, but at the moment, suggested frequency and temperature for optimization or rheological properties of blend is at 25 °C and 0.01 Hz, and rotational viscosity of the rejuvenator at $\dot{\gamma} \rightarrow 0$.

3. Transverse profile on the rutted pavements

The trigger for HIR maintenance is defined by the maximum rut depth (h_{max}) on the level of 16-21 mm. The rut depth profile in Finnish pavements is a result of combined effect of initial compaction after construction, permanent deformation in traffic and studded tire wear. It may be additionally contributed to by the consolidation of the subgrade during freeze-thaw cycles [18].

Because of that the road network is systematically monitored. The survey vehicle based on Greenwood Engineering Profiler technology, mounted with 17 lasers in cross profile in the front of the survey vehicle is used. Used Profiler (width 320 cm, $W_{profile}$) has approximately 18 cm average distances between the laser sensors. Although, the lasers are located more frequently in the bottom of the wheel paths (see Figure 3 for position of the lasers) [19].

3.1. The maximum rut depth (h_{max}) calculations

Different methods and algorithms are being applied to calculate the maximum rut depth (see e.g. [20]). The maximum rut depth is calculated by using wire line method (see Figure 4) with equation:

 $h_{max} = \max(w_i - s_i)$

where i = 1-17 or as a width of the profile *i* belongs to [0, 320] cm; w_i = wire height at point *i*; s_i = road height at point *i*; *i* = location of the transversal point.

3.2. Defining of rut area calculation

It was proposed that by using the rut profile measured at 10 cm interval, using the rut profile area trapezoidal integration, a volume of rut (V_{rut}) could be calculated for each 1 m of the pavement length and 320 cm of measured profile by averaging the result from each 10 cm stretch. Area of the rut is also calculated by using the so-called wire line method [20]. Area of the rut (A_{rut}) is the area which is located between the road surface and virtual wire over the road profile as convex hull over the profile points, and is calculated with the formula:

$$A_{Rut} = \sum_{i=1}^{N-1} (w_i^{width} - w_{i+1}^{width}) \frac{(w_i^{height} - s_i^{height}) + (w_{i+1}^{height} - s_{i+1}^{height})}{2}$$
(9)

where N = profile point count, w_i^{width} = transversal length of the wire at point *i*, w_i^{height} = height of the wire at point *i*, s_i^{height} = height of the road at point *i*.

3.3. Test road sections (TRS)

During the summer 2017 the two Finnish roads were surveyed for TRP and rut volume was calculated for them in addition to the typically computed maximum rut depth (Figure 5). The considered TRS were: TRS1 (8561 cars/day, direction 1), TRS2 (8561 cars/day, direction 2), TRS3 (4462 cars/day, direction 1) and TRS4 (4462 cars/day, direction 2).

Unfortunately the information regarding the true bitumen content, bulk density and other relative parameters for those TRS were not available. Therefore the results are used to demonstrate hypothetically what would be the effect of the true differences in TRP to the rejuvenator amount in order to evaluate the usefulness of this type of measurement for the on-line process control activities.



Figure 3. Schematic explanation of the Profiler and the distribution of used 17 lasers along its length of 320 cm [19].



Figure 4. Sample profile how Area of the Rut is defined. Blue points are defining the road profile and the amount of the profile points is N. Red line defines how wire is adjusted over the profile as convex hull over the profile points [19].

4. The effect of the rut volume on the admixture control during recycling

Typically the consumption Consumption $[kg/m^2]$ of admixture in HIR is expressed in mass (m_{admix}) per surface of the road (S_{road}) . This value can be established using formula

$$Consumption = \frac{m_{admix}}{S_{road}} = \frac{G_{mb_admix}*V_{rut}}{S_{road}} = \frac{G_{mb}*A_{rut}*L}{W_{profile}*L}$$
(10)

where G_{mb_admix} is bulk density (G_{mb}) of admixture (calculated using design air voids for considered specifications [11]), V_{rut} is the volume of rut, $W_{profile}$ is the width of the surveyed profile (in this study 3.2 m), L is the length of the road along the driving distance [m], A_{rut} [m²] is the area of the rut (calculated using eq. 9).

The difference between h_{max} (average per 1 m) and calculated rut volume per 1 m length of the road is presented in Figure 5. Due to differing profile types, the same V_{rut} can be calculated for equal h_{max} . Previously the Consumption was linked on the basis of the h_{max} . It is hereby demonstrated that the value should be more related to the actual V_{rut} than to the h_{max} . Typical practice of purchase is to order e.g. 25 kg/m² or 35 kg/m² of an average Consumption. How that value is understood or altered during construction depends on the operator on the side of the contractor. The resulting over or under estimation of Consumption may lead to increasing waviness of the longitudinal profile (see Figure 5 i-1). The interest would be to study in the future if calculating the Consumption more adequately would allow for correcting of the road profile during HIR type maintenance.

Survey vehicle can be also mounted with an additional Destia Scanner System [DSS], which is located in the rear of the survey vehicle. DSS has a sample distance of 1 cm in the transversal profile and maximum survey width 400 cm. Starting from 2018, calculating the V_{rut} using this upgraded system, should provide more confidence in the transverse profile measurements. The increased width of the DSS, in comparison to the currently used system, will allow for more realistic estimates of the admixture amount, i.e. in line with the actually HIR processed width of the pavement.

5. The effect of the rut volume on the optimal rejuvenator amount to reach rheological targets

Assuming that a milling operation occurs to the 40 mm beneath the surface on the edges, using the G_{mb} (e.g. 2500 kg/m³) of the aged pavement, we can also calculate the mass of aged material per S_{road} [kg/m²]. Knowing the bitumen content (P_b) in both aged material (e.g. $P_{b_aged}=5,8\%$) and fresh admixture (e.g. $P_{b_adm}=5,8\%$), we can easily calculate the ratio between aged and fresh bitumen at each point along the treated distance using formula:

а

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$$=\frac{V_{aged}*G_{mb}{}_{aged}*P_{b}{}_{aged}}{V_{aged}*G_{mb}{}_{aged}*P_{b}{}_{aged}+V_{rut}*G_{mb}{}_{fresh}*P_{b}{}_{adm}}$$
(11)

From that and eq. 4 the $\eta_{VTS_{blend}}$ can be calculated. Then the eq. 4 can be expanded by additional term, connected with rejuvenator's viscosity

 $loglog(\eta_{VTS_target}) = a' * loglog(\eta_{VTS_{blend}}) + c * loglog(\eta_{rejuv})$ (12) where *a*' is a cumulative ratio of aged and admixture bitumen, *c* is the ratio of rejuvenator in the final blend, η_{VTS_target} represents η_{VTS} that should, or should not, be achieved in the product.



Figure 5. For the TRS1-4 a series of graphs depicting the difference between (a-d) the maximum rut depth (h_{max}) and (e-h) the average volume of rut per area (V_{rut}/S_{road}), in relation to the (i-l) calculated required amount of admixture to refil rut volume under the assumption of bulk density of the admixture at 2500 kg/m³ (Consu._{Gmb2500}).

Hereby, the demonstration was performed by calculating "c" that would allow reaching 40Pen or 47Pen characterized binders (see Figure 6), when starting material is 25Pen or 35Pen, and when (η_{rejuv}) is equal to that of 650/900 or V1500. The "c" is presented for typical operation (Consumption = 25 kg/m²) or explored Consumption in line with V_{rut} refill (RV).

The bulk density of both aged pavement and desired bulk density of admixture, have actually very high impact on the results of rejuvenator ratio calculations. For example at 0,03 m³/m² of the treated aged pavement at equal $P_{b_aged}=5,8\%$, the difference is between 4,87 kg ($G_{mb}=2780$ kg/m³) versus 4,26 kg ($G_{mb}=2450$ kg/m³) of aged bitumen per 1 m². In the first case, more rejuvenating power is required, which can be realized by a softer rejuvenator/bitumen in admixture or increased admixture amount.

6. Discussion and field plans

Typically, due to volumetric restrains of the AC, shifting P_b by 0.1-0,25% is considered of low risk in terms of mix stability and bleeding. Once the bleeding is observed during HIR process the rejuvenator amount is decreased. Of course the limiting rejuvenator amount depends on the voids filled with bitumen, but for simplification assumption is that rejuvenator addition should remain under 0.1-0.25 kg/m². The adjustment within the line segment of 20 m is feasible in that mass range, but the increase is rarely practiced after decrease (e.g. [8]). The possibility of control will be studied during field studies.

Looking at the results presented in Figure 6 it is visually simple to evaluate which maintenance types could be prone to bleeding or over softening risk, e.g. the viable maintenance methods for aged

AC characterized by 25Pen are those using V1500. The purchasing party could make the decision on the choice of materials for the HIR process. The operator of the HIR process on the side of the contractor can also easily distinguish in which regions to increase or decrease the rejuvenator amount, depending on the approach to admixture use (rut volume refill or fixed Consumption) and rejuvenator type.



Figure 6. The results of the calculations of required rejuvenator amount (both V1500 and 650/900, a.k.a. B800) at two admixture consumption levels - fixed 25 kg or equal to the rut volume refil (RV) for considered TRS1-4, when both aged and fresh AC have $G_{mb}=2500 \text{ kg/m}^3$ and Pb 5,8%. The upper row of frames is calculated for 25Pen aged material targeting to the rheological characteristics consistant with 40Pen type bitumen (T40), the middle row of frames for 35Pen aged material targeted towards T40, while the lower row of frames for 35Pen aged material targeted towards 47Pen type bitumen (T47).

However, currently the calculations provide only the result of the theoretical estimate of required admixture to refill the rut depth, considering the limited width of the measured profile. Currently the rut volume calculation was incorporated into the survey and allows us to gather information and compare with results of the maintenance activities. The use of DSS in future is promising. Despite the fact, that the calculations are hypothetical, the actual TRP was used. It allows for better understanding of the true deviation between sections, or along the distance within the section, in terms of necessity to refill the rut and its effect on the rejuvenator requirement. Moreover, the above is still in need of coupling with the actual milling depth monitoring to assure the correct binder ratios.

7. Conclusions

This article presented promising theoretical background behind the concept of incorporation of transverse road profile, rheological and volumetric properties of the aged pavement to the on-line control of the hot in-place recycling process. The use of apparent Newtonian viscosity concept was proposed for the field applications. The method is least susceptible to changes of frequency and temperature during the shear measurements, and thus at high possibility for coupling with measurement performed already routinely on bitumen. The transverse road profile, parameter previously ignored, was demonstrated as an important variable.

The combined algorithm presented allows for: the discrimination of sites where HIR type maintenance of pavement in question would result in a substandard product; the choice of the most

promising material combination of the admixture and rejuvenator, as well as for the adjustment of the admixture and rejuvenator amount in-place.

The above presented research provides an initial framework for further field investigations.

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