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USE OF RECYCLED ASPHALT AND WASTE MATERIALS IN PRODUCTION OF HIGH-PERFORMANCE ASPHALT MIXTURES

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Abstract. The research has been conducted to test the asphalt produced in Latvia using local mineral materials and local recycled modifiers (fiberglass, crumb rubber), as well as the recycled asphalt used in the production of high-modulus asphalt mix, which will meet the local Latvian road construction specifications and will be economically, environmentally and technically more attractive. In the theoretical part, the available sources were studied to establish a theoretical framework, assess possibilities for using recycled materials, define the concept of fiberglass, and consider its performance in asphalt mixes. During the experimental stage of the research, different asphalt mix formulas with glass fiber, crushed rubber, RAP, and other additives used to stabilize asphalt mixtures for surface and base layers were designed in the laboratory; they were compared to the reference mixes using performance tests. Then the mixtures with the best results were used in the test section of a high-intensity local road. The samples of the asphalt layers of the paved test section were tested as well. Two asphalt mixes were designed according to local Latvian road-building specifications, using fiberglass reinforcement 0.15% +

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30% RAP for the base layer and crushed rubber 15% and RAP 30%+EVOFLEX CA© variable for the surface layer. The aim of the research is to offer solutions for reducing new asphalt pavement production allowing for the use of recycled asphalt mixes in local road building. The performance tests of the test asphalt mixes showed that recycled asphalt pavement fully meets the requirements of the local Latvian road-building specifications.

Keywords: circular production, recycled asphalt, asphalt mix, glass fiber, reinforcement, crumb rubber, RAP, HMAC.

Introduction

Taking into consideration that more than 90% of European roads are covered with asphalt, the European asphalt industry has the potential to become a key player in the recycling process, given that it is already active in various fields in building a climate-neutral future. Reuse and recycling of asphalt pavements are now well-established and commonly applied practices in Europe. Asphalt materials are 100 % reusable in new asphalt pavement materials without any loss of their original functionality. (European Asphalt Pavement Association, 2019)

While re-use of RAP with standard bituminous binders amounting to up to 50 % addition rates is already successfully implemented, new challenges are arising. Over recent years, more polymer-modified and harder-grade varieties of bitumen have been used in asphalt production (Radenberg, Boetcher, & Sedaghat, 2016); therefore, reclaimed asphalt based on these varieties may not be adequately reused using a 'standard' technology. In this context, the industry has clearly identified a need for new technologies in order to meet the coming needs and technical requirements. (European Asphalt Pavement Association, 2018)

High-modulus asphalt concrete (HMAC) mixtures are produced using hard-grade binders or modified bitumen, they are known to have exceptional resistance to rutting and fatigue. Due to the similarity between the hard binder and aged reclaimed asphalt pavement binder, HMAC mixtures have great potential to incorporate higher percentages of RAP material. The hard-grade binder makes HMAC mixtures highly susceptible to low temperature cracking failure (Geng et al., 2013; Rys, 2017).

Despite the benefits of RAP mentioned earlier, using it in large amounts can reduce the quality of an asphalt mix, lowering its properties in cracking resistance and undermining its low-temperature performance due to the aged binder of RAP (Tran et al., 2012; Mallick et al., 2010; Shu et al., 2010). Therefore, scientists and engineers are constantly trying to improve the performance of asphalt mixtures containing RAP (Fitzgerald, 2000). Modification of the asphalt binder is one of the methods to improve pavement performance (Abtahi et al., 2009). Commonly, fibers and polymers are two most popular materials used for this purpose (Kim, 2009; Wu et al., 2008), they are also used in asphalt concrete mixes. The most popular bitumen modification technology is polymer modification (Airey, 2004) (Yildrim, 2007), but considering high costs of PMB and unpredictable pricing policy, there is a need for a cheaper but stable modifier. It has been argued that among various modifiers for asphalt, fibers have received much attention for their improving effects (Hejazi, 2007).

Circular economy is one of the solutions for reducing production of new asphalt pavements while keeping road quality at high level, its principles can be used in industrial asphalt production. The circular economy aims to replace the existing systems that take resources for use in modern industrial models. Within a circular system, waste and pollution are designed out, aggregates and raw materials are kept in use, and the natural system is regenerated (Drinkwater, 2016) (Pasquale, 2019).

Asphalt pavement renewal process using the principles of circular economy is demonstrated in the figure below.

The paper has focused on optimization of the individual steps of the process chain, starting from the milling of asphalt pavement regained from local roads to the production of the new hot asphalt containing recycled asphalt. This type of production can lead to great

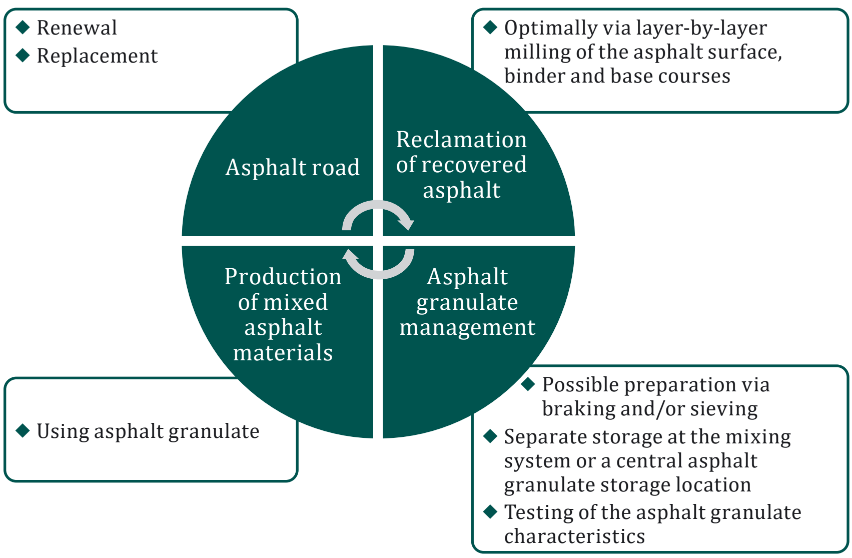

Figure 1. Principles of the circular economy for asphalt pavement renewal used in the trial stage of P2 road

environmental savings in terms of CO_2 emissions, socioeconomic savings in terms of reduced import of raw materials, and saving of quarry reserves at the same time without compromising the quality of the asphalt product.

This research paper reflects on the recycling principles used in road construction and asphalt mixture production in Latvia with an aim to develop new recipes and methods of HMAC production using recycled materials and aggregates, such as RAP, fiber glass, and crumb rubber. The developed mixtures should demonstrate performance properties according to Latvia's Road Specifications (VAS "Latvijas Valsts ceļi", 2020) (VAS "Latvijas Valsts ceļi", 2021).

The main aim of this research paper is to initialize production of high-performance recycled asphalt in Latvia without compromising the functionality and durability of the asphalt pavement.

The following objectives were set:

- To produce three types of experimental mixtures using RAP from local roads, such modifier as crumb rubber and fiber, and binder modifier, in laboratory circumstances for each asphalt layer;
- To assess the properties of experimental mixtures according to LVS EN (European standards adopted by Latvia) and compare them to the reference mixtures;
- To choose the most acceptable experimental mix for each course to be used in the trial pavement;
- To assess compliance of the plant produced experimental mixtures to LVS EN;
- To make conclusions and recommendations for further integration in production of the recycled asphalt pavement.

1. Materials

1.1. Reference mixtures

The reference mixtures were designed according to the requirements of Latvian Road Specifications. For two-layer asphalt pavement, two reference asphalt mixes were designed – HMAC 16 25/55-60 which uses fractioned local dolomite 8/11 with LA – 25 as virgin aggregate and BBTM 11A PMB 45/80-55 (Béton Bitumineux Très Mince (French: Very Thin Bituminous Concrete)) with granite as aggregate, for base and surface layer, respectively. Table 1 shows the physical properties of both mixtures. Maximum density and bulk density were obtained using LVS EN 12697-6, A and B methods respectively (European Committee for Standardization, 2020a). Table 2 and Table 3 show granulometric gradations of the reference mixtures.

1.2. Research mixtures

In the course of research, two mixtures were produced for each layer using laboratory equipment. RAP and glass fibers were used for the base layer mixtures and dry process crumb rubber, RAP and two types of rejuvenators (Evoflex CA© and 160/220 bitumen) were used form the surface layer. Physical properties of the designed research mixtures are given in Table 4.

Glass fibers amount in the research mixtures makes 0.15% of the total volume. The material was obtained from Valmiera Glass Group (Glass fibre benefits, 2021). Physical properties of glass fiber used in this research are listed in Table 5. Used glass fiber is a by-product of the main factory products and therefore it could be a good solution to integrate material as a secondary raw material instead of utilizing it.

Crumb rubber used in this study was acquired from Storimpex AsphalTec GmbH. The material is a pre-treated crumb rubber that can be used to modify asphalt mixes or bitumen during dry or wet processing.

Table 1. Physical properties of the reference mixtures

Mix	Thickness, mm	Compaction T °C	Max. density, Mg/m³	Bulk density, Mg/m³	Bitumen content, %
BBTM 11A PMB 45/80-55	30	150±5	2.472	2.368	5.7
HMAC 16 25/55-60	50	150±5	2.481	2.388	4.5

Table 2. Gradation table for HMAC 16 25/55-60 mixture

Sieve size, mm	<0.063	0.063	0.125	0.25	0.5	1.0	2.0	4.0	5.6	8.0	11.2	16.0	22.4
Passing, %	4.8	8.1	10.2	16.4	27.3	34.4	41.6	52.3	61.8	71.6	80.6	95.8	100

Table 3. Gradation table for BBTM 11A PMB 45/80-55 mixture

Sieve size, mm	<0.063	0.063	0.125	0.25	0.5	1.0	2.0	4.0	5.6	8.0	11.2	16.0
Passing, %	0.0	14.4	17.1	19.8	22.4	26.1	32.9	44.9	56.0	72.8	90.7	100.0

Dry processing was used during this research. This simple and low-cost technology reduces the amount of asphalt filler required by replacing part of it with rubber. Crumb rubber is added directly during production, which allows reducing CO emissions as compared to wet processing. Crumb rubber grants the same properties to asphalt mixtures as polymer-modified bitumen. It also improves low-temperature properties and rut resistance of asphalt mixes modified in that manner and simultaneously lowers noise emissions. This type of crumb rubber can be used for both less-frequently used roads and asphalt pavements subjected to extreme loads, such as motorways or industrial areas (Additives, Rejuvenators and Rubber Modified Asphalt, 2021).

Rejuvenators are used to stabilize aged bitumen in RAP. In this research, two types of rejuvenators were used – Evoflex CA© and 160/220 PMB. A soft 160/220 polymer modified bitumen was selected as rejuvenator in order to stabilize hard, aged bitumen from RAP.

Evoflex CA© is an engineered additive for recycled asphalt materials that maintains the overall low temperature binder characteristics. Users of EVOFLEX CA can increase the amount of recycled asphalt pavement (RAP). The additive increases the motility of the asphalt in recycled

Table 4. Physical properties of research mixtures

Mix	Thickness, mm	Compaction T °C	Max. density, Mg/m^3	Bulk density, Mg/m^3
BBTM 11A 70/100 (RA 30%+EVOFLEX CA©) (CR 15%)	30	150±5	2.470	2.400
BBTM 11A 70/100 (RA 30%+160/220) (CR 15%)	30	150±5	2.493	2.410
HMAC 16 PMB 25/55-60 (RA 30%) – 18/0.15	90	150±5	2.498	2.443
HMAC 16 PMB 25/55-60 (RA 60%) – 18/0.15	90	150±5	2.503	2.402

Table 5. Physical properties of glass fiber

Feature	Unit	Value
Density	g/cm^3	2.58
Tensile str.	MPa	3445
Compressive str.	MPa	1080
Softening temp.	°C	846

materials and improves coating and workability with a wide variety of aggregates. EVOFLEX CA is a liquid product over the full range of typical ambient production temperature conditions (Maximizing Recycled Binder, 2021).

Table 6 presents some information about the properties of rejuvenator Evoflex CA©.

RAP material was milled from the trial stage of local P2 Jugla Paper Factory village – Upesciems road (1.9–2.1 km) and used in the quantity of 30–60% of the total capacity of research mixes. RAP material was fractioned into three batches with fractions of 0/5, 5/8, and 8/16. Tests were made according LVS EN 12697-2 Standard (European Committee for Standardization, 2015).

The granulometric compositions of RAP material were tested, the results are given in Table 7.

Table 6. Physical properties of rejuvenator Evoflex CA©

Feature	Unit	Value
Physical form	–	Liquid
Density	g/cm³	0.839
Specific gravity g/cm³	g/cm³	0.94
Flash point	°C	190

Table 7. Granulometric composition of RAP material

Fraction \ Sieve size, mm	<0.063	0.063	0.125	0.25	0.5	1.0	2.0	4.0	5.6	8.0	11.2	16.0
0/5	0	21.6	27.3	32.4	37.2	45.4	61.3	86.8	99.9	100	100	100
5/8	0	10.4	11.9	13.5	14.6	16	18	21.3	39.3	100	100	100
8/16	0	11.7	12.6	13.6	14.4	15.3	16.8	18.7	20.9	36.9	81.8	100

2. Methodology

The research comprised three main stages. At the first stage, the mixes containing recycled materials (research mixtures) were designed, which theoretically would have matching properties with the reference mixtures. Mixtures were designed adopting the Marshall method.

Then reference and research mixtures were produced in laboratory conditions and tested for performance. The types of performed tests are given in Table 8. All specimens were tested for compliance to local LVS EN standards.

Test results showed that HMAC 16 PMB 25/55-60 (RA 30%) – 18/0.15 for the base layer and BBTM 11A 70/100 (RA 30%+EVOFLEX CA©) (CR 15%) for the surface layer demonstrated sufficiently good performance values compared to the reference mixtures. These mixtures were selected for further research (third stage) and produced in industrial volumes using asphalt factory in order to use the mixes in the trial stage of P2 road. Experimental part is further described in Chapter 3.

At the third research stage, it was necessary to perform trials on the real road. After the trial pavement was completed, asphalt specimens were drilled directly from the new construction. The taken specimens were tested for performance with extended test list given in Table 9.

Table 8. Performance tests conducted on laboratory produced specimens

Test	Standard
Low temperature cracking	LVS EN 12697-46
Rutting	LVS EN 122697-22, method B
Moisture susceptibility	LVS EN 12697-12, method A
Semi-circular bend	LVS EN 12697-44
Four point bending test	LVS EN 12697-24

Table 9. Performance tests conducted on the plant produced specimens drilled from the trial site

Test	Standard
Low temperature cracking	LVS EN 12697-46
Rutting	LVS EN 122697-22, method B
Moisture susceptibility	LVS EN 12697-12, Method A
Semi-circular bend	LVS EN 12697-44
Void content of compacted layer	LVS EN 12697-8
Skid resistance	LVS EN 13036-2:2010A

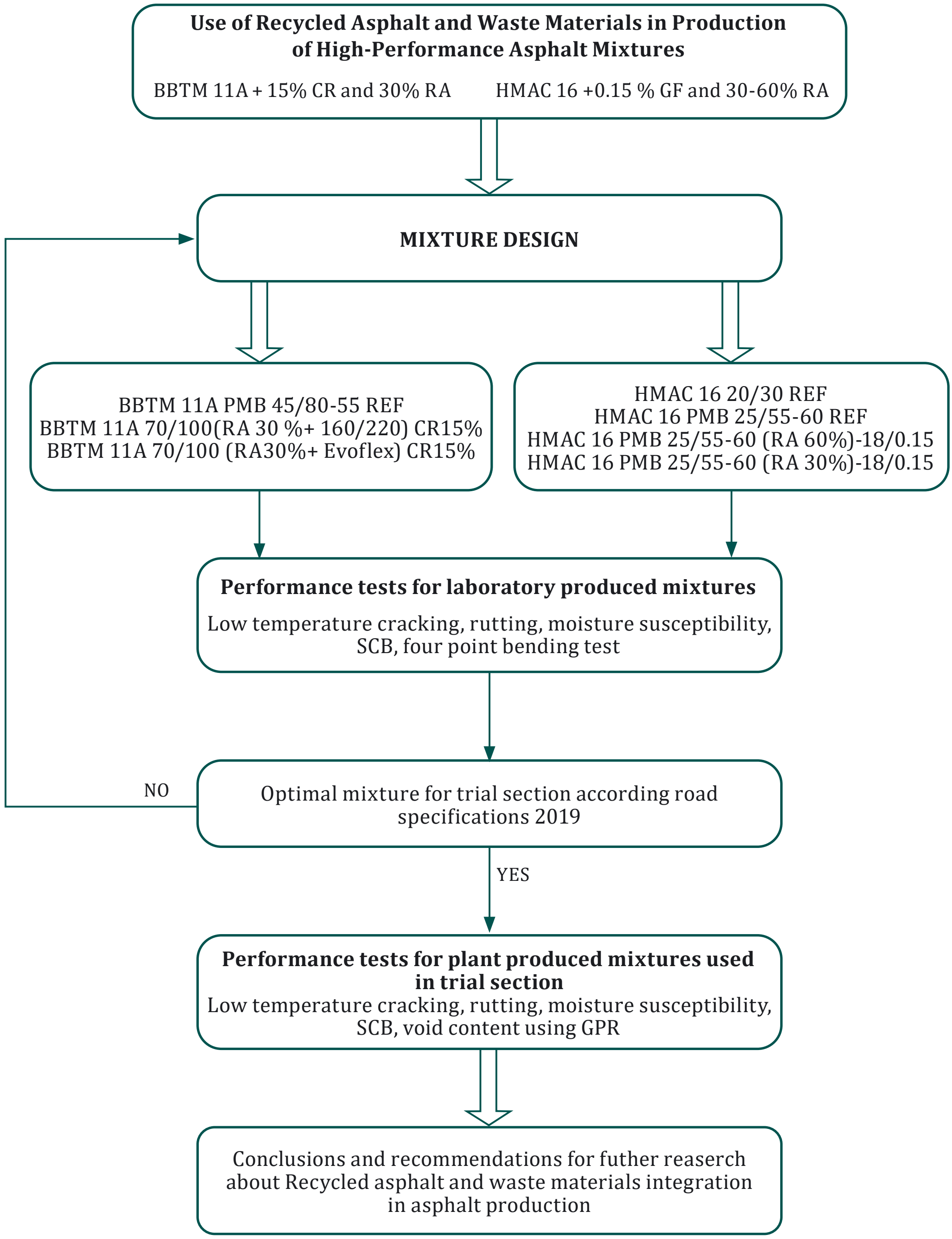

Figure 2. Flow chart of the research process

The collected data and results were analyzed to make conclusions and find matches with the requirements of Latvian Road Specifications in order to further put the research mixtures in practical use.

A flow chart representing the research process is given in Figure 2.

2.1. Low-temperature cracking

Thermal stress restrained specimen test (TSRST) was performed according to EN12697-46 (VAS "Latvijas Valsts ceļi", 2021) to determine the low-temperature cracking performance of the mixtures. The test was conducted by keeping the length of the specimen constant and reducing the chamber temperature until the sample generated cracks due to thermal stress. The initial test temperature was 20 °C and the temperature reduction rate was 10 °C/h until specimen failure. The specimens for the test were prepared by sawing the slabs to the required dimensions (160 mm × 50 mm × 50 mm). For each mixture, the average value was reported according to standards (Izaks et al., 2020) (European Committee for Standardization, 2020b).

2.2. Rutting (Wheel Tracking Test)

The wheel tracking test was conducted in dry conditions according to EN 12679-22 to determine the rutting susceptibility of the mixtures. This test was conducted at 60 °C by applying a load of 700 N using a rubber tire and recording the rut depth using two linear variable deformation transducers (LVDT). The test was run up to 10 000 load cycles. The results of this test indicate rut depth for a single sample tested for each mixture (European Committee for Standardization, 2003a).

2.3. Moisture susceptibility

The tensile strength ratio of bituminous mixtures indicates their resistance to moisture susceptibility and measure of water sensitivity. Moisture damage in bituminous mixtures refers to the loss of serviceability due to water presence. Thus, higher TSR (Tensile Strength Ratio) value indicates good resistance to moisture. Respectively, the higher TSR value, the lesser will be strength reduction by the water soaking condition, or the more water-resistance a mixture will be (Naik, 2017).

The indirect tensile strength test was carried out to determine the effect of reduced temperature on moisture susceptibility of the mixtures according to EN 12697-12 (European Committee for Standartization, 2008). For moisture susceptibility evaluation, Marshall samples were prepared using 35 blows on each side. According to the standard, a test temperature of 5–25 °C can be used for moisture susceptibility evaluation. In this study, a test temperature of 22 °C was used, which was also the measured room temperature, and this was selected to avoid temperature changes in the specimen during the test. The indirect tensile strength of the mixtures was evaluated according to EN 12697-23 (European Committee for Standardization, 2003b). The average of three specimens was reported in the results. The ratio of the indirect tensile strength of wet specimens and dry specimens was calculated and expressed as a percentage to determine the moist damage in the mixtures (Rathore, Haritonovs, & Zaumanis, 2021).

2.4. Semi-circular bend

SCB test is used to assess the fracture toughness of asphalt mixtures. It was performed according to EN 12697-44 (European Committee for Standartization, 2019b). The test was carried out on semi-circular samples that were drilled from the asphalt slab and cut to the required height of 50 mm. Semi-circular samples were then prepared by cutting 150 mm cores in half, a 100 mm notch was cut at the center of the straight edge. As defined by the standard, the test was run at a constant deformation rate of 5.0 mm/min at 0 °C until sample failure (Zaumanis & Valters, 2020).

2.5. Void content of compacted layer

Void content for the sample produced at the laboratory was tested according to LVS EN 12697 – 8 (European Committee for Standartization, 2019a).

Void content of the compacted layer was measured by ROAD DOCTOR Survey Van with ground penetration radar, the data were processed by ROAD DOCTOR v3.4.49 software.

GPR or Ground Penetrating Radar is a geophysical tool emitting short electromagnetic pulses from the radio spectrum and detecting the reflected signals from subsurface structures. The generated pulse is cone shaped. The method consists in determination of the difference of speed of light in different types of materials. The methods involved are similar to reflection seismology, except that electromagnetic energy is used instead of acoustic energy, and reflections appear at the boundaries with different dielectric constants instead of acoustic impedances (O‘Neal & Dunn, 2007; Huisman et al., 2003).

The following factors can be mentioned as advantages of GPR:

- High recording speed;
- Non-destructive and non-coring method. There is no need to drill samples from a newly built road construction;
- GPR is fast and precise method for analyzing the whole section instead of point drillings.

Some disadvantages can be mentioned as well:

- Low penetration in high conductivity ground, for example, clay;
- High concentration of water may cause inaccuracies in radargram.

2.6. Skid resistance

Skid resistance was measured by grip tester for each driving lane at the length of 200 m. Testing machine had a constant speed of 60 km/h, it measured skid resistance index every 10 meters. Skid resistance performance was measured six weeks after the surface layer was laid. Then linear graphic was made for both lanes and average skid resistance index was calculated.

2.7. Four point bending test

The higher content of high modulus binder used in asphalt mixtures makes these mixtures resistant towards fatigue cracking. However, inclusion of high content of RA material may reduce fatigue resistance of asphalt mixtures. To evaluate the fatigue resistance and acquire stiffness modulus for HMAC mixtures, the four-point bending test was performed according to EN 12697-24 (European Committee for Standartization, 2018). To perform the test, it is necessary to produce special prismatic specimens made from laboratory compacted asphalt samples. This test was conducted in strain-controlled mode at the loading frequency of 10 Hz. The specimens were subjected to a sinusoidal loading at strain amplitude in the range of 50–400 μm/m. Before testing, all specimens were conditioned at testing temperature for at least 2 h and the test was conducted at 10 °C. The fatigue cycles cause microcracking of the specimen and decrease stiffness modulus of the beam. The test is run until the stiffness modulus reached half of its initial value or until the specimen broke. Fatigue life (Nf) is defined as the number of cycles required to reach the stiffness modulus in a specimen to 50% of its initial value. The test was also run at 50 μm/m amplitude for all mixtures up to 1000 cycles to measure the stiffness modulus of HMAC mixtures as required by SPENS 2009 specifications (Izaks et al., 2020) (European Commission DG Research, 2009).

3. Results and Discussion

3.1. Low-temperature performance

According to the 2019 road specifications of the Latvian State Roads, in order to meet the required parameters for low-temperature cracking ($TSRST_{min}$), samples for the base or binder layers should perform at temperature which is lower than −20 °C, but for the surface layer this temperature should be below −22 °C (VAS "Latvijas Valsts ceļi", 2020).

The results of critical cracking temperature within TSRST are illustrated in Figure 2 and Figure 3 for the base and surface layers, respectively. The reference mixture is marked in orange. The test

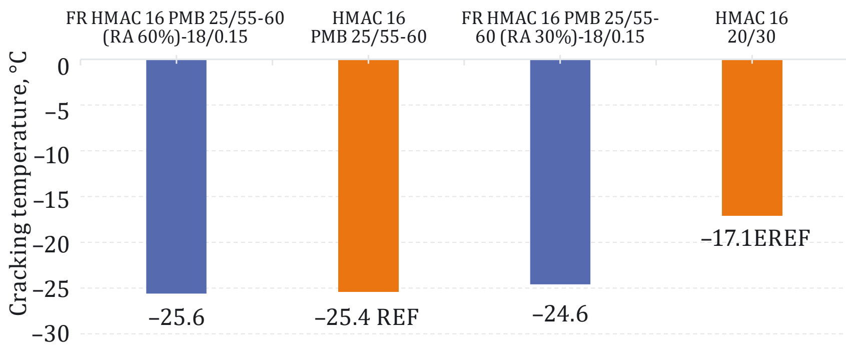

Figure 3. Low-temperature cracking performance results for the base layers

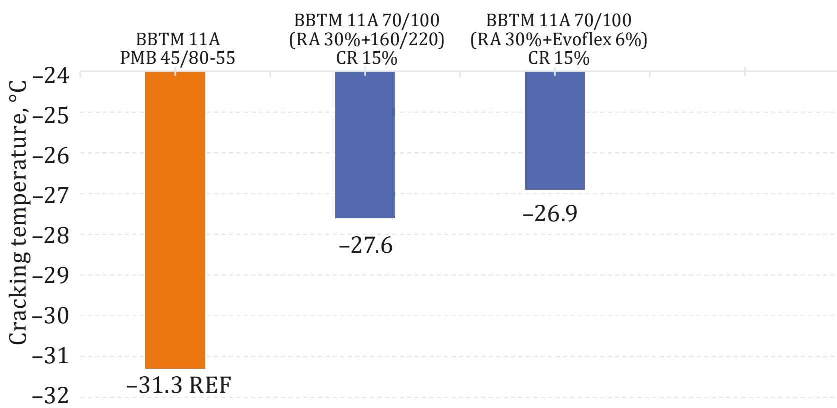

Figure 4. Low-temperature cracking performance results for the surface layers

results vary between −24.6 °C and −31.3 °C and are highly sensitive to the materials that were used in the mixes and proportions thereof. Extra reference HMAC 16 20/30 with the result of −17.1 °C does not meet the established requirements in this case. HMAC 20/30 reference was taken from the research conducted by Izaks, Haritonovs and Zaumanis on the effect on RAP amount on HMAC performance in order to confirm correlations described in the paper mentioned above (Izaks et al., 2020).

It should be noted that distribution of results for individual parallel samples did not exceed 2 °C allowed by the standard. Due to the small number of samples, statistical analysis was not conducted.

The obtained data show that all samples meet the requirements laid down in specifications. It was expected that surface mixes would show better results due to higher binder content. It is important to note that using RA material in 60% of the total mass does not have a significant effect on the binder polymer network. High RAP content does not significantly affect the formation of cracks at low temperatures compared to 30% RAP content, therefore, it can be assumed that the use of PMB in the Nordic countries is economically advantageous. All base layer sample results have shown very similar performance and met the requirements of Road Specifications.

When comparing mixtures for the surface asphalt layer, one can see that additions do not significantly improve mixture performance. The reference sample showed the highest cracking resistance of −31.3 °C while surface asphalt samples with RA material combined with crumb rubber or Evoflex CA© additive showed significantly lower results (−27.6 °C and −26.9 °C, respectively). These results, however, are much better than the required indicators.

TSRST is a widely used testing method for characterization of low-temperature cracking performance of asphalt mixtures. The previous researches and experiments have shown that this parameter is sensitive to binder grade, state of ageing and aggregate characteristics (Jung & Vinson, 1993; Jung & Vinson, 1994; Witsuba, Mollenhauer, & Metzker, 2009; Zaumanis et al., 2018).

3.2. Wheel tracking test performance

Wheel tracking test results showed that all samples demonstrate very good performance against deformations. In order to meet the requirements of Road Specifications 2019 for most intensive roads in Latvia, WTS_{air} index (deformation speed mm / 1000-wheel crossing cycles) should be less than 0.1 mm/1000 cycles.

Test results vary between 0.03–0.18 mm/1000 cycles for WTS_{air} and 2.6–13.7 % for PRDair. All samples except FR HMAC 16 PMB 25/55-60

(RA 60%)-18/0.15 meet the requirements for the most intensive road stages with AADT>5000 intensity. The base layer sample with 60% RA material can be used in road stages of AADT 3501-5000 intensity with result of 0.18 mm/100 cycles. The best result was demonstrated by sample BBTM 11A 70/100 (RA30% +160/220) (CR 15%), which is slightly better than the reference mixture of BBTM 11A PMB 45/80-55. Experiments have shown that the higher content of RA material cause an increase in deformations. The amount of fiber glass can be used as stabilizer and reinforcement to allow using RA materials in the amount of 30%. Fiber glass did not show any positive effect in case of using a

Table 10. Wheel tracking test performance results for the tested samples against the requirements of Road Specification 2019

	Mix type	WTS_{air}, mm/1000 cycles *	PRD_{air}, %	Requirements of Road Specification 2019 WTS_{air}				
				AADT <500	AADT 501-1500	AADT 1501-3500	AADT 3501-5000	AADT >5000
Base layer	FR HMAC 16 PMB 25/55-60 (RA 30%)-18/0.15	0.08	2.6					
	FR HMAC 16 PMB 25/55-60 (RA 60%)-18/0.15	0.18	5.1					
	HMAC 16 PMB 25/55-60 REF	0.06	2.9					
	HMAC 16 20/30	0.06	4.5	1.00	0.8	0.5	0.3	0.1
Surface layer	BBTM 11A 70/100 (RA30% +160/220) (CR 15%)	0.03	8.9					
	BBTM 11A 70/100 (RA 30%+Evoflex CA© 6%) (CR 15%)	0.08	13.7					
	BBTM 11A PMB 45/80-55 REF	0.04	6					

Note: *According to the test report, the uncertainty of the test results for WTS air (wheel tracking test) ± 0.01 has been indicated. The uncertainty is the expanded uncertainty calculated using an overlap factor of 2, which gives a level of confidence of approximately 95%.

bigger amount of RA material (in this case 60%). Correlations can be seen in both layer types. Crumb rubber content in asphalt mixtures favorably affected their deformation resistance.

Deformation speed, proportional rails depth units and the requirements are listed in Table 10.

3.3. Moisture susceptibility performance

Experiments with regard to moisture susceptibility performance showed that all samples successfully meet most strict requirements of Road Specifications published in 2019. For most intensive road stages, moisture susceptibility should be more than 90% (VAS “Latvijas Valsts ceļi”, 2020).

According to the obtained results, the lowest performance was demonstrated by HMAC 16 PMB 25/55-60 with 95% susceptibility. The best result was shown by the base layer sample with 60% added RA material and reinforced with fiber glass. It should be noted that all mixtures reinforced with fiber glass showed better results. Probably, fiber glass provides stronger reinforcement for asphalt carcass making it harder and more stable against water presence (Glass fibre benefits, 2021). Extra reference HMAC 16 20/30 with result of 86 % did not meet the set requirements in this case.

Experimental results for the base layer mixtures are shown in Figure 5.

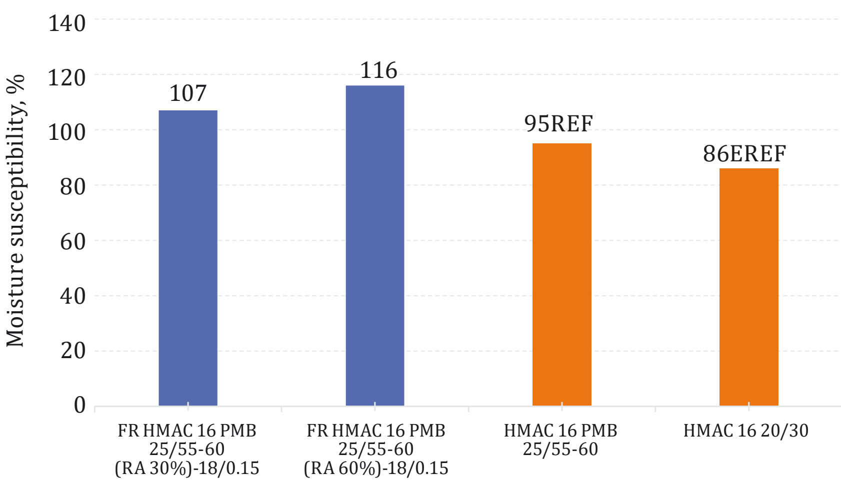

Figure 5. Moisture susceptibility results for the base layers

Surface layer mixtures showed almost identical results that also successfully met the requirements of Road Specifications. Crumb rubber, RA material and additives did not yield any negative or positive effect in this aspect.

The obtained results for the surface layer mixtures are shown in Figure 6.

3.4. Semi-circular bend performance

Fracture toughness of the mixtures was determined using semi-circular bend test. Unfortunately, there are no formal statements with requirements for HMAC and BBTM mixtures. The previous study has shown that typical fracture toughness for AC-16 mixtures used in Latvia is between 28 $N/mm^{3/2}$ for mixtures with unmodified bitumen and 43 $N/mm^{3/2}$ for PMB modified mixtures (Zaumanis & Valters, 2020). The AC-16 grading curve requirements are the same as HMAC-16, thus it can be reasonably assumed that aggregate grading does not play a crucial role in comparing the AC and HMAC mixture fracture resistance. As can be observed from Figure 6 there is a notable difference between results of HMAC 16 20/30 and HMAC 16 25/50-60. The main impact may be caused by the bitumen grade. Speaking of research samples with additives, it may be concluded that adding more RA material can significantly reduce fracture toughness and fiber glass reinforcement does not compensate bending performance, thus fracture toughness of the research samples is lower than that of reference mixture HMAC 16 25/55-60. Therefore, correlation between the amount of RA material and semi-circular bend performance can be established.

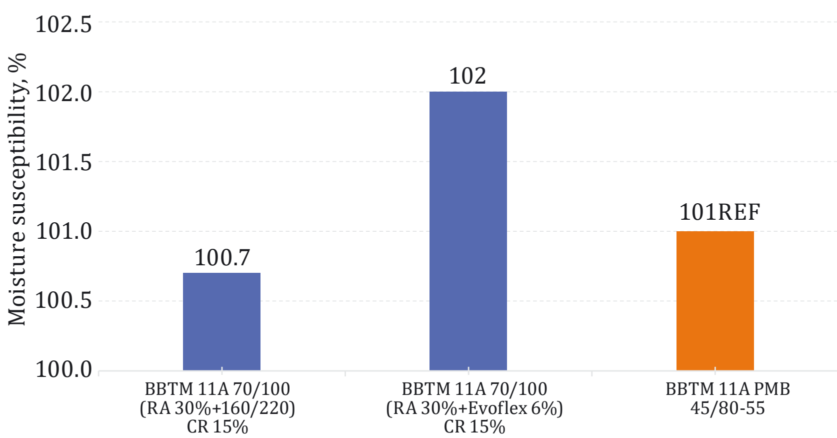

Figure 6. Moisture susceptibility results for the surface layers

As can be seen in Figure 8, research samples still showed a weaker fracture toughness value than the reference sample. Adding crumb rubber to the mixtures did not show any significant impact on reduction of SCB performance. Reduction of the values was not so swift due to rejuvenators. (160/220) grade PMB had more impact on semi-circular bending performance than Evoflex CA© additive, but it did not show sufficiently good performance for the modified bitumen. Therefore, after adding Evoflex CA© to a non-modified bitumen, sample BBTM 11A 70/100 (RA 30%+EVOFLEX CA© 6%) (CR 15%) has shown sufficiently good performance to be used in Latvia.

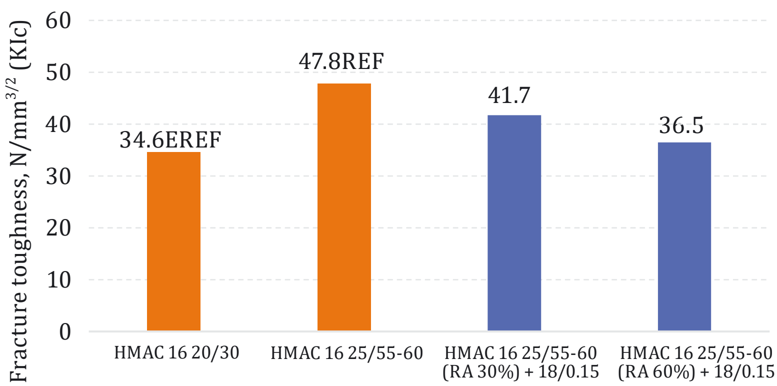

Figure 7. SCB performance results for the base layers

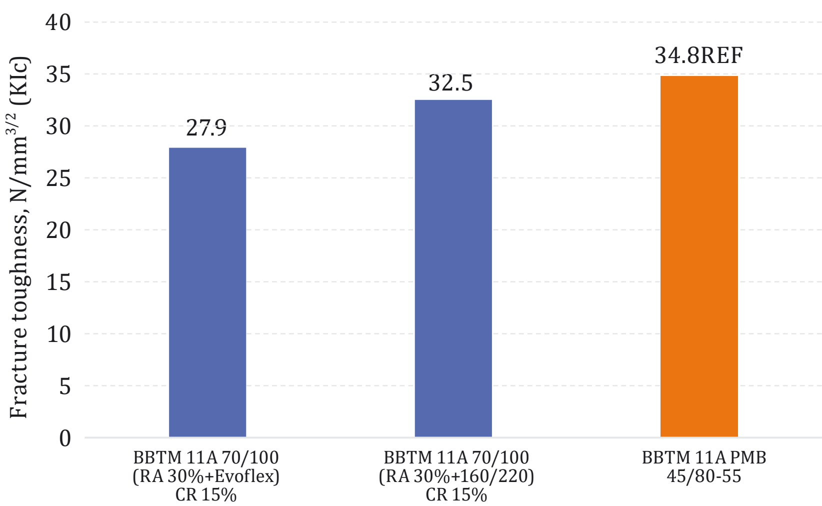

Figure 8. SCB performance results for the surface layers

3.5. Four point bending test performance

Four-point bending test showed that all base layer specimens demonstrated a better stiffness performance than the reference mixture, for which it was 10 419 MPa. It is important to note that the sample with the largest quantity of RA material showed the biggest stiffness modulus (13 250 MPa) compared to other research samples. The reason is that for PMB mixtures, stiffness modulus increased with an increase in the RA content due to hard binder available from the RA material. The minimum stiffness modulus requirement for HMAC

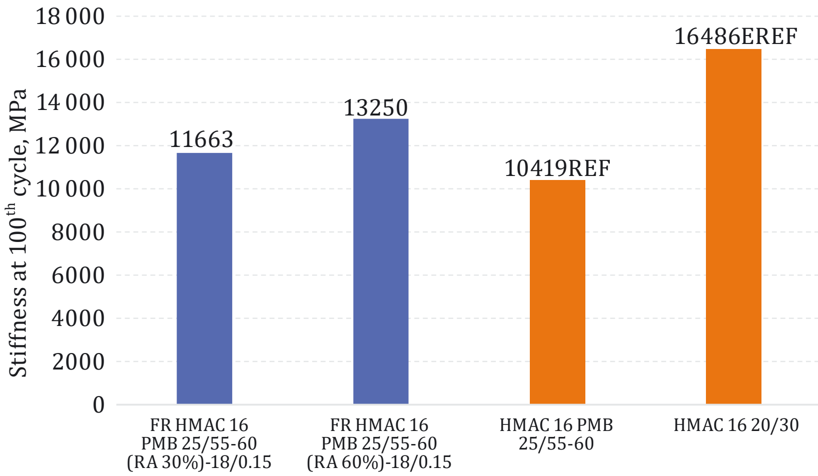

Figure 9. Stiffness modulus for the HMAC mixtures

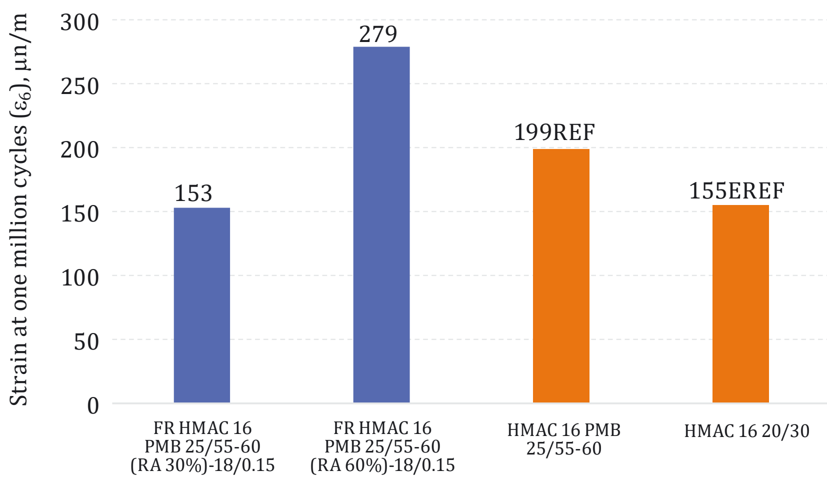

Figure 10. Strain at one million cycles (ε_6) from the fatigue equations for HMAC mixtures

mixtures is 14 000 MPa according to SPENS 2009 specification, so in this case, only extra reference of HMAC 20/30 complied with the requirements. The samples reinforced with fiber glass showed a better stiffness modulus than the reference mixture HMAC 16 PMB 25/55-60. The PMB mixture without RA material is thus not stiff enough to be used as a HMAC, and the addition of RA in fact serves to increase the stiffness modulus. For PMB mixtures, stiffness modulus increased with an increase in the RA content due to hard binder available from the RA material. The same correlations were detected by Izaks et. al. (2020). The results are shown in Figure 9.

Figure 10 presents the data from the computed fatigue equations, which show the strain level corresponding to 10^6 cycles (ε_6). SPENS 2009 specification requires a minimum ε_6 value of 130 μm/m (European Commission DG Research, 2009). As it can be seen, all samples fulfilled the minimum requirements. Value (ε_6) is significantly higher for the fiber reinforced mixture with 60% of RA material (279 μm/m). The lowest value was shown by the fiber reinforced mixture with 30% of RA material (153 μm/m). The extra reference sample, which showed the best result in terms of stiffness among all tested samples, demonstrated one of the worst fatigue values of 155 μm/m.

3.6. Trial stage pavement performance

Two asphalt mixes were selected for the trial stage in order to make pavement of two layers using HMAC mixture reinforced with fiber glass and containing 30% of RA material and BBTM 11A surface layer with added 15% crumb rubber, 30% of RA material and 6% of Evoflex CA© additive. Despite the fact that HMAC with 50% of RA material has shown better performance in some aspects, such as moisture susceptibility or cracking temperature. According to Road Specifications 2019 (VAS "Latvijas Valsts ceļi", 2020), it is possible to use mixtures with no more than 30% of RA. In order to reduce the use of non-renewable fossil resources, such as new bitumen, priority was given to recycled bitumen rejuvenators. The mixtures were chosen so as to meet recycled asphalt production rules and the requirements of the Latvian State Roads Specifications 2019. Asphalt mixtures taken from the trial stage pavement were tested for fundamental performance, such as rutting, cracking temperature, and moisture susceptibility. Void content and skid resistance were evaluated for the surface layer, but stiffness and fatigue tests were performed for the base layer only. The results of the conducted tests are shown in Table 11. As it can be seen from the table below, asphalt mix layers mostly achieve the required criteria laid down in Road Specifications 2019. The base layer's rutting performance was the only property which did not meet the requirements. WTS_{air} in this case was slightly higher than it was supposed to be for most intensive motorways. According to specifications, WTS_{air} should be below 0.1 mm/1000 cycles, but in case of tested HMAC 16 PMB 25/55-60 (RA 30%) – 18/0.15, the result was 0.115 mm/1000 cycles. It is necessary to note that laboratory produced sample of this asphalt mix met the requirements. There are many factors that can cause difference between results, starting from unproper mixing level and ending with insufficient compacting level during pavement construction.

Void content tests were conducted in the middle and on the rut of each driving lane in length of 200 m. The results are displayed in Figure 11.

Table 11. Fundamental performance of the trial stage pavement by layers

Mixture	Thickness, mm	WTS_{air}, mm/1000 cycles	PRD_{air}, %	Moisture susceptibility, %	Cracking temp. °C	Stiffness, MPa	Fatigue, µm/mm	Void content, %	Skid resistance	Fracture toughness, $N/mm^{3/2}$
BBTM 11A 70/100 (RA 30%+Evoflex 6%) (CR 15%)	30	0.08	13.7	102	–26.9	–	–	2.83	0.58	27.9
HMAC 16 PMB 25/55-60 (RA 30%) – 18/0.15	90	0.115	4.2	96.8	–25.9	11990	157	–	–	41.7

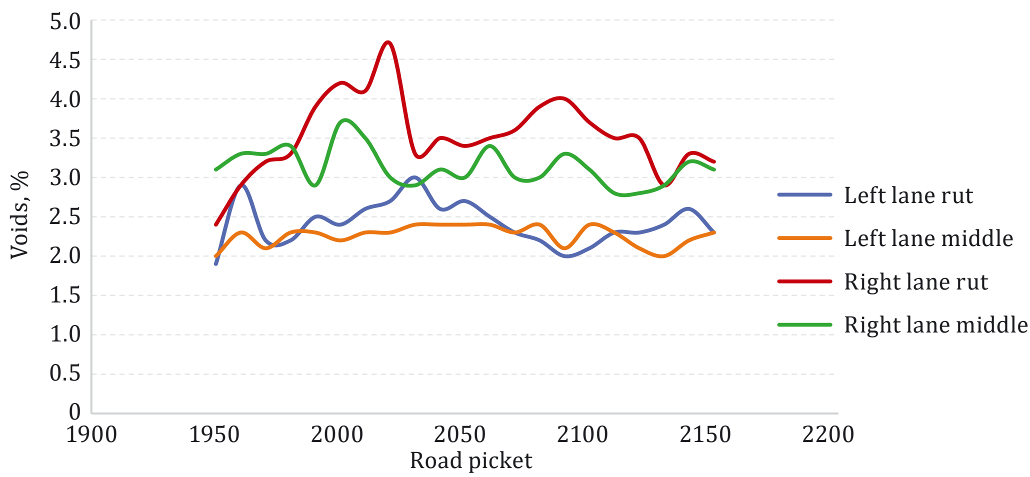

Figure 11. Void content of the compacted surface layer on the trial stage of P2 road

Conclusions

In this study, the laboratory performance of HMAC and BBTM asphalt mixtures containing fiber glass, crumb rubber and different content of RA was evaluated. Two mixtures for each layer – base and surface – were analyzed and tested for fundamental properties, such as rutting, cracking temperature, semi-circular bend, and moisture susceptibility. After laboratory evaluation, the most suitable mixtures were selected for the trial stage pavement. After trial stage was performed, testing was run repeatedly including four-point bending test for the base layer and skid resistance with void content of the compacted layer for the surface. Based on the analysis of results, the following conclusions were made:

1. All evaluated samples met the requirements for thermal stress restrained specimen test. For HMAC mixtures using fiber glass and RA material did not show notable effect on this criterion. On the other hand, adding crumb rubber with additives and RA material for BBTM mixtures slightly reduces performance with regard to thermal cracking because of ageing of RA bitumen. Evoflex additive can still stabilize aged RA bitumen in order to reduce the amount of added virgin binder.
2. The rutting tests showed that wheel tracking slopes were satisfactory for almost every sample mixture. A correlation between the RA content in the mixture and wheel tracking test performance was noticed. The more RA material a mixture contained, the more it was susceptible to deformations. Fiber glass can be used as a stabilizer and reinforcement to allow for the use of RA materials of 30%. In order to use more RA material, it is necessary to have a higher PMB grade as well. Crumb rubber content in asphalt mixtures has favorably affected deformation resistance.
3. All mixtures have met the minimum requirements for water sensitivity. For HMAC mixtures, fiber glass positively affects this criterion helping create a stable reinforced carcass which notably increases the tested parameter. The reference mixture also met these requirements.
4. Semi-circular bending tests showed that adding RA material to the amount of more than 30 % could significantly reduce fracture toughness. Fracture toughness index mostly depends on bitumen grade.
5. Fiber glass reinforcement notably increases stiffness modulus even in the mixtures with high content of RA material. The more RA materials is contained in the fiber glass reinforced mixture, the stiffer the mixture is. Fatigue test showed

common results and correlations. The samples did not meet the minimum requirements for stiffness according to SPENS 2009 specifications, not even the indicator of the reference mixture HMAC 16 20/30. HMAC 16 20/30 reference showed that stiffness highly depends on bitumen grade and modifications.

6. The trial stage performance almost fully met the requirements of the Latvian State Roads Specifications 2019 for motorways with traffic intensity AADT >5000. Only wheel tracking slope for HMAC 16 PMB 25/55-60 (RA 30%) – 18/0.15 mixture was slightly weaker for the designed traffic intensity. It is necessary to note that the laboratory produced sample of this asphalt mix met the requirements. There are many factors that can be the reason for the difference between results. Further research regarding this aspect is necessary.

The study has demonstrated that there are good chances to use waste materials like fiber glass and crumb rubber in addition to a 30% content of RA material for developing HMAC and BBTM mixtures for asphalt pavements that will meet the requirements of the Latvian State Roads Road Specifications 2019, which would allow implementing recycled production principles in the Republic of Latvia and save virgin material. A combination of different types of binder and different amounts of waste material could be investigated in future studies as this may help design HMAC mixtures that fulfil the stiffness modulus requirements.

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