Effect of new type of synthetic waxes on reduced production and compaction temperature of asphalt mixture with reclaimed asphalt

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Abstract. Lowering mixing and paving temperatures of asphalt mixtures, which are an important issue in recent years, with respect to increased energy demand of civil engineering structures during their processing, allow reduction of this demand and result in minimized greenhouse gas production. In present time, there are many possibilities how to achieve reduction of production temperature during the mixing and paving of an asphalt mixture. The existing solutions distinguish in target operating temperature behaviour which has to be achieved in terms of good workability. This paper is focused on technical solutions based on use of new types of selected synthetic and bio-based waxes. In case of bio-based additive sugar cane wax was used, which is free of paraffins and is reclaimed as waste product during processing of sugar cane. The used waxes are added to bituminous binder in form of free-flowing granules or fine-grained powder. Synthetic waxes are represented by new series of Fischer-Tropsch wax in form of fine granules as well as by polyethylene waxes in form of fine-grained powder or granules. Those waxes were used to modify a standard paving grade bitumen dosed into asphalt mixture of ACsurf type containing up to 30 % of reclaimed asphalt (RA).

1. Introduction

First technologies of warm asphalt mixtures (WMA) were available and further tested already about 20 years ago in Europe. It was developed in response to the demand of the road industry to decrease the energy consumptions and reduce the release of greenhouse gases as well as other harmful gases, which cause serious air pollution. Warm mix asphalt is a kind of new pavement material, generally, they are produced and compacted at lower temperatures compared to hot-mix asphalt (HMA). The range of mixing temperature for WMA is 100 °C to 140 °C and this type of mixtures is placed on the temperature scale between hot mix asphalt and cold mix asphalt [1, 2]. The main mechanism of this technology involve the use of organic or synthetic waxes (F-T wax, polyethylene wax, amide wax, Montan wax, fatty acid amides etc.), chemical additives (include combination of emulsification agents, surfactants, polymers, adhesion promoters), foaming techniques (which are divided into water-based and water containing), that helps to reduce the viscosity of bitumen at lower temperature and improve coating, mixture workability, and compaction. In such a way, good workability and reasonable long-term performance of the asphalt mixture should be achieved [3].

Lowering asphalt production emissions in the plant and compaction emissions in the field are one of the most important benefits of utilization of WMA. The properties of bitumen are improved by
means of organic and synthetic WMA additives and the viscous behavior of used binders is changed, which leads to decrease mixing and compaction temperature. [2, 4, 5] The lower production temperature also reduces the ageing of the bitumen during the production stage, which results in an improved thermal and fatigue cracking resistance. [2] For the maximization of the mixing temperature reduction, the best solution for the production of WMA mixtures with the incorporation of synthetic waxes is by using softer base bituminous binders. [6] Consequences shown in this respect by the research [6] was that, the addition of synthetic waxes does not significantly change the water sensitivity of the studied WMA mixtures. The use of these additives increase the stiffness modulus and the rut resistance of the WMA in comparison with the HMA mixture produced with the same bitumen, allowing the use of a softer bitumen to obtain a WMA mixture with a similar performance.

Further, it should be stated that WMA additive enables the utilization of reusing more reclaimed asphalt (RA) in the pavement structure. Variations in RA properties complicate the characterization of the rheological properties of binder, which consists of added virgin bitumen and reclaimed asphalt binder. [4] Based on the study [7], which presents impact of selected types of WMA technologies involved also some kind of organic wax combined in an asphalt mixture with 35 % of reclaimed asphalt, which was applied in real production conditions as well. The results of this study showed that WMA produced with a high RA content is feasible, contributing to the reduction in energy consumption and in costs. The level of mechanical performance of WMA was in this case satisfactory and similar to the values obtained for the HMA used as reference. Nevertheless, the warm-mix with surfactant additive revealed high sensitivity to temperature. WMA with RA can be seen as a suitable alternative to conventional HMA for base and binder layers of pavements. [7]

2. Basic definition of the asphalt mixture variants for surface courses under assessment

2.1. Design of mixture ACsurf 11+ with 30 M% reclaimed material

The reference variant for the starting design of a mixture with 30 M% RA was the ACsurf 11+ mixture of a known and optimised grading curve using aggregate from the Měrunice quarry. The mixture was designed with 5.8 M% bituminous binder. A typical paving grade bitumen 50/70 was chosen as the basic binder for the reference mixture. This reference variant served as the base for asphalt mixture comprising 30 M% sorted reclaimed asphalt of 0/11 mm gradation, sourced from the Měcholupy mixing plant deposit. This is material obtained from various pavements which is subsequently crushed and sorted, i.e. no exact origin and homogeneous composition can be determined for the material. Using asphalt extraction lab procedure, the quantity of bituminous binder in the reclaimed material was determined (5.9 M%) and a grading analysis was performed.

| Labelling of the asphalt mixture | ACsurf 11+ | ACsurf 11+ |
|---------------------------------|-----------|-----------|
| Bitumen                         | 50/70     | 50/70     |
| Bitumen content [%]             | 5.80 %    | 3.60 %    |
| Mix design Content [%]          | In the mix | Content [%] | In the mix |
| Měrunice 8/11 mm                | 21  19.8  23  22.2 |
| Měrunice 4/8 mm                 | 21  19.8  15  14.4 |
| Měrunice 0/4 mm                 | 52  49.0  26  25.0 |
| RA 0/11 mm                      | 0  0.0  30  28.9 |
| Filler                          | 6  5.7  6  5.8 |
| Bitumen                         | 5.8  3.6 |           |
The input characteristics were then used to design mixture AC_{surf} 11+ with 30 M% RA; this allowed determining the quantity of the bituminous binder added. The mixture needed optimisation where the original reference asphalt mixture best corresponds with the variant with a total of 5.4 M% binder, which is the equivalent of 3.6 M% of virgin bitumen 50/70 addition (note: the quantity of binder addition was modified depending on the analysis of the reclaimed material concerned). The mix design and representation of the individual components are indicated in Table 1.

2.2. Definition of low temperature mixtures with selected types of natural and synthetic waxes on test

There are a number of possibilities nowadays of reducing production temperature during the preparation as well as processing of asphalt mixtures using so-called warm mix asphalts. However, they principally differ by their behaviour in the working temperature range which we intend to achieve to ensure sufficient processing. The paper concentrated on the technology of applying a new generation of additives based on selected types of both synthetic and natural (bio-based) waxes. These are added directly to the bituminous binder. The main advantages of using synthetic and natural waxes in asphalt mixtures, or bituminous binders to be precise, are lower viscosity and improved workability under reduced working temperatures while the required asphalt mixture characteristics are maintained. In the case of natural waxes, a product based on sugar cane extract with no paraffin content was used – this is waste from sugar cane processing (hereinafter referred to as “BIT”). The synthetic wax group supplied representatives of a new generation of polyethylene waxes (E-wax). Another option from the synthetic wax range was the RH wax of Chinese origin. The additives were applied to modify the basic binder, paving grade 50/70, used to prepare asphalt mixture type AC_{surf} 11+ which allowed lowering the working temperature to 125-130 °C. Simultaneously, the variants of binders modified by the selected types of synthetic and natural waxes were applied to mixture AC_{surf} 11+ with 30 M% reclaimed asphalt. In the case of the variants with RA, two types of rejuvenating additives were used to ensure activation of the degraded binder in the reclaimed asphalt. The degraded binder had been exposed to oxidative ageing. In case we wish to re-activate the aged binder, a rejuvenator needs to be added to the reclaimed material. We chose a Czech-made rejuvenator, RE182 – refined rape seed oil-based additive, and S-RP1000, a rejuvenator based in tall oil from lignin depolymerisation in pinewood processing. The selected rejuvenators were added to heated reclaimed materials and mixed together; only afterwards was this material combined with new aggregate and the bituminous binder.

3. Selected test methods to examine the cold asphalt mixture behaviours

3.1. Basic characteristics of cold mixture variants

The major asphalt mixture characteristics include the voids content (for mixtures AC_{surf} 11+ the test specimens are compacted by 2x50 blows in the Marshall compactor) and maximum bulk density under CSN EN 12697-8. The individual parameters are listed in Table 2. In compliance with the requirements of the relevant product standard, the voids content in AC_{surf}11+ asphalt mixtures should fall within the range of 2.5-4.5 %. The test specimen preparation temperature was identical for all versions, 150 °C; contrastingly, the compaction temperature could be reduced by 20-25 °C with respect to the application of the individual additives.
Table 2. Determination of fundamental empirical characteristics of assessed asphalt mixtures.

| Asphalt mixture | Mix type acronym | Bitumen | Bitumen content [%] | Temperature for production / compaction | Bulk density [g·cm\(^{-3}\)] | Maximum density [g·cm\(^{-3}\)] | Voids content [%] |
|-----------------|------------------|---------|---------------------|----------------------------------------|--------------------------------|----------------------------------|------------------|
| AC\(_{surf}\)11+ | Ref              | 50/70   |                     | 150/150 °C                            | 2.587                          | 2.692                            | 3.91              |
|                 | 3E               | 50/70 + 3% E-wax | 150/150 °C  | 2.629                          | 2.694                            | 2.44              |
|                 | 2E               | 50/70 + 1.5% RH + 1.5% E-wax | 150/125 °C | 2.588                          | 2.713                            | 2.41              |
|                 | BIT              | 50/70 + 3% BIT  | 150/125 °C | 2.613                          | 2.722                            | 4.00              |
|                 | RefR             | 50/70    | 150/150 °C  | 2.606                          | 2.671                            | 2.45              |
| AC\(_{surf}\)11+ | 3E               | 50/70 + 3% E-wax | 150/130 °C | 2.629                          | 2.677                            | 1.80              |
| 30 % RA RE182   | RR               | 50/70 + 1.5% E-wax + 1.5% RH | 150/130 °C | 2.546                          | 2.632                            | 3.26              |
|                 | 2ER              | 50/70 + 2 % E-wax | 150/130 °C | 2.513                          | 2.605                            | 3.54              |
|                 | BR               | 50/70 + 3 % BIT  | 150/130 °C | 2.560                          | 2.646                            | 3.25              |
|                 | RefS             | 50/70    | 150/150 °C  | 2.609                          | 2.681                            | 2.69              |
| AC\(_{surf}\)11+ | 3ES              | 50/70 + 3% E-wax | 150/130 °C | 2.597                          | 2.665                            | 2.55              |
| 30 % RA S-RP1000| RS               | 50/70 + 1.5% E-wax + 1.5% RH | 150/130 °C | 2.587                          | 2.671                            | 3.16              |
|                 | 2ES              | 50/70 + 2 % E-wax | 150/130 °C | 2.569                          | 2.665                            | 3.58              |
|                 | BS               | 50/70 + 3 % BIT  | 150/130 °C | 2.565                          | 2.673                            | 4.02              |

A superior graphic representation of the voids content obtained is given by Figure 1 which also indicates the limits for minimum and maximum void content in AC\(_{surf}\) 11+ type asphalt mixtures for wearing courses. The reference asphalt mixture as well as the version with 2% E-wax with no reclaimed asphalt met the requirements for the range. This means that in this case, a lower temperature still allows achieving results identical to those of the reference mixture compacted at 150 °C. In the case of the variant with natural BIT wax with no reclaimed asphalt, the voids content of the mixture 5.72 % exceeded the maximum limit for the variable. A high void content might result in poor resistance to water in the wearing course; an asphalt layer of a high voids content is more water-permeable and the connection between bituminous binder and the aggregate deteriorates more easily. With respect to comparing the voids content of asphalt mixtures with RA content, the values are lower than those for mixtures without RA. This is not the case of variant R whose voids content was higher while the standard requirements were met. With a higher dose of E-wax (variant 3E) with rejuvenator RE182, the voids content dropped to 1.88 % to the minimum limit; this suggests that the compaction temperature could be lowered even further to achieve the required optimum.

3.2. Determining resistance to water and frost (ITSR)
The test specimen resistance to water test was conducted in compliance with CSN EN 12697-12 technical standard, applying the modified method under AASHTO T-283 which considers one freeze cycle on top of the standard requirements. The test delivers the ratio of indirect tensile strength of a group of saturated specimens to the indirect tensile stress of a dry specimen group (for ITSR-CSN values see Figure 2, ITSR-AASHTO see Figure 3). The required indirect tensile strength ratio according to CSN EN 13108-1 is currently set to at least 70 % for AC\(_{surf}\)11+ mixtures. Within the framework of harmonised standard review in relation to the wearing course asphalt mixture requirements, this ITSR ratio requirement for this type of mixture is expected to become more stringent, to a minimum of 80 %. However, all of the variants on test exceeded even the 80% limit.
which suggests that the selected variants do not tend to lose indirect tensile strength due to water. The same may be noted for ITSR evaluation under the modified AASHTO test method which currently has no specific requirements in place and is not required by the European standards.

![Figure 1](image1.png)

**Figure 1.** Comparison of voids content for assessed asphalt mixtures and the requirements according to ČSN EN 13108-1 (NA).

From the point of view of assessing the resistance to negative effects of water and frost test on selected mixtures, the generally best results were achieved by ACsurf 11+ mixture with 30 M% reclaimed asphalt and rejuvenator RE182 in all variants, except for BIT mixtures according to the Czech technical standard. In the case of ACsurf 11+ mixtures with 30 M% RA, to which rejuvenator S-RP1000 was applied, the ITSR values are generally similar to the mixtures without RA.

![Figure 2](image2.png)

**Figure 2.** Comparison of water susceptibility test results of assessed asphalt mixtures with the requirements of CSN EN 13108-1 (NA).

![Figure 3](image3.png)

**Figure 3.** Comparison of water susceptibility test results of assessed asphalt mixtures according to AASHTO.

### 3.3. Stiffness modulus test

The next comparison of ACsurf 11+ mixtures without and with reclaimed asphalt was related to the stiffness modulus determination according to CSN EN 12697-26 by the IT-CY non-destructive test of indirect tensile stress on cylindrical specimens. The stiffness values of individual mixtures were determined under three different temperatures (0 °C, 15 °C a 27 °C) and are listed in Table 2. If we focus on the stiffness modules measurements, the essential ones, according to the usual application of the characteristic in the Czech pavement design manual, are those taken under the temperature of
15 °C – the determining temperature from the perspective of pavement structure design under Czech technical conditions TP 170.

Figure 4. Comparison of stiffness @ 15 °C for tested asphalt mixtures.

The stiffness results measured on unaged test specimens at 15 °C (see Figure 4) clearly show that the lowest values were taken for the mixture with 30 M% reclaimed asphalt with RE182, except for the reference mixture variant which recorded its highest stiffness modulus at 15 °C. In the case of the highest scores for the characteristic, we can conclude that aside from the aforementioned reference mixture and 3E variant, the highest stiffness values were achieved by the mixture variants with reclaimed asphalt which included rejuvenator S-RP1000. The stiffness values taken are rather high (the minimum stiffness modulus value for HMAC mixtures with required high stiffness modulus is set by the standard to 9,000 MPa, this limit would be met even by the asphalt mixture for wearing courses), which, from the perspective of long-term behaviour in the pavement structure, could potentially have negative impact due to reduced life under cold temperatures (increased cracking risk).

Another characteristic assessed in the case of the stiffness modules measured at varying temperatures could be the indicator of thermal susceptibility of the asphalt mixture (Table 3). The lower the $S_{0}/S_{27}$ stiffness ratio, the less susceptible the mixture is to temperature changes. In the case of mixture variants with no reclaimed asphalt, the lowest susceptibility was measured for the reference mixture and, contrastingly, the highest susceptibility was taken for the variant with a combination of two waxes. Focusing on thermal susceptibility in variants with RE182, the lowest susceptibility was noted for the reference asphalt mixture while a double value with the greatest thermal susceptibility and, therefore, the highest difference between the stiffness modules measured at 0 °C and at 27 °C, was recorded for mixture 2ER, which contained a lesser quantity of E-wax. For mixtures with rejuvenator S-RP1000, the RS variant had the lowest thermal susceptibility while 2ES had the highest thermal susceptibility indicator.

A part of the measurements taken within the experimental study was also dedicated to a laboratory simulation of long-term asphalt mixture ageing which was applied to the test specimens within the framework of the stiffness modulus test. The ageing simulation utilised one of the possible methods viable for standard road construction laboratories at the moment. A simple method where the cylindrical test specimens are put in a thermal chamber with forced air circulation at 85 °C for 5 days (120 hours) according to the method as stipulated in the prEN 12697-52 standard. The comparison of the stiffness modulus values measured in the test specimens exposed to ageing (see Figure 5) suggests that, with respect to the incomplete data set, the highest stiffness modulus value was achieved by the variants with S-RP1000. The asphalt mixtures with RE182 recorded a drop in comparison to the variants with no RA. However, the results have not been verified for all of the variant designs.
Table 3. Determination of stiffness modulus of assessed asphalt mixtures.

| Asphalt mixture | Mix type acronym | Bitumen content [%] | Stiffness modulus [MPa] @ T= | Thermal susceptibility S0/S27 [-] | Voids content [%] |
|-----------------|------------------|---------------------|-----------------------------|---------------------------------|------------------|
| ACsurf 11+      | Ref              | 50/70               | 23 627 8 755 3 138          | 7.53                             | 3.91             |
|                 | 3E               | 50/70 + 3% E-wax    | 23 735 9 858 2 820          | 8.42                             | 2.44             |
|                 | R                | 50/70 + 1.5% RH + 1.5% E-wax | 5.8 | 22 092 7 192 1 961 | 11.26 | 2.41 |
|                 | 2E               | 50/70 + 2% E-wax    | 20 840 7 647 2 257          | 9.23                             | 4.00             |
|                 | BIT              | 50/70 + 3% BIT      | 20 347 7 290 2 245          | 9.06                             | 5.72             |
|                 | RefR             | 50/70               | 22 770 11 525 4 270         | 5.33                             | 2.45             |
| ACsurf 11+ + 30% | 3ER              | 50/70 + 3% E-wax    | 19 662 6 511 2 371          | 8.29                             | 1.80             |
| RA RE182        | RR               | 50/70 + 1.5% E-wax + 1.5% RH | 3.4 | 17 629 5 697 1 855 | 9.50 | 3.26 |
|                 | 2ER              | 50/70 + 2% E-wax    | 16 461 4 745 1 565          | 10.52                            | 3.54             |
|                 | BR               | 50/70 + 3% BIT      | 18 560 7 043 2 226          | 8.34                             | 3.25             |
|                 | RefS             | 50/70               | 24 895 9 676 3 337          | 7.46                             | 2.69             |
| ACsurf 11 + 30% | 3ES              | 50/70 + 3% E-wax    | 23 611 9 696 3 161          | 7.47                             | 2.55             |
| RA S-RP1000     | RS               | 50/70 + 1.5% E-wax + 1.5% RH | 3.6 | 22 770 11 358 3 945 | 5.77 | 3.16 |
|                 | 2ES              | 50/70 + 2% E-wax    | 22 629 9 257 2 793          | 8.10                             | 3.58             |
|                 | BS               | 50/70 + 3% BIT      | 20 861 8 956 3 031          | 6.88                             | 4.02             |

Figure 5. Comparison of stiffness @ 15 °C for aged tested asphalt mixtures.

3.4. Comparison of the results from the perspective of resistance to crack propagation

The comparison of the results of resistance to crack propagation by the bending test on semi-cylindrical test specimens in compliance with CSN EN 12697-44 is indicated in Figure 6. The only difference to the mentioned standard is, that 100 mm diameter test specimens were used. With respect to the assessment of low-temperature asphalt mixture behaviour in the low temperature range, the critical fracture toughness values for mixtures with reclaimed asphalt and RE182 record almost the same course as in the case of mixtures with S-RP1000. Only the variant with a combination of waxes RH + E-wax had a lower result (mixture with RE182). The values of mixture resistance to crack propagation in relation to both rejuvenator types show no influence of the higher stiffness values as
measured which would induce a lower resistance in the low temperature range; this might be obvious from the results taken after the long-term ageing simulation.

![Figure 6. Comparison of fracture toughness @ 0 °C for tested asphalt mixtures.](image)

The critical fracture toughness values were also measured for aged test specimens. The test, aiming to determine the asphalt mixture resistance to crack propagation by bending on semi-cylindrical specimens, was conducted with the Marshall test specimens compacted by 2x50 blows in the compactor and subjected to an ageing cycle. The laboratory simulation of long-term ageing was performed according to the method described in prEN 12697-52. For the comparison of mixture resistance to crack propagation prior to and after the ageing simulation, it is obvious that ACsurf 11+ mixtures without reclaimed asphalt record increased critical fracture toughness values due to the ageing. The same trend can be seen in ACsurf 11+ mixtures with reclaimed asphalt and RE182. The opposite trend is visible in the case of variants with S-RP1000 where the critical fracture toughness value fell as a consequence of ageing.

4. Conclusion

The experimental tests taken and the comparison of the individual low-temperature mixture variants including the determination of selected functional asphalt mixture characteristics depending on a lower compaction temperature (i.e. asphalt mixture production temperature) yield the following findings. The application of a new generation of synthetic/natural waxes should primarily achieve a reduction in the production and paving temperature for the asphalt mixes; this has been verified as viable based on the results as presented. With respect to the parameters examined, the application of selected types of natural and synthetic waxes in asphalt mixtures for wearing courses using reclaimed material allows reducing the compaction temperature in the laboratory while maintaining the quality of common hot asphalt mixtures. This, as a consequence, facilitates a more favourable recycling of reclaimed material which would not have to be heated to extremely high temperatures; that, in turn, would prevent excess degrading thereof. Simultaneously, this opens the option of a more effective use of rejuvenators. Nonetheless, some variants of the asphalt mixture designs with various waxes and reclaimed asphalt, the void contents were lower than the minimum value required by the relevant product standard; this points out the potential for an even bigger reduction of the compaction temperature, or for a reduction of the additive dose. At the same time, no significant deterioration in the functional characteristics examined was observed for any of the assessed mixture variants.

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