ASSESSMENT OF RISKS IN THE HOT IN-PLACE RECYCLING IN FINLAND DURING THE SUMMER OF 2016

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Abstract. The hot in-place recycling of asphalt concrete is a major road maintenance technique in Finland for high volume roads. The use of this technique peaked in the beginning of 1990's and the volumes have stayed at a steady level since then. The first experiences back then were very positive and the technique appeared as both economical and environmentally friendly. However, in the recent decade the quality and performance of the pavements treated with HIR has decreased, especially the resistance to the studded tire abrasion has declined. It has been postulated that the change in materials used for the construction of asphalt concrete roads in Finland – fillers, aggregates, rejuvenators and bitumen are the reasons for the declined performance. However, the process control, mix design and the overall design of construction work at site are playing an important role as well.In our previous research, we have studied in detail the performance of Highway no. 1 and Ring Road II, which both are high volume major arterials. Based on results, the risk assessment for the maintenance process was developed and verification tests and further evaluations were proposed for the second stage of the project. This research investigated and recorded experiences of hot in-place recycling during the summer of 2016 in five major maintenance contracts all conducted by different contractors. The paper discusses the observed best practices, but the major focus is on issues, which need improvement, both on client's and contractor's site.

Keywords: hot in-place recycling, process control, heat transfer, recycling,

1. Introduction

The project "Pavement Life Cycle Research Program, Recycling and rejuvenation" previously investigated two major arteries (Makowska, et al., 2014) (Makowska, Pellinen, 2015) (Makowska, *et al*., 2017). From those studies we identified the material composition oriented risk factors which may have been affecting to the success rates of the hot in-place recycling (HIR) process. Additionally, the nomenclature for the HIR maintenance was defined as:

– the rehabilitation is achieved when the final binder rheology is characterized by lower stiffness and higher phase angle than prior to construction; the air voids remain on the design level described by specifications for each traffic class;

– the maintenance is achieved when the final binder rheology is similar to those of the binder prior to construction; the air voids remain on the design level described by specifications for each traffic class;

– the damage, a failure to achieve maintenance or rehabilitation, occurs, if the final binder rheology characterised by higher stiffness and lower phase angle than prior to construction; the air voids significantly increase and reach levels above those specified in specifications for considered traffic.

Although a prior statistical analysis of the pavements' performance in Finland indicated that each recycling decreases performance of the resulting structure (Rantanen, Suikki, 2009). The subsequent investigations of the material properties and the process control suggest otherwise. The material properties had more effect on the success than the number of HIR maintenances when one contractor on one road used same process control activities (Makowska, et al., 2017). The recent review of the statistical data suggested, that the drop in performance on the low trafficked roads is much more substantial after 3rd HIR treatment (up to -43%), than on the main arteries (-25%) (Suikki, Spoof, 2017). The practice is in fact to use different materials for different traffic classes (*Finnish Asphalt Specifications*, 2011), while the same HIR process guidelines apply to all of the asphalt pavements.

During the summer of 2016, several roads were monitored closely in the project in order to evaluate how much each of the previously identified risk factors would affect the outcome. The considered aspects were: sampling, sample processing, open flame heating unit operation, compaction of the treated layer, the speed of convoy and mix design.

The contemporary guidelines require to take five samples from homogeneous area during the planning stage, and to provide information during the contract preparation regarding bitumen Penetration prior to maintenance, air voids content and gradation. This information is used in the contract preparation stage but samples are not required afterwards to verify the outcome. The suggested amount of raw materials to be used during the HIR maintenance is on the level of ca. 25 kg/m^2 of fresh admixture and up to 250 g/m^2 of soft bitumen 650/900 as a rejuvenator. The bitumen in the admixture is not specified, but the aggregates need to meet the requirements of the Finnish Asphalt Specifications regarding the resistance to the studded tire wear.

The objective of the 2016 field study was to investigate if the enhanced information about the composition of the existing old asphalt concrete (mineralogy, estimated mastic stiffness, overfilled voids in aggregate) would aid the contractor in process control. In addition to material selections, the process control parameters such as production capacity i.e., speed of the convoy and thermal control was to be evaluated as well.

The problematic aspects under the assessment were the changes in the existing road surface due to HIR maintenance such as the increase of air voids and decrease of penetration instead of maintaining or improving it. The other previously identified problem areas were the bleeding of bitumen to the surface after the work and a sudden ignition of the old asphalt during the heating stage. The suggestions to mitigate these were to be presented in the project, if possible.

2. Test sites and methodology

Highway no. 4 (Oulu region – H4), 6 (the ring road around Lappeenranta – H6), 7 (Porvoo area – H7) and 12 (between Tampere and Hämeenlinna – H12) and motorway number 303 (M303) were included in the evaluation.
The contractors were asked to conduct the preparation for maintenance and reporting activities in a normal way in order not to complicate their busy schedules. Afterwards the aggregates and bitumen were transferred to Aalto University's laboratory for additional material characterization. In case a possibility of collecting extra samples was available they were obtained for the Indirect Tensile Strength (ITSr) (SFS-EN 12697-23) and Stiffness (ITSt), as well as for resistance to abrasion by studded tires testing (SFS-EN 12697-16 method A) after the HIR ($Prall_{HIR}$). The contractors were offered extra information regarding the filler, aggregate and bitumen. One contractor decided to attempt to test the effect of speed of work progression on homogeneity of resulting product (H7) and took two sets of samples from the finished surface. The summary of executed tests for each test road is provided in Table 1.

The collected samples were typically tested so that the bulk density measurement (SFS-EN12697-6) was followed by maximum density measurement (SFS-EN 12697-5), which was then followed by extraction of bitumen with dichloromethylene (DCM) (SFS-EN 12697-1). The liquid was then recovered (SFS-EN 12697-3), tested by Fourier Transform Infrared spectroscopy in the Attenuated Total Reflectance Mode (FT-IR-ATR) for the presence of DCM (Pellinen & Makowska, 2/2016) and Penetration (SFS-EN 1426) was measured.

Table 1. The summary of experimental plan performed on corresponding sample sets

Road	Bitumen before HIR	Bitumen after HIR	Aggregate / air voids before HIR	Aggregate / air voids after HIR	$Prall_{HIR}$	Mechanical before HIR	Mechanical after HIR	Thermal camera
H4	x	x	x	x	x	x	x	x
H6	x	x	x	x				x
H7	x	x	x	x	x	x	x	x
H12	x		x			x		x
H5	x	x	x	x				

Extracted aggregates were then sieved in order to obtain a gradation curve (SFS-EN 12697-2). The material passing 0.063 mm was retained separately and measured by FT-IR-ATR (iS50, Thermo Fischer Scientific) (Makowska, *et al.*, 2014).

According to the Beer-Lambert law, the Absorbance (Abs) at certain frequency is proportional to the absorption path length (l), molar absorption coefficient (ε) and molar concentration (c). In order to allow for lowest sample processing and fast quality control screening, while eliminating the effect of the gradation and air void content in the powder sample on the intensity of the Abs, the ratio between the Abs of peak characteristic for calcium carbonate (Abs_{CaCO3} – 1434 cm^{-1}) and silica (Abs_{SiO2} – 1000 cm^{-1}) was related to calcium content (recalculated into calcium carbonate) measured with a hand-held Thermo Scientific Niton XL3t X-Ray Fluorescence (XRF) Analyzer. Both silica and calcium carbonate are interesting minerals in the context of Finland, because only limestone and fly ash have been widely used as filler during the road construction. The relationship between calcium containing compounds and silica is different in case of hydrated lime usage as an additive.

With the help of our previous studies on materials collected from Highway no. 1 in Finland, a calibration between the mineral composition measured by FT-IR-ATR and XRF results, which is provided in Figure 1, was produced. The content of limestone in the fines in the subject roads in 2016 was established using such obtained calibration curve.

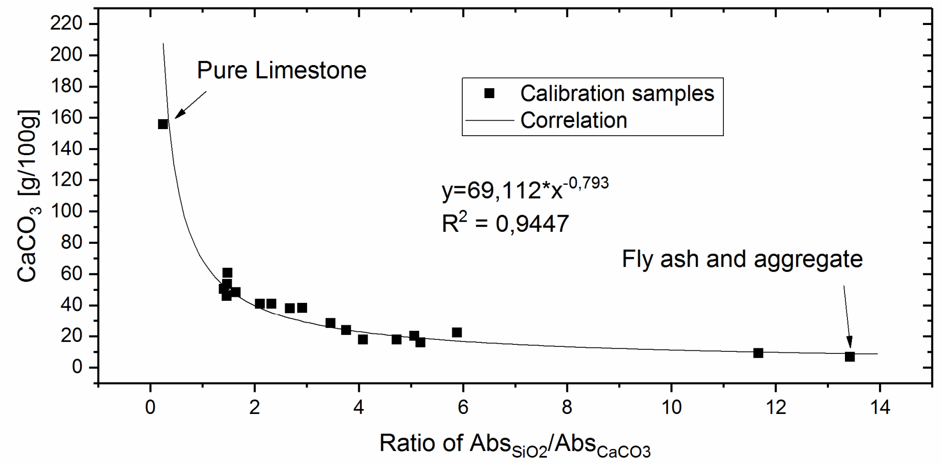

Fig. 1. The calibration curve linking the amount of calcium carbonate, calculated from the calcium content determined by XRF, to the ratio of intensities of silica oxide and calcium carbonate peak measured by FT-IR-ATR in absorbance (Abs) mode.

The remaining coarse and fine fractions of the aggregate, when possible, were measured for their densities (*SFS-EN 1097-6* and *1097-7*) in order to calculate the Voids Filled with Bitumen (VFB). In the case of H5 aggregate was discarded by the original processing laboratory and the effective specific gravity of the aggregate was back calculated from the maximum density of the asphalt mixture.

3. Results and discussion

Evaluation of the success of the HIR based on the comparison of rheological parameters and air voids is an appropriate to assure similar performance of the recycled and non-recycled pavements. According to previous research the drop in Penetration during the heating stage of HIR process (without addition of admixture or rejuvenator) is between 20-25% (Asphalt Recycling and Reclaiming Association, 2001) or up to 15-28% (Aromaa, 2016).

However, the aspect of correctness of the test data should be first discussed. In the Table 2, the samples with DCM detected in the bitumen by Aalto laboratory are marked. Based on the difference of the Penetration result before and after HIR, we should conclude that the significant damage occurred during HIR on H6. However, the confidence in the rheological results before HIR is low due to the presence of DCM. We propose that an additional spectroscopic analysis of bitumen is always provided along the rheological data in order to increase the confidence in the evaluation of construction. This is in the interest of both parties in order not to penalize the contractors where the fault remains in the failed sample processing rather than in the process control.

The second aspect is related to the sampling and location of sampling sites. H12 has two Penetration values. It was revealed during discussions with staff, that the higher Penetration was obtained from samples collected in the area of patching rather than the homogenous structure. The success of the construction should be evaluated on the basis of most representative samples. Patching stretches should be marked and perhaps removed from evaluation. According to the guidelines, patches should be milled away before HIR process but the final decision is on the contractor side.

The third aspect is the amount of admixture and rejuvenators used and the type of selected rejuvenator. The reason to do HIR in Finland is to fill ruts abraded by studs. As these roads have typically two driving lanes next to each other, the HIR is confined by the fact that the thickness of the new treated layer cannot exceed the existing surface. If this would happen, the shoulder and the adjacent lane should also be treated or overlaid. Therefore, the depth of the rut is driving the calculations of the amount of admixture per kg/m^2 to be used. Because of that, the focus should be on tweaking the rheology of the rejuvenators and bitumen in admixture in order to assure the rheological rehabilitation, if the admixture and rejuvenator amount are confined.

A fourth aspect to consider is the target for the rehabilitation of the existing surface. This takes us back to the nomenclature we developed to demonstrate the success rate of the HIR process, discussed in the introduction. Therefore, knowing wheatear the Penetration of the old pavement is 20 or 50 is crucial for the decision making as will be demonstrated below. Figure 2 shows the outcome of the pre-calculated and the actual observed change of the Penetration after HIR work. The outcome in Figure 2 is defined as rehabilitation when penetration of old pavement surface is increased due to the treatment and road will be damaged if the penetration decreases due to the treatment. A minimum rheological property acceptable for a fresh overlay (for instance penetration relative of the use of virgin 70/100 bitumen) should, however, be included as an additional evaluator of success.

Table 2. The summary of results gathered from the evaluation of sites treated with the HIR maintenance in 2017. n/a – not available, DCM – presence of dichloromethane observed in FT-IR analysis, thin – overlay with wearing course layer below 20 mm thickness, thick – overlay with wearing course layer above 20 mm thickness, slow – HIR convoy speed of 4m/min, fast – HIR convoy speed of 8m/min

	H4		H5		H6		H7		H12
	thin	thick	Site A	Site B	Site A	Site B	slow	fast	
type of pavement	SMA16		SMA16		SMA16		SMA16		AC16
maximum density before [Mg/m^3]	2537	2643	2717	2703	2426	2453	2421		2790
Penetration before [dmm]	45	39	31	53	70 (DCM) est. 65	101 (DCM) est. 80	38		52 (85)
Penetration after [dmm]	33		45	54	59		24	23	n/a
P_b before [%]	6.3	5.7	5.8	6.1	5.9	5.6	5.7		6.2
P_b after [%]	5.5		6,2	6,0	5,8		6.1	6.0	n/a
VFA [%]	**95.1**	82.7	75.7	79.8	**95.4**	92.6	88.6		87.1
V_{aSSD} before [%]	**0.8 ±0.6**	2.8 ±0.4	4.7 ±0.7	3.8 ±0.6	**1.0 ±0.3**	**0.6 ±0.5**	**1.6 ±0.5**		1.9 ±0.4
V_{aSSD} after [%]	4.1 ±1.2		1.5 ±0.6	1.8 ±1.1	2.4 ±1.5	2.0 ±1.4	2.5 ±1.2	4.2 ±1.3	n/a
$P_{CaCO3/0.063}$ [%]	47.9		23.5		52		9		28.9
Estimated limestone filler CC75 [%]	7.6 -10		3.4		7.1		1.2		4,0
$Prall_{HIR}$[ml]	27,3 (II)		n/a	n/a	n/a	n/a	25,4 (II)	28,0 (II)	n/a

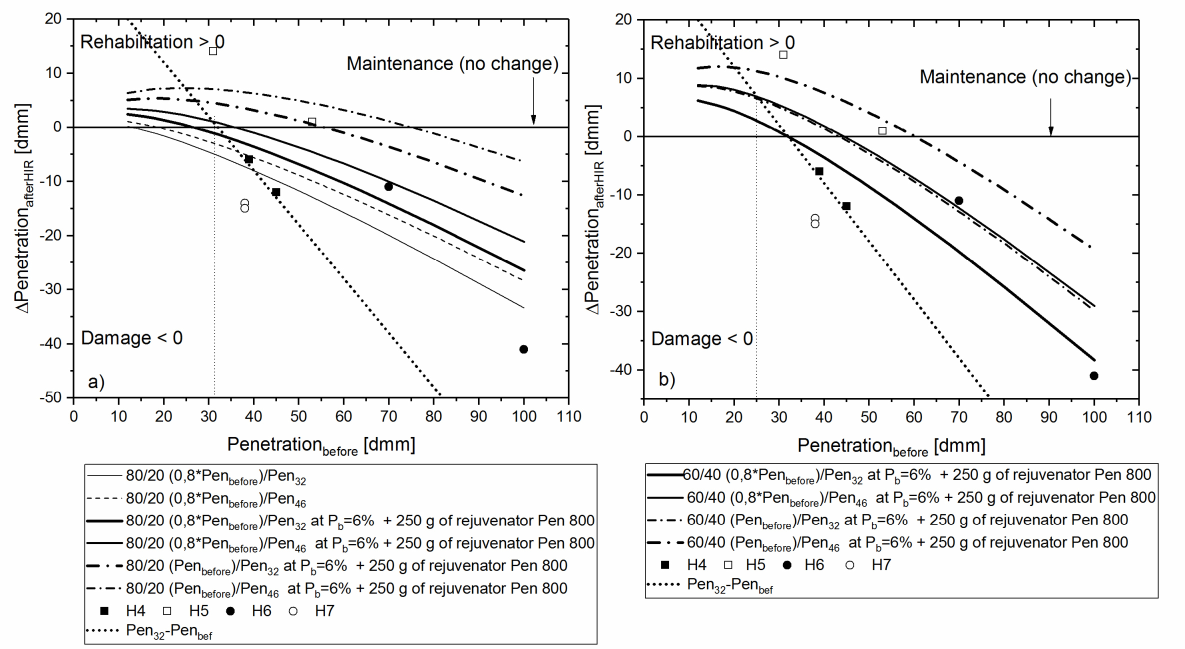

Fig. 2. The change in Penetration after the HIR of 2016 for H4, H5, H6 and H7 compared to the pre-calculated change in Penetration for:
a - mass ratio of bitumen in aged pavement and admixture of 80 %wt. to 20%wt., on the example of 80 kg aged pavement with 20 kg admixture, assuming bitumen content in both at 6 %wt., with or without 250 g rejuvenator 650/900 added; b - mass ratio of bitumen in aged pavement and admixture of 60 %wt. to 40%wt., on the example of 80 kg aged pavement with 53 kg admixture, assuming bitumen content in both mixes at 6 %wt., with or without 250 g rejuvenator 650/900 added

The strive on contractor's side and from purchasing party is to obtain simple "rules" or guidelines for selecting the amount of admixture and rejuvenator that would be applicable for all the roads in Finland, similar to the existing guidelines. Preliminary, it was proposed by the contractors that increasing the amount of admixture from 25 kg/m^2 to 50

kg/m^2 would solve this issue countrywide. In order to demonstrate the outcome of expected damage/rehabilitation, a simple simulation was performed using equation

$$Pen_{blend} = 10^{\frac{a\log(Pen_{before})+b\log(Pen_{addmix})+c\log(Pen_{rej})}{100}} \quad (1)$$

where Pen_{blend} – Penetration of bitumen blend in the finish mixture after rejuvenation, 1/10 mm, Pen_{before} – Penetration of aged bitumen, Pen_{addmix} – Penetration of bitumen in admixture (32-46 dmm), Pen_{rejuv} – Penetration of rejuvenator (800 dmm), a, b, c - mass percentage of aged binder and rejuvenator, respectively.

Two ratios between old and fresh bitumen were used, namely 80/20 and 60/40 by weight percent of bitumen, which corresponds to the ca. 20 kg/m^2 and ca. 53 kg/m^2 admixture per 80 kg of old pavement.

According to the Finnish Asphalt Specifications, the requirement for the retained Penetration after RTFO test for bitumen 70/100, used in a typical admixture, is above 46% (32-46 dmm). RTFO indicates the changes in bitumen, which take place during production of asphalt mixture, transport to the site and compaction. All these changes will take place in the admixture during HIR process. Considering the change in Penetration in aged pavement just due to the action of the heating units is ca. 20%, the input into the calculations Pen_{before} was multiplied by 0,8 to be on the conservative side. The aging of rejuvenator is not considered as the rejuvenator is applied in-situ (transport time and thin film spreading during mixing do not apply).

The Figure 2 demonstrates that the effect of the better control of the heating process, is as significant as the use of rejuvenators. Of course, using softer rejuvenators (that do not have Penetration value) would allow us to rehabilitate the pavement better, but in that case the Eq. (1) is not directly applicable.

The more important aspect for consideration is that one technical solution is not ideal nor even applicable for all pavements in Finland. Indeed, the 60/40 ratio of aged bitumen and admixture bitumen will work better for heavily aged “hard” pavements with low Penetration, but applying the same to the “softer” pavements with high initial Penetration will result in significantly more relative rheological damage.

However, when compared to the lowest allowed Penetration level for 70/100 after RTFO, which is 32 dmm and which has been determined to be sufficient for highway performance (Makowska, *et al.*, 2017), the “damaged” soft pavement can still be compared to the overlay in which bitumen 70/100 was used. From Figure 2 it is apparent that the ratio 80/20 with full rejuvenator use is safe only above Pen_{bef} = 32 dmm, while in the 60/40 ratio Pen_{bef} on the level of 25 dmm could be rehabilitated to the desired level.

The current guidelines were developed in 1990’s based on the recycled AC material (containing typically bitumen 70/100 or 100/150, whose Pen_{bef} was in the range of 60-70 dmm (Apilo, Eskola , 1999)). For this range of penetration the current suggestion of 25 kg/m^2 and 250 g/m^2 of bitumen 650/900, at moderate levels of heating (in 2009 the maximum surface temperature measured after heating units during HIR was in the range of 180°C) is sufficient.

The suggestion is to divide the pavements into different classes based on their rheological properties, e.g. Penetration range, and to design the best HIR process for each class. Since the statistical comparison of the performance has been conducted in comparison to performance of the fresh overlay in each traffic class, it is suggested to define the acceptable or desired rheological properties (target) for each of the classes in order for contractors to optimize the HIR process to reach the targets.

Additionally, it was found that some locations before maintenance, were not meeting the VFB criterion set for mix design corresponding with appropriate traffic class. The allowed range for SMA pavements is VFB 75-90% with range for V_{aSSD} 2-5%, while AC16 is VFB 75-93% with V_{aSSD} within 1-4%. The abnormal values have been bolded in the Table 2. From this we have expected a bleeding risk. However, no significant observations from contractors about bleeding was reported. The significance of this parameter to the outcome was low.

The gradations of the aggregate were outside of the required envelope for corresponding asphalt mixture types. This had not been observed during the analysis of H1, because the thickness of the surface layer on that road needing treatment was over 40 mm. In the cases presented in this article majority of the surface layers treated and samples taken from them were below the 40 mm thickness. In the case of H4 within 40 mm from the surface, two layers could be identified of which the top one was between 5-25 mm (samples marked as “thin” and “thick” in Table 2). One of the risks identified here is associated with the transfer of the lower layers into the wearing course. The results (Table 2) indicate lower class of resistance to abrasion by studded tires in collected samples than desired. Typically, SMA16 is chosen for the wearing course due to its higher resistance to abrasion by studded tires. The lower layers are typically normal Asphalt Concrete (AC) with lower quality aggregate (Finnish Asphalt Specifications, 2011). As the increase of rut depth is the main quality parameter used in the performance evaluations, in order to prevent risk of increased rutting due to aggregate transfer and change of gradation, one should not recycle too thin surface layers.

The current method of purchasing asphalt by kg/m^2 instead of specifying the actual thickness of layer is problematic. For instance, instead of ordering 40 mm thickness, the agency uses 100 kg/m^2 of mixture assuming to get the 40 mm thick layer. For a heavy aggregate with G_{mm} in the range of 2790, a 100 kg at 2% air voids content is equal to 36 mm instead of 40 mm. Although the influence of the recycled layer thickness on the wear resistance has not been tested, a minimum layer thickness of 40 mm should be specified to prevent mixing the base course to the surface.

In terms of analysis of aggregate composition, the filler content at level of up to 7% for fresh SMA16 and up to 4% for fresh AC16 is normal. The limestone filler content below those numbers for respective mixture types indicate that road has been recycled before and in the process mixtures contingin different filler types, namely fly ash and limestone filler, have been mixed together

The shift towards higher ITSr and ITSt results after the HIR process in tested samples is still evident indicating the lower resistance to thermal cracking but higher resistance to permanent deformation (Pellinen, 2003) (Figure 3), yet the values are strongly air void content dependent.

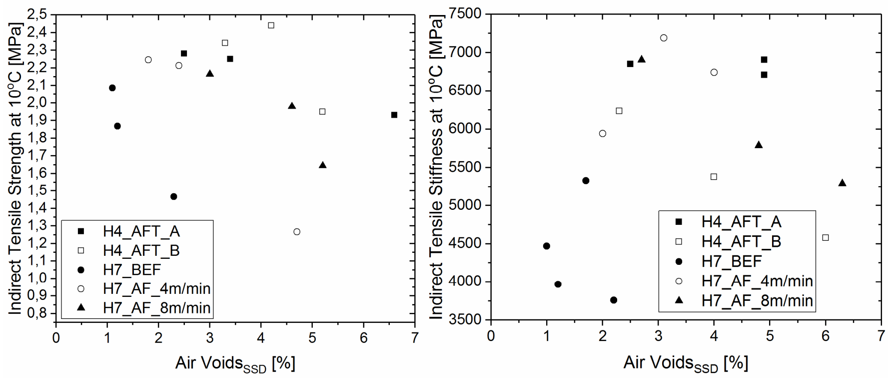

Fig. 3. Mechanical properties of tested samples in relationship to the surface saturated air voids content of tested sample:
a - Indirect Tensile Strength at 10°C, b - Indirect Tensile Stiffness at 10°C.

The recycling of fly ash containing mixture (H7) was troublesome due to heating problems. Overall, the drop in Penetration was substantial on that construction site, indicating problems with heating or inadequate material choice. In terms of homogeneity evaluation due to the speed of construction it was concluded that the gradation collected from the area processed at 8 m/min had an average gradation curve closer to the desired SMA16 (Finnish Asphalt Specifications, 2011) and the lower standard deviation at each aggregate fraction was recorded than in the case of 4 m/min construction. However, the significantly higher air voids obtained on the 8m/min stretch discourage the use of higher speed. The increased speed without the addition of extra roller, insufficient time for the temperature equalization within surface layer before remixing action with admixture, or inadequate pre-compaction by the paver screed are speculated as culprits.

The other problematic road was H4, which contained slag aggregate. The slag aggregate, despite being rich in heavy metal compounds, is highly porous material and also used as insulation. Reheating of such aggregate may pose challenges related to catalytic aging of bitumen and burning of the surface, if too high power is applied on the insulator. In the end, only Site H5 could be judged to have achieved a successful rehabilitation according to the criterion set previously. Unfortunately, the thermal data from the process was not collected from this Site. Site H6 was on the borderline of maintenance and slight damage, due to the lack of confidence in the quality assurance results. However, the final rheology of the binder extracted from that site after HIR was in line with the typical overlay of 70/100. H4 and 7 were damaged during the HIR and the rheology of the binder is deemed insufficient for a good resistance to thermal cracking and raveling (Makowska, *et al.*, 2017). H12 cannot be evaluated as no samples were collected after the work. .

4. Thermal control of the process and Finite Element Modelling of heat transfer

Figure 4 shows the hand-held thermal camera temperature readings of road surface upon during hot in-place recycling from the sites on highways H4, H6, H7 and H12. This in-situ data allows for calibrating and validating the Finite Element Method simulations of the in-place recycling. Those simulations are most useful, as they not only allow for reproducing the observed patterns, but also for monitoring the temperatures within the material. The Finite Element modelling also allows to study how to optimally control the heating of the process and to identify the possible best practices, which could be tested in-situ in the future.

The current guidelines for the in-place recycling suggest not to exceed the temperature of 240°C measured at the surface after the heating units passed. However, contractors would like to see that value increased as it would lead to reduction of time and thus reduce the cost of the procedure. Nonetheless, the required maximum temperature of 240°C is consistent with the bitumen ignition temperature and therefore should not be exceeded in the recycling process. Such bitumen ignitions were, in fact, observed in the areas where the suggested temperature had been raised above 240°C. The bitumen ignition leads to generation of smoke which is a health risk for the process operators, it causes permanent damage to the bitumen and decreases environmental friendliness of the process.

It seems that the presence of slag aggregates increases the risk of ignition, as observed on the highway H4, see Figure 4. Yet, the contractor complained that the overall temperature of the processed mixture was too low, even though the measured admixture temperature arriving on site was higher than expected (190°C). Therefore, the contractor's remedy was to reduce the intervals between the grills, which in turn resulted in more bitumen ignitions.

The Finite Element Modelling (FEM) is a numerical method, which allows for studying the effect of the process variables on the hot in-place recycling process. This study takes the flash point of bitumen (which is above 230-240°C (Finnish Asphalt Specifications, 2011) as the risk temperature. Already, the very simple 1D model (Figure 5) created in COMSOL Multiphysics 5.2 allows the surprisingly accurate estimation of the risks during the heating stage of HIR.

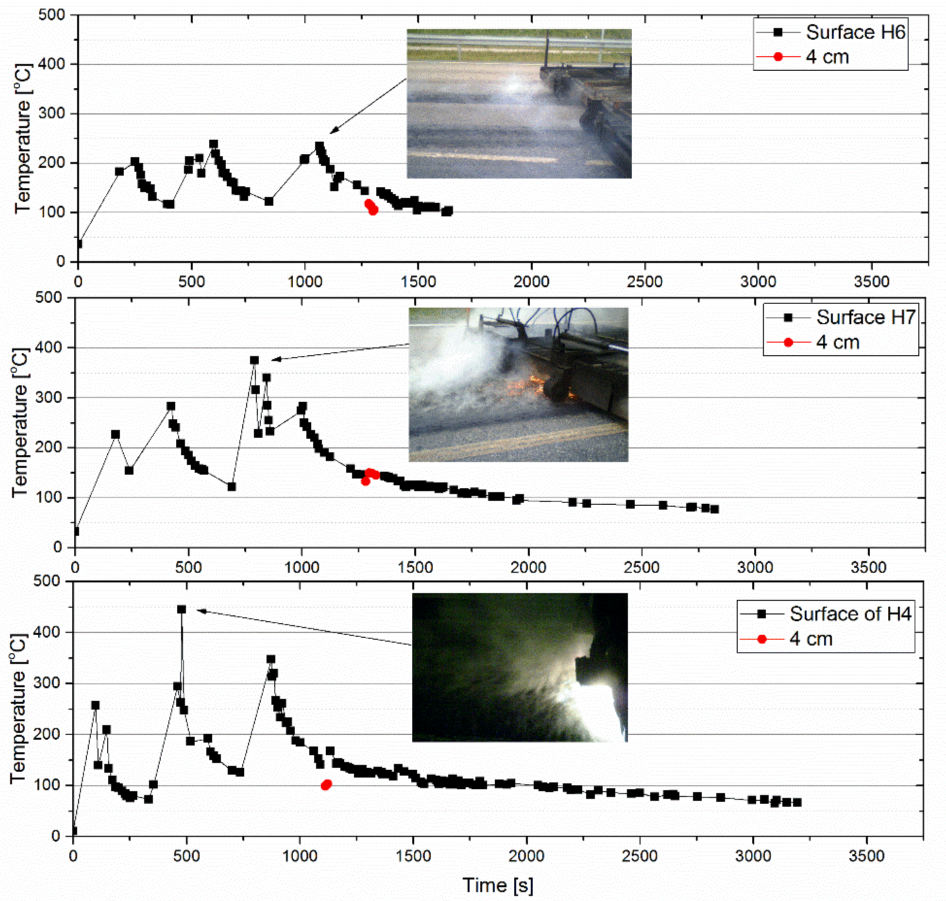

Figure 4. Results from chosen sampling spots during the thermal camera evaluations on roads H4, H6 and H7.

In the calculations the Fourier's law of thermal conduction defined as

$$\vec{q} = -k\nabla T \quad (2)$$

where $\vec{q}$ is the local heat flux density [W/m^2], k is the material's conductivity [W/(mK)] and ∇T is the temperature gradient [K/m]. The time depended heat flux ($Q_b=f(P, t)$) [J] approximates the grill heating. The time of heating is such that it corresponds to the passing of the heating units.

In Scenario 2, we demonstrated how changing just the time interval between the heating units, as practiced in field, affects the surface temperature and affects the risk of ignition (Figure 4). In the last Scenario 3, we explored how such reduced time interval between the heating units coupled with reduced P of each heating unit, while extending the time that each of the units spent above the surface so that Q_b coming from each heating unit is the same as in Scenario 1, influences the risk of ignition.

The heat capacity (C_p) on a per mass basis of material, expressed with an equation

$$C_p = \frac{Q}{\rho * V * \Delta T} \left[\frac{J}{kgK}\right] \quad (3)$$

where Q is the heat (either applied to or radiated by a material), r is the density of the material [kg/m^3], V is the volume [m^3] and DT is the change in temperature of material during heat exchange [K], for the asphalt concrete composite is estimated from the sum of its components – bitumen (2093) and aggregate (920 for limestone and 790 for granite).

The material specific values such as C_p, ρ and k can be estimated based on the analysis provided in Table 2. The k was estimated by using the series, parallel and geometric mean model of particle distribution (Progelhof, et al., 1976) in the composite, using k values for limestone (1.26-1.33), bitumen (0.17) and granite (1.7-4) as an input. The obtained range was between 0.8 and 3.4, with the lower geometric mean result of 1.2. Similar values have been measured (Zhou, et al., 2012) and modelled (Chen, et al., 2015) for coarse graded asphalt concrete, thus the value of 1.2 was used. Definitely, establishing k for asphalt concrete at hand in the laboratory would increase confidence in the results of modeling.

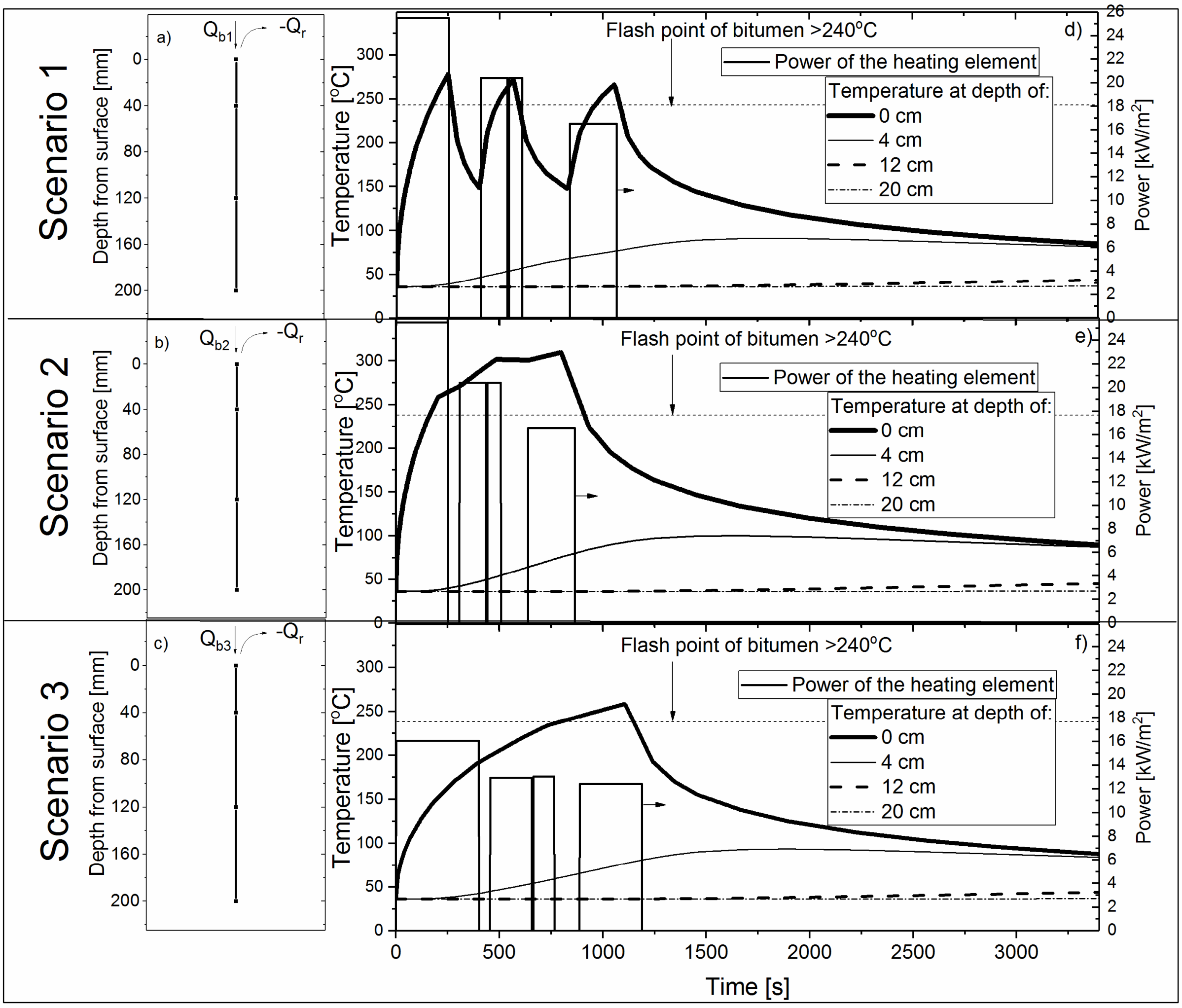

Figure 5. The conditions used as input values and the changes of temperature at chosen vertices in the FEM of heat transport in asphalt pavement during the hot in-place recycling:
a, b, c - the 200 mm 1D road structure used in the calculations for Scenario 1, 2 and 3 where Q_b is the applied heat and Q_r is the radiation; d - the applied heat characteristic, that assured best fit of field collected data with simulation in Scenario 1 and the results of the modelling aimed at reproducing the surface temperature pattern at H6 location; e - The applied heat characteristic used in Scenario 2, depicting the reduction in the time interval between the heating elements during the HIR process while sustaining the same heating Power; f - The applied heat characteristic used in Scenario 3, depicting the reduction in the time interval between the heating elements during the HIR process, while reducing the heating Power and keeping the $Q_{b3}=Q_{b1}$.

Table 3. The summary of parameters used during calculations

Modelling parameter		**Material parameter**		**Environmental parameter**	
Mesh size	Extra fine Maximum element size of 2 mm	Thermal conductivity [W/(m*K)]	1.2	Initial surface temperature (T_{ini}) [K]	309,15
Structure depth [mm]	200	Emissivity coefficient (ε)	0.93 (Ibos, et al., 2006)	Temperature of ambient [K]	293,15
Thermal insulation of the system	At depth of 200 mm	Heat capacity (Cp) [J/(kgK)]	869	Ambient pressure [atm]	1
		Density (r) [kg/m^3]	2450	Wind velocity [m/s]	0
				Ambient solar irradiance [W/m^2]	1000

Based on the data collected from the field investigations and material evaluations, a simplified one dimensional Finite Element Model of heat transfer in the solid structure was created. In this publication data from highway H6 was used as the control input for calculations. As is presented in Table 3, a wide range of parameters affect the outcome of the heating stage in the process. However, a number of those parameters is known before the construction and could be used in simulation. Availability of the crucial parameters in Building Information Models could in the future provide ways to further improve the control of the heating actions.

This article also presented the effect of the change in spacing between the heating units, when the P of each unit was unaltered. That led to the higher end surface temperature substantially increasing the ignition risk. Reduction of intervals between the heating units and their power, while extending the time that each individual heating unit spends above the considered location, according to the FEM would allow for similar consumption of energy, achievement of desired end surface temperature, while minimizing the risk of ignition.

5. Conclusions

1. The Stone Mastic Asphalt and Asphalt Concrete mixes should be divided into separate recycling classes and the rules specific for them should be established separately.
2. Increased attention to the maximum density of the pavement and thickness of the surface course should be paid to assure no transfer of base courses to the wearing course.
3. More attention should be paid to the laboratory processing of the samples used as an input in the evaluation of the success rates of the process.
4. The enhanced level of information about the material was not incorporated into the process. It is suggested that application based educational activities should surround the setting of future requirements.
5. Fast operation of the process lead to increased air voids, despite increasing homogeneity of the wearing course.
6. Finite Element Modelling of heat transport in asphalt is a promising tool allowing for the development of the best heating approach during the hot in-place recycling process.

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Mass ratio of aged to admixture bitumen	Aged pavement	Admixture	Rejuvenator	No aging in the process Pen	Aging during the process Pen*0,8
80/20	80 kg	20 kg	no	x	x
80/20	80 kg	20 kg	250 g/m^2	x	x
60/40	80 kg	53 kg	no	x	x
60/40	80 kg	53 kg	250 g/m^2	x	x