PETER GALLO[1)]
MAJDA BELHAJ[2)]
JAN VALENTIN[3)]
PAVLA VACKOVA[4)]

LABORATORY EVALUATION OF COMBINED EFFECT OF JUTE FIBRES AND REJUVENATORS ON SOME PERFORMANCE CHARACTERISTICS OF ASPHALT MIXTURE CONTAINING RECLAIMED ASPHALT

LABORATORYJNA OCENA ŁĄCZNEGO WPŁYWU WŁÓKIEN JUTOWYCH I ŚRODKÓW ODŚWIEŻAJĄCYCH (REJUVENATORÓW) NA NIEKTÓRE WŁAŚCIWOŚCI UŻYTKOWE MIESZANKI MINERALNO-ASFALTOWEJ ZAWIERAJĄCEJ DESTRUKT ASFALTOWY

STRESZCZENIE. Zastosowanie destruktu asfaltowego (RA) w mieszankach betonu asfaltowego przynosi korzyści ekonomiczne i środowiskowe i jest ważne w dążeniu do stosowania zasad zrównoważonego rozwoju i gospodarki o obiegu zamkniętym. Celem niniejszej pracy jest ocena skuteczności dodatku dwóch środków odświeżających na bazie biologicznej i włókien jutowych na właściwości użytkowe mieszanki mineralno-asfaltowej zaprojektowanej z 30% udziałem destruktu asfaltowego według masy. Przeanalizowano siedem wariantów mieszanki, różniących się dodatkiem środka odświeżającego i/lub włókien. Właściwości mechaniczne zostały ocenione za pomocą testów laboratoryjnych mierzących podatność na wilgotność (ITSR), moduł sztywności (IT-CY), odporność na propagację pęknięć (SCB) i moduł dynamiczny (4PB-PR). Mieszanki z włóknami jutowymi wykazywały niższą podatność na wilgotność. W porównaniu z mieszanką referencyjną, w odniesieniu do mieszanek ze środkami odświeżającymi wykazano spadek modułu sztywności. Odwrotną tendencję zaobserwowano po dodaniu włókien. Najlepsze wyniki w zakresie odporności na propagację pęknięć i modułu zespolonego uzyskano poprzez dodanie do mieszanki włókien jutowych ze środkiem odświeżającym.

SŁOWA KLUCZOWE: destrukt asfaltowy, włókna, środek odświeżający, recykling, mieszanka asfaltowa.

ABSTRACT. The use of reclaimed asphalt (RA) in asphalt concrete mixtures have achieved economic and environmental benefits and it is important when we want to get in line with sustainable development and circular economy. This paper aims to evaluate the effectiveness of the addition of two bio-based rejuvenators and jute fibres on the performance of asphalt mixture designed with 30% by mass RA content. Seven mix variants, varying with the addition of the rejuvenator and/or fibres, were analysed. Mechanical performance was evaluated through laboratory tests measuring moisture susceptibility (ITSR), stiffness modulus (IT-CY), resistance to crack propagation (SCB) and dynamic modulus (4PB-PR). Mixtures with jute fibres showed lower ITSR. In comparison with the reference mixture, a decrease in the stiffness modulus has been shown for mixtures with rejuvenators. Opposite trend was observed when fibres were added. Best performance in resistance to crack propagation and complex modulus was achieved by adding jute fibres with rejuvenator to the mixture.

KEYWORDS: reclaimed asphalt, fibres, rejuvenator, recycling, asphalt mixture.

DOI :10.7409/rabdim.023.022

[1)] Faculty of Civil Engineering, Czech Technical University, Prague, Czech Republic; peter.gallo@fsv.cvut.cz ✉
[2)] Faculty of Civil Engineering, Czech Technical University, Prague, Czech Republic; majda.belhaj@fsv.cvut.cz
[3)] Faculty of Civil Engineering, Czech Technical University, Prague, Czech Republic; jan.valentin@fsv.cvut.cz
[4)] Faculty of Civil Engineering, Czech Technical University, Prague, Czech Republic; pavla.vackova@fsv.cvut.cz

[*)] An extended version of the article from the Conference "Modern Road Pavements – MRP'2023" – Recycling in road pavement structures co-edited by Martins Zaumanis and Marcin Gajewski, published in frame of the Ministry of Education and Science project No. RCN/SP/0569/2021/1

1. INTRODUCTION

Over the last decades, the use of the reclaimed asphalt (RA) was increasingly encouraged and promoted by the road industry due to the economic, environmentally-friendly, and natural resources benefits [1]. This material has proven to meet the requirement of sustainable development of road engineering along with the cost reduction [2]. According to the statistics from the European Asphalt Pavement Association (EAPA) [3], the Czech Republic has recorded about 2.8 million tons of available RA in 2019, but on average only 39% of the recovered material is used in cold, or hot/warm recycling processes. Hence, more than 60% of the RA end-up either accumulated in stockpiles, used in technically low-value and non-bituminous applications (e.g., aggregate in unbound layers) – downcycling process, or have been dumped. The effective recycle and re-use of asphalt pavements has become a major demand for the environmental development of the transportation industry. However, the dosage of RA in asphalt mixtures is still low.

As the RA content is rising in asphalt mixes, it becomes challenging to counteract the effect of RA's bituminous binder brittleness. This brittleness results in decreasing of the bitumen's flexibility, its cohesive (the bonding inside the bituminous binder) and adhesive capability (the bonding between the bitumen and aggregate) and leads to a significant impact on the cracking resistance of the mixture [4]. The commonly used method to counteract this brittleness is the introduction of rejuvenators into asphalt mixtures.

A rejuvenator is a material that has the ability to adjust and improve the composition of the aged bituminous binder by restoring partially or fully the maltenic fraction and providing to some degree the original viscoelastic properties of the binder [5, 6]. Rejuvenators are widely known as petroleum-based additives which are non-renewable materials and do not satisfy the sustainable development requirements. For these reasons, in recent years, developing new types of rejuvenators from different sources has become a new development direction to fulfil more efficient and environmentally-friendly materials in the field of road materials. Whereas, depending on the nature of these additives, the interaction between the aged binder contained in the RA and these rejuvenators is different and thus the performance of the mixture [7]. Accordingly, not all rejuvenators would apply similar effect on the rheological properties of the aged binder leading to variations in the final mechanical performance of the asphalt mixture.

Several studies evaluating the effect of the use of bio-rejuvenators with reclaimed asphalt show an improvement in the thermal stability and the low-temperature crack resistance of the aged asphalt mixture, consequently leading to an extended fatigue life and a reduction in the stiffness of the mixture [8, 9, 10]. Another method that was able to reduce the plastic deformation and the fatigue cracking is to incorporate fibres with RA into asphalt mixtures [11]. Fibres are usually categorized by their origin, either natural or synthetic. Typically, they are used as a reinforcing additive for asphalt mixtures as the results of their incorporation showed an effective improvement in the tensile strength, moisture susceptibility, rutting resistance, and crack propagation resistance [11, 12, 13].

Using natural, plant-based fibres into hot asphalt mixtures has gained a considerable amount of attention over the last years because of its ability to absorb the bitumen and enhance its rheological properties [14]. A few studies have been devoted to evaluation of the effect of natural/cellulose fibres on the performance of asphalt mixture. The results showed a positive effect on the mixture's properties by increasing the stability and decreasing the flow value [15]. Therefore, it was anticipated that adding jute fibre can raise the potential to improve the performance of asphalt mixtures. However, very limited amount of research has been conducted on the performance of adding jute fibre to the mixtures with RA content.

Therefore, the objective of this study was to investigate the performance of hot mix asphalt with RA content, jute fibre and rejuvenator. To achieve the goals, asphalt mixture containing 30% RA reinforced with 0.2% (by weight of the mixture) of jute fibre and two different bio-based rejuvenators were produced. Mass of rejuvenators was 6% by weight of the aged binder contained in the reclaimed asphalt. Air voids content, stiffness, moisture susceptibility, cracking resistance and dynamic modulus of all mixtures were evaluated. Finally, a comparison with reference mixture without fibres and rejuvenators was performed for a better understanding of the reinforcing effect caused by jute fibre and the effectiveness of the rejuvenators. To test the effect and the quality of the rejuvenated asphalt mixture with jute fibre, two methods of mixing were used: adding the rejuvenator straight into the RA and adding the rejuvenator to the fibre.

2. EXPERIMENTAL PLAN

2.1. ASPHALT MIXTURE

To evaluate the effectiveness of the two bio-based rejuvenators and the jute fibres on improving the properties of asphalt mixture with 30% RA, 7 mixtures were made for this study. The experimental design of all mixtures was in accordance with a typical AC_{base} 16 mix for the base layers with a nominal maximum aggregate size (NMAS) of 16 mm (according to the Czech technical standard CSN 73 6121:2019 denoted as ACP 16+). The same aggregate size distribution curve (Fig. 1), RA content (30% by weight) and bituminous binder content and type (paving grade bitumen 50/70, the standard bitumen in the Czech Republic) were used for all mixes. Bitumen content of RA was found to be 6%. The targeted binder content in the mixture with 30% RA was 4.5% by weight divided between added amount of virgin binder of 2.7%, and the rest was assumed to be reactivated from RA. The amount of added rejuvenator is calculated from the amount of binder in RA, i.e. 6% of any rejuvenator means 6% from 6% (binder content) of 30% (RA content), which means 0.108% of total asphalt mixture.

According to the past studies [16, 17], rejuvenators can be provided from different sources. The best rejuvenating agents are the ones which should react properly with the aged binder to produce a high-quality recycled binder and, consequently, a high-quality asphalt mixture. Therefore, it is important to select the appropriate type and dosage of these rejuvenators. In this study, two commercialized bio-based rejuvenators – RAPFix denoted in this paper as “RF” (oil-based additive) and SylvaRoad denoted as “SR” (crude tall oil and crude turpentine oil derived additive) were selected and dosed by 6% by mass of the aged binder contained by the reclaimed asphalt. This dosage was a result of a comparison of selected tests such as penetration at 25°C, softening point test, frequency sweep test, and MSCR (Multiple Stress Creep Recovery test) which will not be presented in this paper. So far, only few published research papers

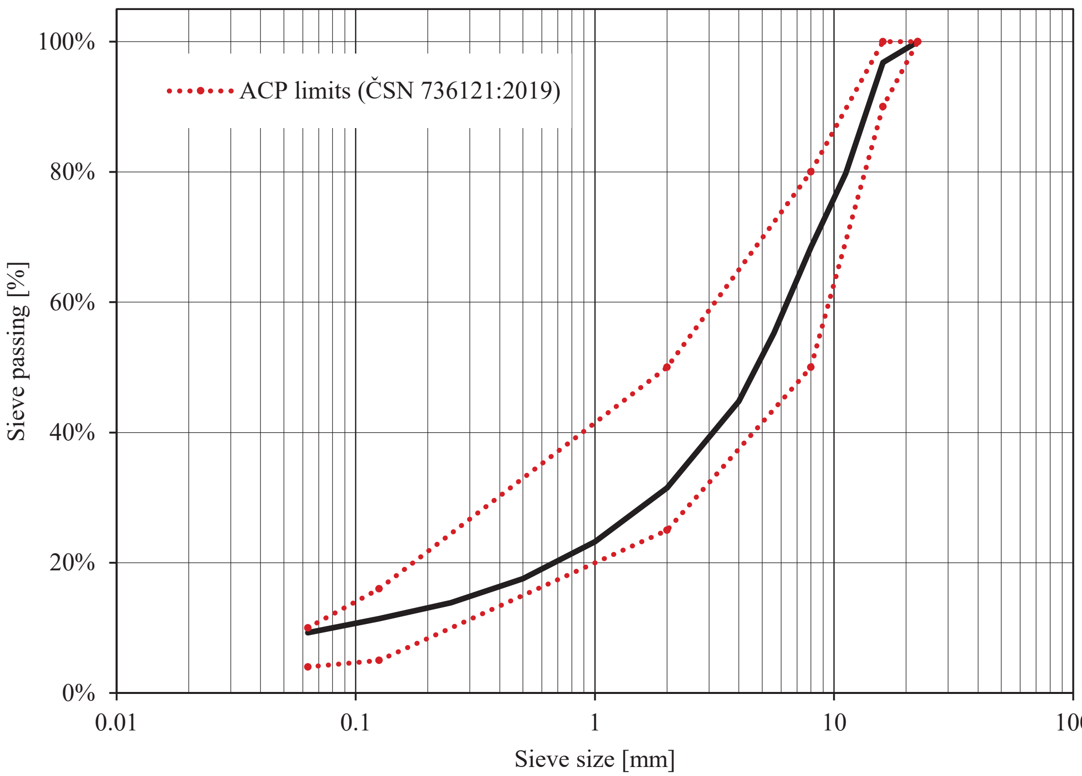


Fig. 1. Granulometric curve of the reference mixture

Table 1. Description of tested mixtures

Mixture's label	Description
Ref	Reference mixture - containing 30% RA but no rejuvenators nor fibres
0.2% J300	+ 0.2% (by weight) of added jute fibre
6% SR	+ 6% (by mass of aged binder) of SR rejuvenator
0.2% J300 6% SR	+ 0.2% (by weight) of added jute fibre, and 6% (by mass of aged binder) of SR rejuvenator onto fibres (ii)
6% RF	+ 6% (by mass of aged binder) of RF rejuvenator
0.2% J300 6% RF_fibres	+ 0.2% (by weight) of added jute fibre, and 6% (by mass of aged binder) of RF rejuvenator. The addition of this rejuvenator was onto the fibres (ii)
0.2% J300 6% RF_RA	+ 0.2% (by weight) of added jute fibre, and 6% (by mass of aged binder) of RF rejuvenator. The addition of this rejuvenator was directly to the RA (i)

[18, 19] about the performance of these types of products are available although their features can be found on the company's website.

Additionally, this study is using the natural-based jute fibres to enable the physical enhancement of recycled asphalt mixtures. In the present paper jute fibres with 20 mm length were added at a rate of 0.2% by weight of the total mixture. Jute fibres were provided by JUTEKO s.r.o company in form of a yarn with fineness of 300 g/km. Yarn was cut in desired length of 20 mm on a precise desktop manual paper cutter and placed in a water bath for at least 4 hours at room temperature. This step led to disintegration of the yarn into separate fibres. After the water bath, the fibres were hand-squeezed, put on a stainless-steel plate, and were placed in the oven with fan induced air circulation. They were dried for at least 12 h at 50°C.

For preparing the specimens (Table 1), reclaimed asphalt and virgin aggregates were kept at 160°C. Next, the rejuvenator was added by two different methods: (i) directly to the RA (oil-based) or (ii) onto the fibres (both types). Rejuvenators were hand-mixed with the fibres at room temperature. Their dosage was slightly higher than the required amount to compensate leftovers adsorbed on gloves and bowl surface. Then, the fibres were moved in another bowl and put in an oven at 150°C for 5 minutes. After this step, part of the bitumen binder was applied onto fibres, quickly hand-mixed and the fibres partially coated by bitumen were gradually added to the mix with the rest of bitumen. The final mixture was then compacted at 150°C. The asphalt mixes were produced and tested in the lab according to the Czech national specifications given in the national standard ČSN 73 6121:2019 [20].

2.2. TEST PLAN

To evaluate the performance of asphalt mixtures, a selection of laboratory tests were performed and examined (Fig. 2):

- air voids content according to EN 12697-8,
- resistance to water immersion (ITSR) according to EN 12697-12 and to the water + one freezing cycle according to AASHTO T283 (modified procedure),
- determination of stiffness modulus according to EN 12697-26, Annex C - IT-CY test method,
- resistance to crack propagation according to ČSN EN 12697-44 with a modified procedure: loading rate (2.5mm/min), diameter of test specimens 100 mm and compaction of test specimens by Marshall compactor same like for stiffness determination,
- dynamic modulus according to EN 12697-26, 4PB-PR method.

3. RESULTS AND DISCUSSION

3.1. AIR VOIDS

The assessed mixtures were compacted according to EN 12697-30 (by Marshall impact compactor) at temperature of 150°C according to the Czech technical specifications given in the national standard ČSN 73 6121:2019.

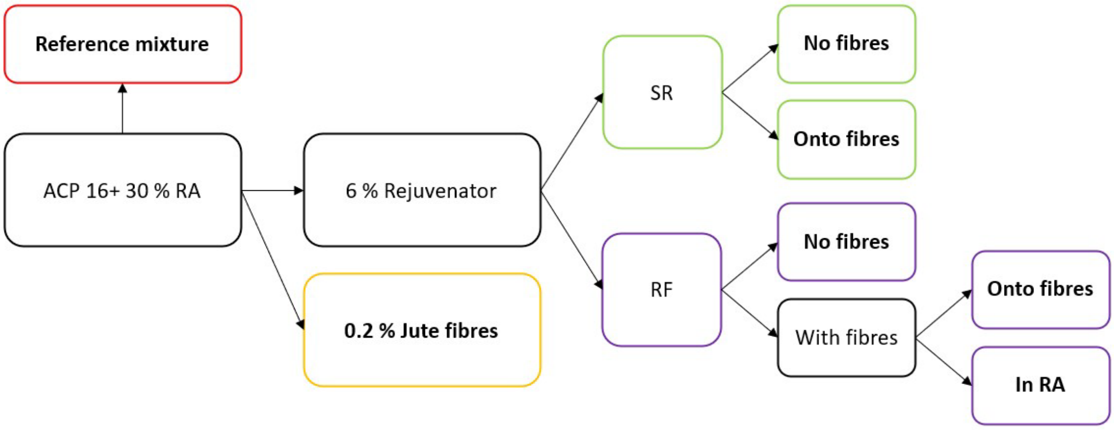


Fig. 2. Test plan scheme

Analysing the results shown in the Fig. 3, it is evident that the addition of rejuvenator and/or jute fibres has a positive influence on the compactability since these have shown a lower air void content comparing to the reference mixture. Except the latter, all tested mixtures have fulfilled the type testing (mix design) criterion for air voids content (ČSN 73 6121:2019). The mixing method of rejuvenator has no influence on the compaction of the mixes. Lower voids content of mixtures with jute fibres is a little bit surprising. Interestingly, there is a significant drop of air voids content for a mixture with virgin fibres (0.2% J300). Previous experience [21] showed an opposite trend. Unlike in previous research [21], a different procedure to incorporate the fibres into mixture was used in the study presented by this paper. Although with the highest air voids content, the reference mixture still verifies the control testing requirements.

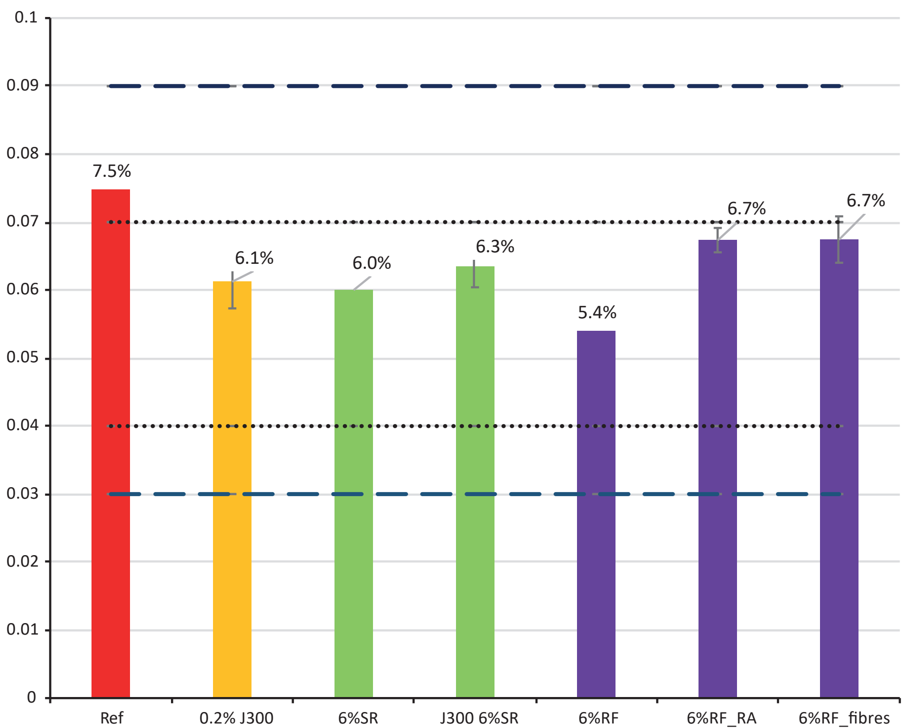


Fig. 3. Air voids content (the dotted lines show the interval for type testing limits, the dashed lines show the interval for control testing requirements in Czech Republic for AC_{base} mixtures)

3.2. MOISTURE AND FREEZE-THAW SUSCEPTIBILITY

Moisture susceptibility test was performed according to EN 12697-12, whereas the freeze-thaw test was performed according AASHTO T283-3 (modified test procedure was used). Contrary to the general requirements by the AASHTO T283-3 test protocol, the test specimens were not compacted by gyratory compactor and 7% air void content but instead by an impact compactor (compacted by 2x25 blows of Marshall). The specimens were tested at a temperature of 15°C and a speed of 50 mm/min according to EN 12697-23 on universal Marshall press.

Based on the analysis of the ITS of the dry specimens (Fig. 4), an increase in the indirect tensile strength was reached by the mixtures with jute fibres and a decrease was displayed by the addition of rejuvenators. Both these results were expected, because fibres tend to reinforce the mixture thus increase the strength properties. As for the rejuvenators, they tend to soften the aged binder in RA and consequently lower the strength properties.

Following the ITSR indices of the analysed mixtures, the lowest $ITSR_{EN}$= 54% was showed by the mixture with 0.2% J300 and 6% SR. The same influence was shown for the ITSR according to AASHTO T283 protocol with one freezing cycle. This test was conducted for better evaluation of the effects of moisture and frost on the road surface durability. Significant decrease of ITSR is often observed in asphalt mixtures with fibres (especially the plant-based) [21]. However, the use of the latter in asphalt mixtures containing RA, the decrease is more perceptible. This can be supported by the fact that part of the bitumen binder is soaked by the fibres and, therefore, a thinner bitumen film is coating the aggregates. Furthermore, only 2.7% of virgin binder was added to the mixture. Apart from nature of the fibres, this can be one reason for such decrease of ITSR for mixtures with jute fibres. On the other hand, wet indirect tensile strength of these mixtures

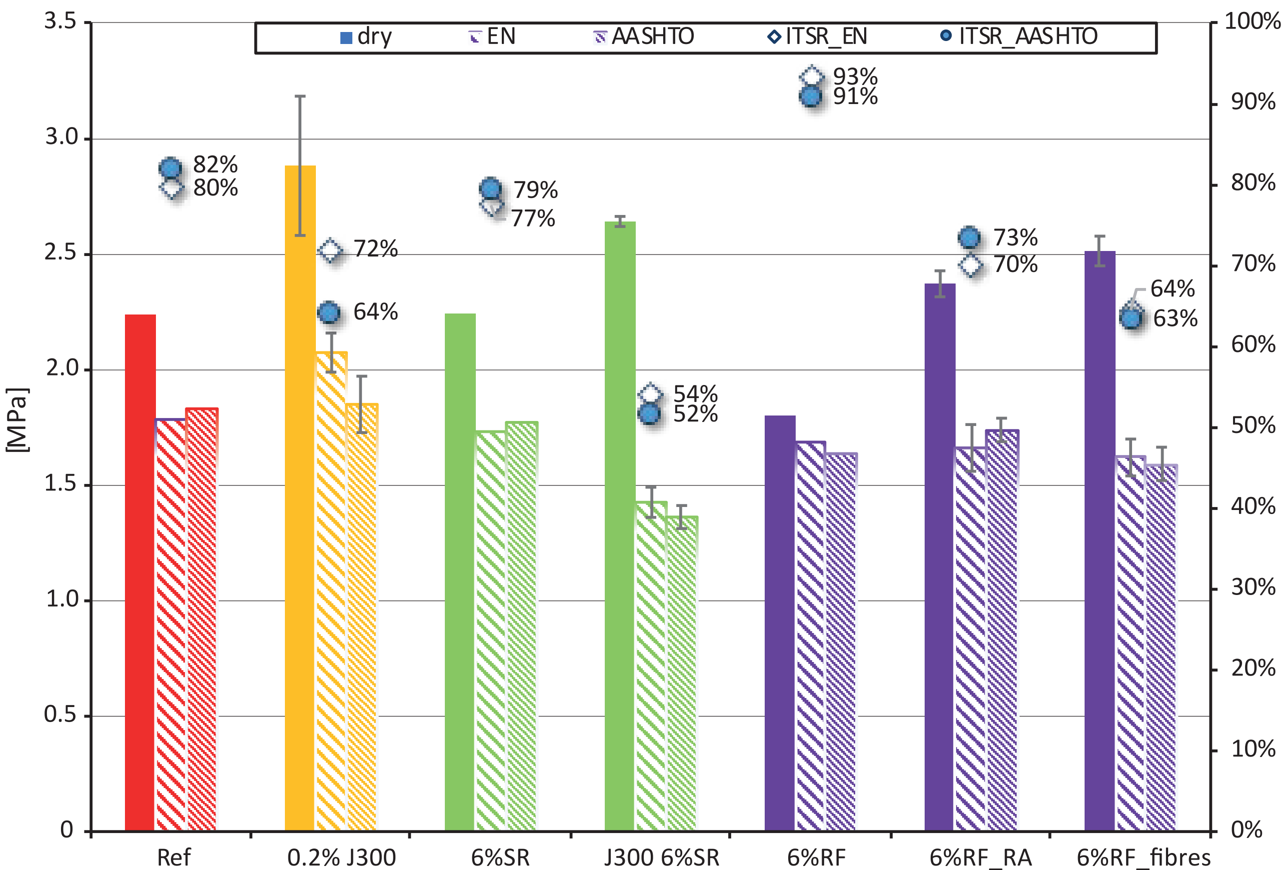


Fig. 4. Water susceptibility and freezing and thawing results

stayed in the range of mixtures without fibres, except for the mixture 0.2% J300 6% SR.

3.3. STIFFNESS

The stiffness modulus test was conducted on Marshall specimens by IT-CY test method (repeated indirect tensile stress) according to EN 12697-26 at three test temperatures 0°C, 15°C and 27°C. These are the most frequently used temperatures in the Czech Republic, used for pavement design and for long term data collection representing different seasons during the year. Further, the thermal susceptibility was calculated as a ratio of stiffness modulus at 0°C and 27°C. It is known that the lower the thermal susceptibility is, the less sensitive to temperature changes an asphalt mixture is, with respect to its deformation characteristics. Similarly, to the ITSdry results, the addition of rejuvenators to the asphalt mixture containing RA should represent a decrease in the stiffness of the mix due to its rejuvenating properties. Although, mixture with 6% of "RF" showed the highest thermal susceptibility value, there is a significant decrease of stiffness at all tested temperatures. The stiffness modulus (Fig. 5) of all the rejuvenated mixtures with jute fibres regardless of the temperature, the rejuvenator type, and the approach of rejuvenator incorporation, have shown similar values. According to Haiming and White [22], fibres have approved to be able to increase the viscosity and the stiffness of bitumen thus, able to increase the stiffness of the asphalt mixture as well. This is the case for all tested mixtures with jute fibres. In previous research [21], a decrease of stiffness modulus of the mixtures with jute fibres was reported. Different procedure to incorporate the fibres into mixture was used in the study presented by this paper. Together with different bitumen mixture type, this can be a major reason for different performance in stiffness test. Mixtures with jute fibres showed higher stiffness at all temperatures compared to equivalent mixtures without fibres. This fact fits in with the prediction of increasing stiffness. Moreover, rejuvenated fibrous mixtures showed higher stiffness at 27°C. In case of the combination with rejuvenator "RF", there was also a decrease of stiffness at 0°C, which resulted in the best thermal susceptibility of all mixtures. Such mixtures should perform better in hot environment as well, as they are not prone to thermal induced cracking at low temperatures. In fact, addition of jute fibres leads to the lower thermal susceptibility in all cases. Finally, the stiffness results of the two different incorporation methods of rejuvenators showed slight increase in mixture 0,2%J300 6%RF_RA at all temperatures.

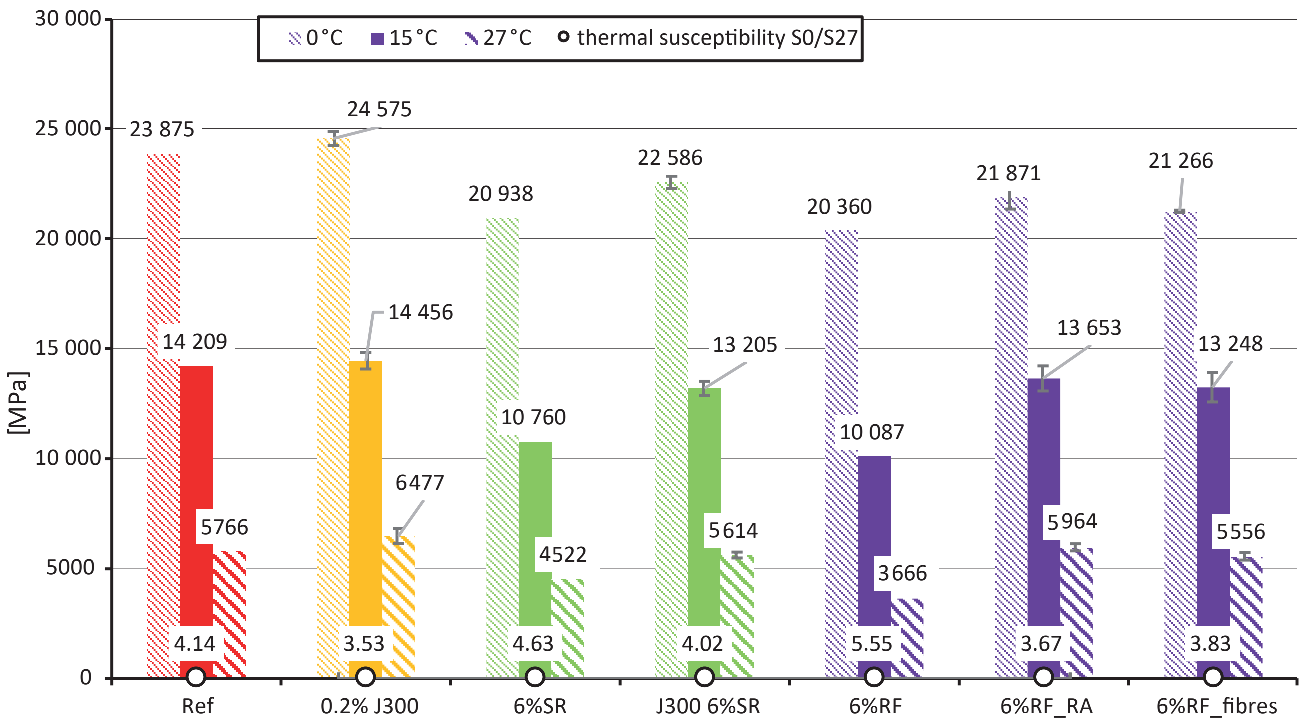
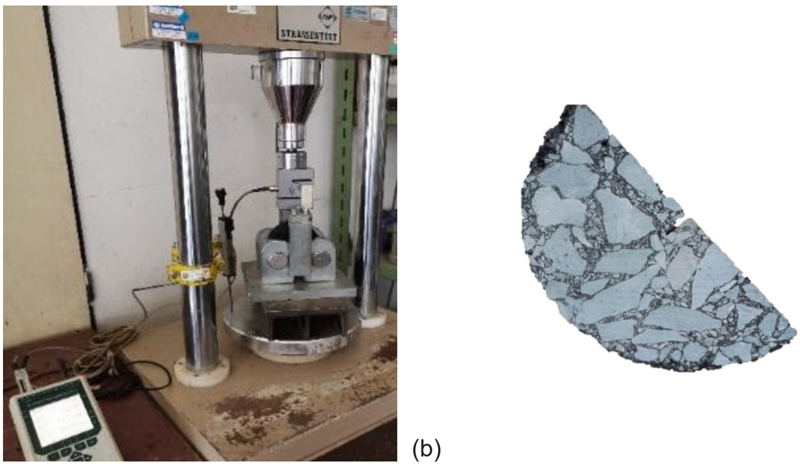


Fig. 5. Stiffness modulus results

3.4. RESISTANCE TO CRACK PROPAGATION

For the semi-circular bending (SCB) fracture test, the compacted Marshall specimen was cut into semi-circular specimens (Fig. 6 (a)). The specimen's diameter was reduced from 150±1 mm as defined in the standard to 101±1 mm. Then the specimens were notched in the middle and at the bottom. For a better evaluation and calculation of the fracture toughness and the fracture energy, the loading rate was reduced from 5.0 mm/min as set in the standard to 2.5 mm/min which is in accordance with long term research as described in [23]. This decrease in the loading rate will lead to a more accurate load-displacement curve. This test was performed at two temperatures: 0°C related to the thermal induced cracking risk and 25°C, related to the potential fatigue cracking. Test setup of this test is shown in Fig. 6 (b).



(a) (b)

Fig. 6. (a) Semi-circular specimen, (b) SCB test setup

The highest fracture toughness (Table 2) at 0°C was reached by the mixture with "0.2%J300 6% SR" as 43,5 $N/mm^{1.5}$ comparing to the reference mixture which only reached the 36,2 $N/mm^{1.5}$. The lowest fracture toughness value was achieved by the mixture with the rejuvenator "RF" (only 31.0 $N/mm^{1.5}$). The same mixture also showed the lowest fracture energy values. Addition of jute fibres helped to increase selected fracture parameters. Surprisingly, they did not help to increase a difference between fracture energy till maximum force and total fracture energy as much as in the case of reference mixture.

At higher test temperature, a logical decrease in fracture toughness can be seen, along with an increase in total fracture energy. Once the maximum test force was reached, there was a greater energy consumption required to fully propagate the crack. The highest values of calculated parameters were achieved by the "0.2%J300 6%SR" mixture which showed the best overall crack propagation resistance performance. Regarding the rejuvenator incorporation method, the mixture with rejuvenator added to the RA proved to be the better rated at 25°C while the difference between fracture parameters at 0°C is negligible. Fracture toughness and energy values relative to the reference mixture (Fig. 7) were calculated for clearer presentation of the results. It must be stated that standard deviation of some fracture energy results is elevated. This phenomenon is most visible at 0°C, when SCB specimens tend to have a brittle fracture mechanism.

Table 2. Selected fracture parameters of SCB test

	Fracture toughness				*Fracture energy till Fmax*				*Total fracture energy*			
	[N/mm^3/2]				[J/m^2]				[J/m^2]			
	0°C	st.dev	25°C	st.dev	0°C	st.dev	25°C	st.dev	0°C	st.dev	25°C	st.dev
Ref	36.2	4.2	18.4	1.8	927	324	951	149	1590	618	1867	308
0.2% J300	36.0	5.6	26.4	2.1	868	304	1128	162	1022	286	2182	319
6%SR	39.0	–	–	–	1110	–	–	–	1215	–	–	–
0.2% J300 6%SR	43.5	3.3	21.2	1.2	1493	384	1246	226	1763	512	2560	267
6%RF	31.0	–	–	–	702	–	–	–	1064	–	–	–
0.2% J300 6%RF_RA	36.7	4.0	23.2	2.8	1101	406	1178	372	1426	392	2336	625
0.2%J300 6%RF_fibers	37.9	4.2	21.1	1.5	1115	605	999	153	1322	629	2172	461

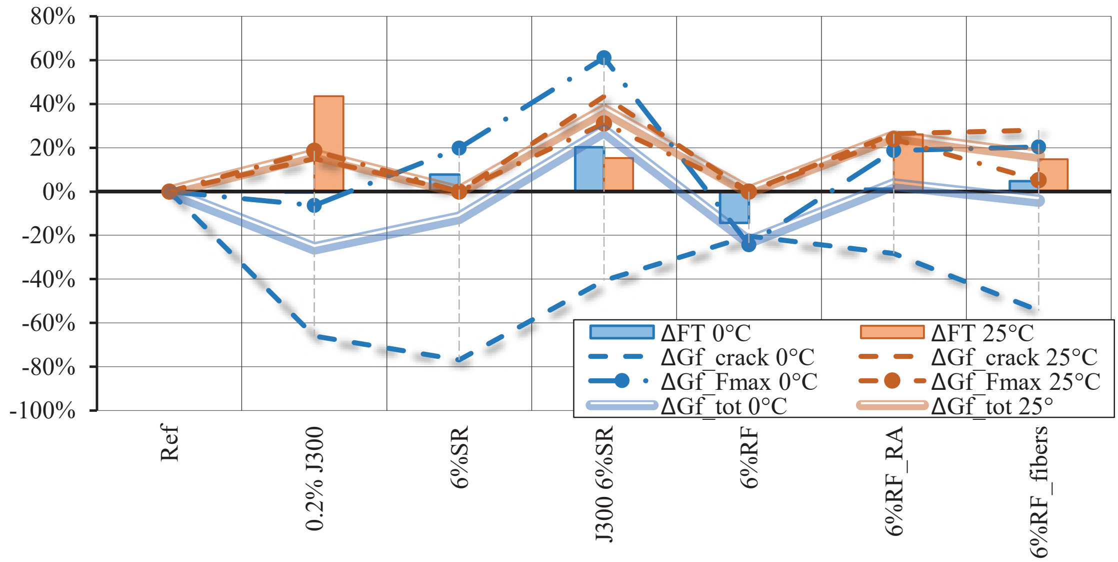


Fig. 7. Fracture parameters relative to the reference mixture (FT: Fracture Toughness, Gf_Fmax: Energy to the maximum force, Gf_tot: Total fracture energy)

Also, only 6 semi-circular specimens were tested for each mixture and temperature.

3.5. DYNAMIC MODULUS

The dynamic modulus test was conducted on a prismatic beam specimen by 4PB-PR test method according to EN 12697-26. The test was performed at four temperatures 0°C, 10°C, 20°C, and 30°C, and eleven selected test frequencies 50, 30, 20, 15, 10, 8, 5, 3, 2, 1 and 0.1 Hz for each temperature. This test is conducted by applying a haversine force to achieve a target strain amplitude of 50 micro strains. Originally, the testing temperatures should be decreased from the highest to the lowest level. However, based on previous experiences with the application of this test, at the temperature of 30°C the specimen shows from time-to-time damage. Therefore, the measurement at 30°C was carried out by the end of the test process i.e., as the last one after the other temperatures. As for the frequencies of loading, the test starts with the highest frequency and proceeds to the lowest one.

The master curves of all mixtures shown in Fig. 8 were constructed for a reference temperature of 20°C using the principle of time-temperature superposition. The standard of the dynamic complex modulus |E*|, represents the material's stiffness which is a tool for a better understanding of the load's distribution in the pavement's structure.

The effect of the addition of fibres only shows a higher stiffness than the control mixture in the range of low/medium frequency. Moreover, it shows the same dynamic modulus at the range of the high frequency since the master curves are merging. The effect at the high temperature (low frequency) range was in accordance with the results from IT-CY testing. However, the analogy between the two stiffnesses – the stiffness modulus by IT-CY test method and the dynamic stiffness modulus by 4PB-PR test method, was not always given.

As mentioned in the previous parts, rejuvenators tend to soften the bituminous binder and thus decreasing the stiffness of the asphalt mixture. However, this result was not consented by all the mixtures with rejuvenators – the mixture with rejuvenator "SR". The addition of this rejuvenator showed similar or lower complex (dynamic) modulus along the low/medium frequency (high/medium temperature) range to the control mixture and higher moduli along the low temperature. High thermal susceptibility from IT-CY testing method confirms this observation. Lower values of complex modulus were in case of mixtures with rejuvenator "RF". Most favourable behaviour was shown by mixture 0.2%J300 6%_RA. This master curve was basically just a down-shifted version of mixture with fibres only (0.2%J300) and thus, it was the best result from all mixtures.

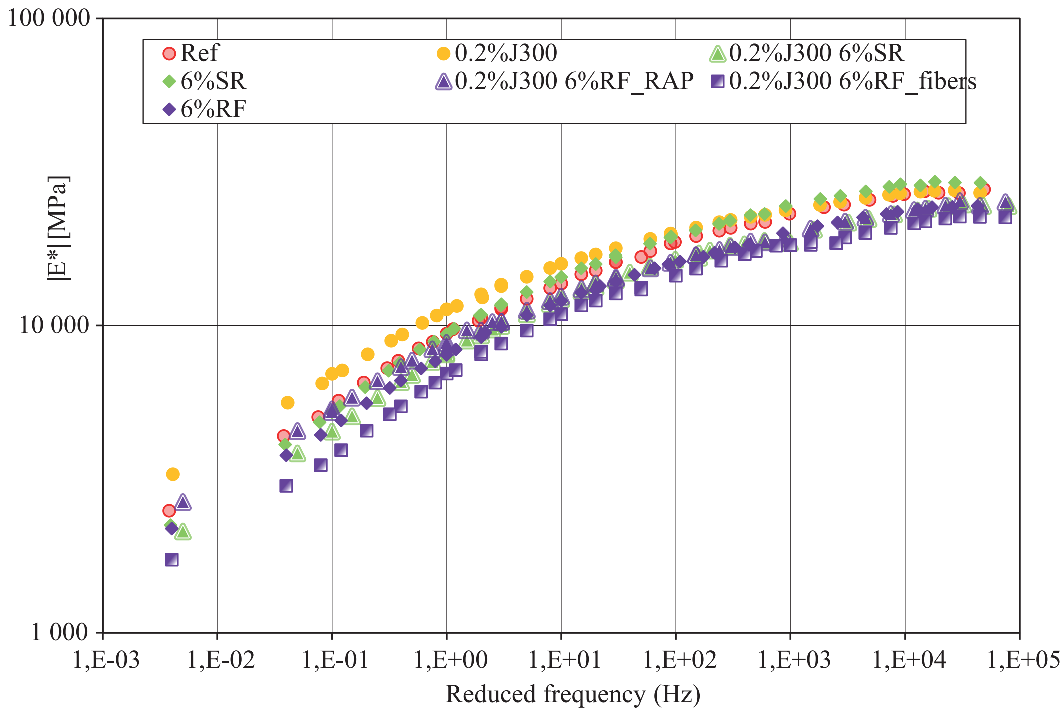


Fig. 8. Master curves for 4PB complex modulus of tested mix variants

The Black space diagram is a plot of the dynamic complex modulus |E*| vs. the phase angle δ. It is considered as a valuable rheology tool since it enables users to evaluate the relationship between the material stiffness and its elasticity independently from the time-temperature superposition principle. It is known that with increasing of the dynamic modulus |E*| and decreasing the phase angle δ, the mixture tends to be more likely to crack. As for the phase angle δ, it represents the elastic or viscous predominance of the mixture.

As illustrated in Fig. 9 the Black space diagram of the mixture with 6% SR showed an increase |E*| at the whole temperature range, leading to more susceptibility to crack. It was followed by mixtures without rejuvenators. Other mixtures had lower |E*|, from which the 0.2%J300 6%RF_fibres showed the lowest cracking susceptibility at low phase angle (temperature). This conclusion is mismatched with the SCB test. However, mixture “0.2%J300 6% SR” has one of the lowest |E*| at low temperature, so there is some correlation between tests. Curve of this mixture was as well the only one to cross the reference mixture in the range of high temperature.

Once the complex modulus has been measured at all test temperatures, the beams were exposed to a thermal-oxidative ageing process. It will simulate the long-term aging by conditioning the beams in a tempering chamber at 85°C for 5 days according to prEN 12697-52. After the aging, the beams were then tested for the dynamic modulus at temperature 20°C. Based on the results, aging index was calculated as a ratio between aged and virgin dynamic modulus value. It is assumed that the lower the aging index is, the more durable the mixture might be.

As it was mentioned in the test description, the test is performed under 11 frequencies. Through them, it is possible to study the performance at a wider range of frequencies and not be limited to the resonance. In this context, Fig. 10 reports the influence of three chosen frequencies – 0.1 Hz, 1 Hz, and 10 Hz on the aging index. It is shown that the ageing index increases with the decrease of the frequency and the 0.1 Hz illustrates the frequency where the mixture exhibits its most susceptibility to ageing.

Even though the use of the rejuvenator “SR” had shown the best results at 10 Hz, it showed the highest (worst) results at both 1 Hz and 0.1 Hz with the highest increment of 24% and 43% respectively comparing to all the mixtures. Thus, in order to define the best rejuvenator in accordance

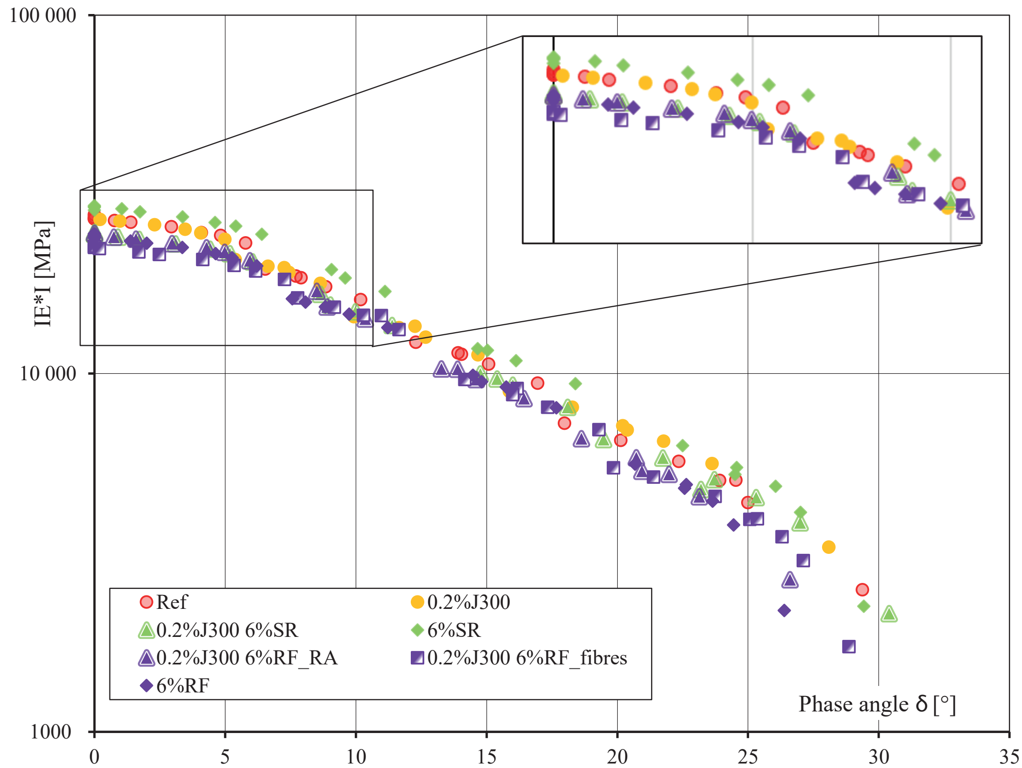


Fig. 9. Black space diagram

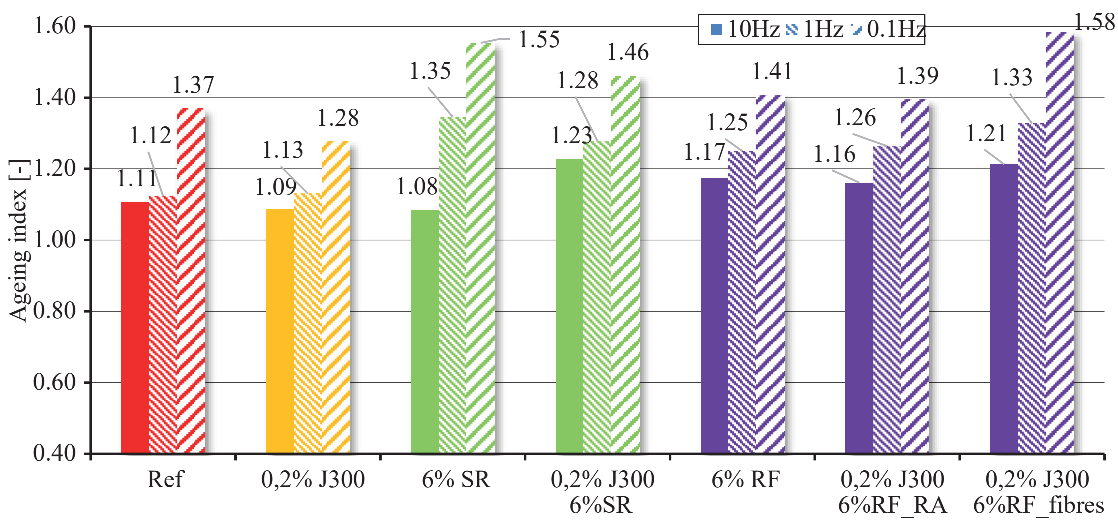


Fig. 10. Influence of the frequency on the ageing index

with the long-lasting effect, multiple characteristics should be considered. Here again, the incorporation method of rejuvenator showed the same results along the three tested frequencies and the addition of the rejuvenator on fibres brought even worst result comparing all the asphalt mixtures.

The addition of jute fibres provides the undoubtedly best result in all frequencies comparing to all the mixtures. However, mixtures with higher initial stiffness caused by oxidized bitumen will not increase their stiffness ad infinitum and thus, can exhibit lower ageing index.

4. CONCLUSIONS

The review of the literature and the analysis of the test results for the 7 variants of asphalt mix ACP 16+ with 30% RA allow formulating the following conclusions:

- The addition of rejuvenator has a positive influence on the compactability of the asphalt mixture with RA content.
- The combination of the rejuvenators with the jute fibres showed the worst ITSR values. It is well known that the lower the ITSR is, the lower the durability of the mixture would be. However, the dry ITS values of mixtures with fibres were superior and absolute values of wet ITS stayed on the same level, except one mixture. The binder absorption by fibres and low virgin binder content are possible reasons behind the decrease of the ITSR. As a solution, an increase in the binder content and fibres treatments can be suggested.
- Mixtures with rejuvenators have shown a decrease in the stiffness in comparison to the reference mixture – ACP16+ with 30% RA which indicates a good softening effect to the aged binder in the used RA. Thus, the use of these additives can be promising as new alternatives to a future increase the RA content in the mixtures. Incorporation of jute fibres leads to the increase of stiffness and decline of thermal susceptibility.
- The addition of the rejuvenators with the RA or with the fibres showed a negligeable difference in the influence of the different properties, except ageing index. Mixtures with the rejuvenators dosed onto the fibres showed worse ageing results.
- The addition of rejuvenator and jute fibres showed lower dynamic modulus along the whole range of frequency comparing to the control mixture. Despite that the addition of "SR" rejuvenator displayed similar dynamic modulus along the low/medium frequency (high/medium temperature) range to the reference mixture and higher modules along the low temperature.
- Jute fibres showed the best aging index results at 20°C and at all the frequencies.
- The effect of aging differs from one rejuvenator to another. Each has its own strength and its weakness depending on the testing boundaries like e.g., frequency in case of complex dynamic modulus.

ACKNOWLEDGEMENT

This paper was supported by the project No. SGS22/040/OHK1/1T/11.

REFERENCES

[1] *Li N., Zhan H., Yu X., Tang W., Xue Q.*: Investigation of the aging behavior of cellulose fiber in reclaimed asphalt pavement. Construction and Building Materials, **271**, 121559, 2021, DOI: 10.1016/j.conbuildmat.2020.121559

[2] *Zaumanis M., Mallick R.B.*: Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art. International Journal of Pavement Engineering, **16**, 1, 2015, 39–55, DOI: 10.1080/10298436.2014.893331

[3] Asphalt in figures 2019. European Asphalt Pavement Association (EAPA), Brussels, 2019

[4] *Pouranian M.R., Rahbar-Rastegar R., Haddock J.E.*: Development of a Soybean-based Rejuvenator for Asphalt Mixtures Containing High Reclaimed Asphalt Pavement Content. Proceedings of the 5th International Symposium on Asphalt Pavements & Environment (APE), 2019, 264–273, DOI: 10.1007/978-3-030-29779-4_26

[5] *Brownridge J.*: The role of an asphalt rejuvenator in pavement preservation: use and need for asphalt rejuvenation. in: Compendium of papers from the first international conference on pavement preservation. University of California, Berkeley, 2010, s. 351–364

[6] *Kuang D., Jiao Y., Ye Z., Lu Z., Chen H., Yu J., Liu N.*: Diffusibility Enhancement of Rejuvenator by Epoxidized Soybean Oil and Its Influence on the Performance of Recycled Hot Mix Asphalt Mixtures. Materials, 2018, **11**, 5, 833, DOI: 10.3390/ma11050833

[7] *Huang S.C., Qian Q., Grimes W., Pauli A.T., Glaser R.R:*. Influence of rejuvenators on the physical properties of RAP binders. Journal of Testing and Evaluation, 2015, **43**, 3, 594–603, DOI: 10.1520/JTE20130314

[8] *Lehtimäki H.*: Rejuvenating RAP with light oil products and a new mixing. Via Nordica 2012, Congress, Reykjavik, **1**, 8, 2012

[9] *Fini E.H., Oldham D.J., Abu-Lebdeh T.*: Synthesis and characterization of biomodified rubber asphalt: Sustainable waste management solution for scrap tire and swine manure. Journal of Environmental Engineering, **139**, 12, 2013, 1454–1461, DOI: 10.1061/(ASCE)EE.1943–7870.0000765

[10] *Xin Q., Liu Q., Wang Ch., Wang D., Oeser M.*: Effect of co-production of renewable biomaterials on the performance of asphalt binder in macro and micro perspectives. Materials, **11**, 2, 2018, 244, DOI: 10.3390/ma11020244

[11] *Park K.S., Shoukat T., Yoo P.J., Lee S.H.*: Strengthening of hybrid glass fiber reinforced recycled hot-mix asphalt mixtures. Construction and Building Materials, **258**, 2020, 118947, DOI: 10.1016/j.conbuildmat.2020.118947

[12] *Ziari H., Aliha M.R., Moniri A., Saghafi Y.*: Crack resistance of hot mix asphalt containing different percentages of reclaimed asphalt pavement and glass fiber. Construction and Building Materials, **230**, 2020, 117015, DOI: 10.1016/j.conbuildmat.2019.117015

[13] *Fakhri M., Hosseini S.A.*: Laboratory evaluation of rutting and moisture damage resistance of glass fiber modified warm mix asphalt incorporating high RAP proportion. Construction and Building Materials, **134**, 2017, 626–640, DOI: 10.1016/j.conbuildmat.2016.12.168

[14] *Arafat S., Kumar N., Wasiuddin N.M., Owhe E.O., Lynam J.G.*: Sustainable lignin to enhance asphalt binder oxidative aging properties and mix properties. Journal of Cleaner Production, **217**, 2019, 456–468, DOI: 10.1016/j.jclepro.2019.01.238

[15] *Gazia K.K., Sukhmanjit A.*: Use of natural fiber and binder quality in stone mastix asphalt mixture. International Journal of Latest Research in Engineering and Computing, **5**, 3, 2017, 73–78

[16] *Zaumanis M., Mallick R.B., Poulikakos L., Frank R.*: Influence of six rejuvenators on the performance properties of Reclaimed Asphalt Pavement (RAP) binder and 100% recycled asphalt mixtures. Construction and Building Materials, **71**, 2014, 538–550, DOI: 10.1016/j.conbuildmat.2014.08.073

[17] *Zaumanis M., Mallick R.B., Frank R.*: Evaluation of Rejuvenator's Effectiveness with Conventional Mix Testing for 100% Reclaimed Asphalt Pavement Mixtures. Transportation Research Record: Journal of the Transportation Research Board, **2370**, 1, 2013, 17–25, DOI: 10.3141/2370-03

[18] *Lu D.X., Saleh M.*: Laboratory evaluation of warm mix asphalt incorporating high RAP proportion by using evotherm and sylvaroad additives. Construction and Building Materials, **114**, 2016, 580–587, DOI: 10.1016/j.conbuildmat.2016.03.200

[19] *Kalvaitis M.*: Influence of Application Temperature on Mechanical Performance and Interface Bonding of Bituminous Mixtures Containing Reclaimed Asphalt Pavement. Vilnius, 2015

[20] Road construction – Compacted asphalt layers – Implementation and conformity control. 2019

[21] *Gallo P., Belhaj M., Valentin J.*: Asphalt concrete performance with selected types of plant-based yarns. 7th Eurasphalt & Eurobitume Congress, Madrid: Stichting Eurasphalt, 2021

[22] *Huang H., White T.D.*: Dynamic properties of fiber-modified overlay mixture. Transportation Research Record: Journal of the Transportation Research Board, **1545**, 1, 1996, 98–104, DOI: 10.1177/0361198196154500113

[23] *Vacková P.*: Výzkum a zhodnocení vybraných vlastností ovlivňujícíchživotnost asfaltových vozovek. Research and evaluation of selected properties influencing durability of asphalt pavements. Doctoral thesis. Praha, Katedra silničních staveb, Fakulta stavební ČVUT v Praze, 2020

[24] *Booshehrian A., Mogawer W.S., Bonaquist R.*: How to Construct an Asphalt Binder Master Curve and Assess the Degree of Blending between RAP and Virgin Binders. Journal of Materials in Civil Engineering, **25**, 12, 2013, 1813–1821, DOI: 10.1061/(ASCE)MT.1943-5533.0000726

[25] *Copeland A.*: Reclaimed asphalt pavement in asphalt mixtures: State of the practice. United States. Federal Highway Administration. Office of Infrastructure Research and Development, 2011

[26] *Huang B., Shu X., Vukosavljevic D.*: Laboratory Investigation of Cracking Resistance of Hot-Mix Asphalt Field Mixtures Containing Screened Reclaimed Asphalt Pavement. Journal of Materials in Civil Engineering, **23**, 11, 2011, 1535–1543, DOI: 10.1061/(ASCE)MT.1943-5533.0000223