Sustainability & Environment

Is there potential of using recycled pulverzied admixtures in asphalt mixtures as a substitute for limestone filler?

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Abstract

The general effort to reduce the exploitation of non-renewable resources and to minimize the amount of materials (waste and industrial by-products) placed on landfills form the key targets of sustainable development and circular economy. The generation of various waste materials increases continuously every year. Similarly the trend of expedient reuse or recycling of such waste materials in various construction areas and for various structures has a growing tendency and is widely supported in developed countries. Within an ongoing experimental study done by CTU Prague one of the key efforts was to find possible solutions to utilize mineral material in the form of crushed and milled (pulverized) concrete, blast furnace slag and milled gypsum boards containing calcium sulphate dehydrate with or without any additional additives. One of the possible areas for possible utilization of these different materials is its use as an alternative admixture and finely ground admixture coming from either a by-product or as treatment of C&D waste which might by applicable as an activated filler in the asphalt mixtures. The laboratory testing included empirical characteristics and determination of mechanical or functional characteristics especially stiffness modulus, resistance to water susceptibility and resistance to crack propagation which were performed on selected asphalt mixtures. For the determination of the resistance of asphalt mixture to ageing and its thermal sensitivity if added pulverized materials are used as substituents to traditional limestone filler in an asphalt mix, long-term laboratory ageing was processed and mechanical as well as functional tests were performed again. In this experimental study the alternative fillers were not tested on specific tests for fillers like sand equivalent, delta ring test or methylene blue test.

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1. IINTRODUCTION

Any construction undertaking, building as well as maintaining and reconstructing, generates construction and demolition waste. This is encountered in various adjustments to completed buildings, as well as in the process of building deconstruction. According to the Czech Statistical Office, construction and demolition waste accounted for 36.1% of the total amount of waste (24.9 million tonnes) generated in the Czech Republic in 2017. Systematising waste involves all sorts of activities related to waste management, various ways of processing up to the final exploitation wherein the waste metamorphoses into raw material for further manufacturing or another product, or is used to generate energy. In the Czech Republic, recycling of construction and demolition waste has become increasingly common (see Figure 1); nevertheless, a considerable amount of waste ends still up in landfills or is incinerated. At the same time, the target of recycling 70 % of construction and demolition waste, as envisaged in the EU strategy for 2020, is highly likely to remain unmet.

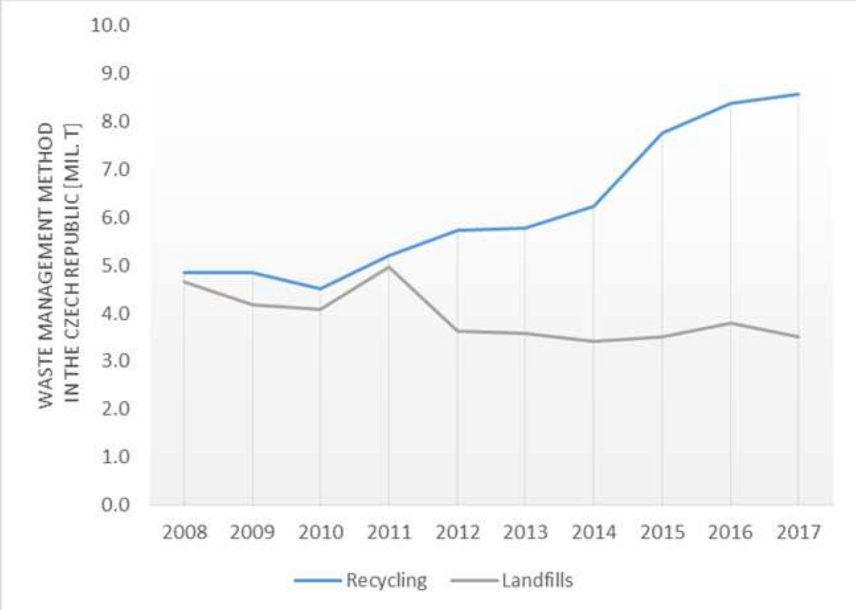

Figure 1: Waste management methods (recycling and landfills) in the time range 2008-2017 for the Czech Republic

The construction industry is the largest consumer of natural resources as well as a major producer of recycled materials transformed from construction and demolition waste. The Waste Management Plan (WMP) of the Czech Republic for 2015 - 2024 for construction and demolition waste lists increasing the proportion of re-use and recycling of construction and demolition waste (at least 70 % by mass of total waste generated) as one of the targets set for this decade. The plan focuses on making a priority of those waste management practices according to the European waste management hierarchy, and of achievement of the targets across all waste handling areas. The strategy proposed in the WMP for the Czech Republic declares a clear shift away from landfills (this is a necessity with regard to European legislation as it must be achieved by January 1, 2024) through prevention of waste generation, increased recycling and reuse of waste materials. [1, 2, 3]

2. VARIOUS TYPES OF CONSTRUCITON AND DEMOLITION MATERIALS AS A SUBSTITUTE FOR THE TRADITIONAL LIMESTONE FILLER

Recycling of construction materials is an important instrument within the efforts towards sustainable development and bridging the gap between economic growth and environmental protection. If applied correctly, recycled materials are as valuable as standard materials in many cases. Three different types of inorganic waste materials, pre-processed by high-speed milling, were used for further application: (i) fine grained and micronised recycled concrete from cement-concrete pavement (“BET” mixture); (ii) finely ground fractions of blast furnace slag in the form of active microfiller ("ST" mixture); and (iii) finely ground gypsumboard shavings ("MS" mixture) after partial cardboard removal and disintegration of material which comes from partition walls construction, with the intention of replacing the traditional filler (reference mixture labelled "R") in asphalt mixtures which normally use limestone filler. There are two different functions of filler in the asphalt mixture: on the one hand, it fills fine cavities, reducing their size, and on the other hand, it has some impact on the properties of the bituminous binder in the mixture, i.e. increasing its viscosity and reducing thermal and water susceptibility at the same time, helps to improve adhesion and impacts the mix stiffness.

2.1. Cuttings of gypsum boards and panels

Gypsum boards and panels are produced by a pressing technology using two layers of cardboard. The core itself consists of a porous mass comprising calcium sulphate - dihydrate ($CaSO_4.2H_2O$ - gypsum) and hemihydrate ($CaSO_4.0,5H_2O$), reinforced with paper or glass fibers and other substances to modify the ultimate properties of the final product, such as resistance to mould or fire, low water absorption etc. such alternative additives can be e.g. silicon. [4, 5]

2.2. Blast furnace slag

The research activities discussed herein involved stable air-cooled blast furnace slag from Kladno which were produced during the period between 1900 and 1980 and it was assumed to use this material as an alternative to the traditional limestone filler. Screened fractions with fine grain or material additionally treated by high–speed milling were selected for the research. Generally, metallurgical slag is classified in two basic groups - blast furnace slag and steel industry slag. Blast furnace slag is a loose grainy metallurgical material which is produced as a by-product in the metal melting and refining processes - in the production of pig iron in blast furnaces. During pig iron production in the blast furnace, the slag binds all non-ferrous parts of the iron ore. During the blast furnace tapping, the end-stage blast furnace slag is tapped together with pig iron at a temperature of around 1450 °C. The two materials are kept separate due to their different densities. The slag is separated from the pig iron in the main tap trough by means of a baffle which navigates the lighter slag to the slag trough conveying it to slag pans or for direct processing. The chemical composition of the slag depends primarily on the input materials of the production. In addition, blast furnace slag depends on the type of iron produced and the amount of coke used in production. The basic components of tapping slag include CaO, MgO, Al2O3 and SiO2, which account for 80-90 % of the total system weight and determine the properties of the slag. Blast furnace slag has a broad range of uses in the construction industry. One possibility is using it as a granular material for backfills/embankments or as aggregate in the structural layers of roads. Another solution especially for slag with high SiO2 content is the use for blended cements. [6, 7, 8, 9]

2.3. Recycled material from cement-concrete road surfaces

The last choice of a substitute for the traditional asphalt mix filler was recycled concrete from the surface of motorway D2 between Brno and Bratislava. The recycled concrete (screened 0/2 mm fractions) was milled using mechano-chemical activation by high-speed milling in a disintegrator to achieve a maximum particle size of less than 50 µm and a specific surface above 300 m2/kg to allow a broader range of application and modify its technological properties. The effect of mechano-chemical activation by high-speed milling delivers a significant improvement in the use of energy dedicated to the milling, as has been reported in several other articles by CTU Prague. It is based on the accumulation of a part thereof in the form of increased enthalpy of the substance processed. This effect also permits inducing chemical reactions in the solid state of the material during milling (e.g. oxidation or exchange reactions) or initiating phase changes (rather than just amorphisation) in various substances, or initiating catalytic reactions in organic and inorganic systems during grinding/milling in the high-speed milling machines (disintegrators). [10, 11]

3. ASPHALT MIXTURE DESIGN

The assessment of how selected types of traditional filler substitutes affect the properties of the asphalt mixture involved research of mixture BBTM 8A for very thin wearing courses of non-rigid and semi-rigid pavements (A - mixtures with a high proportion of small aggregate and fine particles, with maximum aggregate grain size of 8 mm). This type of asphalt mixture was chosen with respect to the fact that its grading curve can generally be defined using two narrower fractions while a reasonably higher amount of filler components can be used therein. BBTM asphalt mixtures, originally developed in France in the early 1990s, are usually applied in a thickness of 20-30 mm. The design of BBTM 8A used aggregate of a spilite petrographic composition from the Sýkořice (Zbečno) quarry, fractions 4/8, 2/5 and 0/2. In the case of the reference mixture (“R”), the filler was a limestone powder (JMV) from Velké Hydčice; the quantities amounted to 7.6 %-vol. according to the adopted mix design. In the case of other mixtures, the relevant filler substituted was used - the doses were determined by weight to the same quantity regardless of the degree of fine grinding of selected materials and, consequently, their specific densities and specific surface areas. Polymer-modified bitumen (PMB) 25/55-60 was used as a binder; although it is not the ideal type for this particular sort of asphalt mixture, it absolutely suffices for laboratory purposes. The production and design of the mixture, including the percentages of individual components, comply with product standard CSN EN 13108-2.

Table 1. The asphalt mix design of BBTM 8A

Asphalt mixture	Bituminous binder PMB 25/55-60	Filler	DDK 0/2 Zbečno	HDK 2/5 Zbečno	HDK 4/8 Zbečno
BBTM 8A	5.5	7.6	19.9	28.4	38.8

4. THE EFFECT OF AGEING

Thermo-oxidative ageing is a huge problem of thin asphalt layers with regard to the weather conditions at play. Ageing occurs through reactions of the asphalt with atmospheric oxygen and its interaction with UV radiation; as a result, the binder solidifies and becomes increasingly brittle. Such pavements are more susceptible to cracking. As ageing is faster on the surface of the pavement, thin asphalt layers are more susceptible to ageing than thicker layers. This is why we believe this aspect must, and should, be researched within experimental designs and asphalt mix development for the relevant type of structural layer. One of the simulations of long-term ageing which is also listed in prEN 12697-52 was selected based on research experience of the Road Laboratory at CTU Prague. The method includes the conditions for test specimen conditioning at 85 °C for 5 days in an oven with forced air circulation.

5. THE PARAMETERS OF BBTM 8A ASPHALT MIXTURES RESEARCHED

The assessment of the suitability of traditional filler substitutes in BBTM asphalt mixtures was made on the basis of tests, determining indirect tensile strength, water sensitivity, stiffness modulus and thermal susceptibility. Knowledge yielded from selected tests including the effect of long-term ageing according to prEn 12697-52 also formed a part of the test set.

5.1. Basic physical properties of the mixture designs

The determination of voids content in the asphalt mixtures is based on ČSN EN 12697-8; the calculation depends on the density of the compacted test specimen and the maximum density of the asphalt mixture. ČSN EN 13108-2 stipulates a permissible voids content range of 3.0-6.0 %-vol. for BBTM 8 A mixtures. With respect to the selected grading curve and the specified binder quantity, the observed voids contents with no additional optimisation steps amount to values comparable to reduced surface noise mix modifications of the BBTM 8NH type (asphalt concrete for thin wearing courses with reduced noise levels, grain size 0/8 mm), while the 2017 Technical Specifications declare voids content as 10.0 to 14.0 %-vol. From the point of view of researching the resistance to water in combination with asphalt film ageing, this result is more favourable.

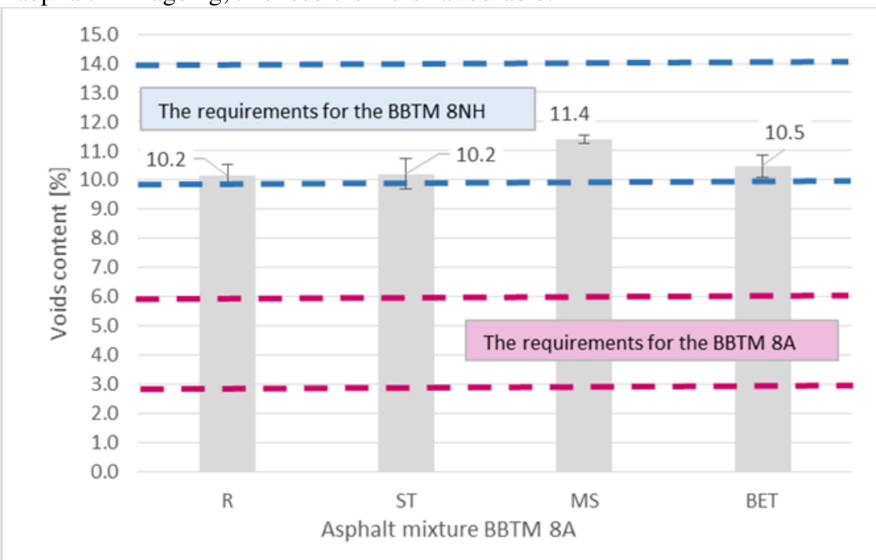

Figure 2: Voids contents of BBTM 8A asphalt mixtures for very thin wearing courses

5.2. Water Susceptibility

Discussing the tests performed, the fundamental parameter is the resistance of assessed asphalt mixtures to water, which was determined in accordance with the relevant ČSN EN 12697-12 standard as well as by the modified method based on the US standard, AASHTO T-283, as has become established practice at CTU Prague in the last 6 years. The essence of the test is dividing the test specimens compacted by 2x25 blows of impact compactor prepared from every single asphalt mixture version into three groups - dry specimens kept in air at room temperature, specimens exposed to water saturation followed by immersion in a water bath at 40±1 °C for 70±2 hours, and specimens undergoing an accelerated ageing process with subsequent keeping at -18±3 °C for at least 16 hours. After this time, the specimens are immersed in a water bath at 60±1 °C for 24±1 hour. Such prepared test specimens were then used to determine the indirect tensile strength according to ČSN EN 12697-23 at the stipulated test temperature. The diagram in Fig. 3 summarises the indirect tensile strength ratios of the test specimens immersed in a water bath compared to the indirect tensile strength values of the specimens kept in air, expressed as a percentage.

According to the requirements of ČSN EN 13108-2, the minimum value of the indirect tensile strength ratio for BBTM 8A is set at 80%, which is also required if the mixtures assessed in the experiment are to be evaluated under the requirements of Technical Specifications TP 259 for BBTM NH mixtures. The comparison of the indirect tensile strength ratios for mixtures with various substitutes for the traditional limestone filler (Fig. 3) shows that the minimum ITSR value was achieved for the reference asphalt mixture and for the mixtures with blast furnace slag and fine-grained recycled concrete. In the case of the blast furnace slag, the indirect tensile strength ratio even exceeds 100 percent, when the indirect tensile strength values measured on saturated test specimens conditioned in water bath score higher than test specimens kept just in dry air. The result obtained may be genuine; nonetheless, it must be accepted with caution as the indirect tensile strength test itself is sensitive to the test temperature, and any deviation therefrom, by 1 °C even, may result in a slight underestimation or exaggeration of the results for the individual asphalt mixtures. This is always emphasised if the results of specimens which had undergone water conditioning at higher temperatures exceed the values achieved by the dry test specimens.

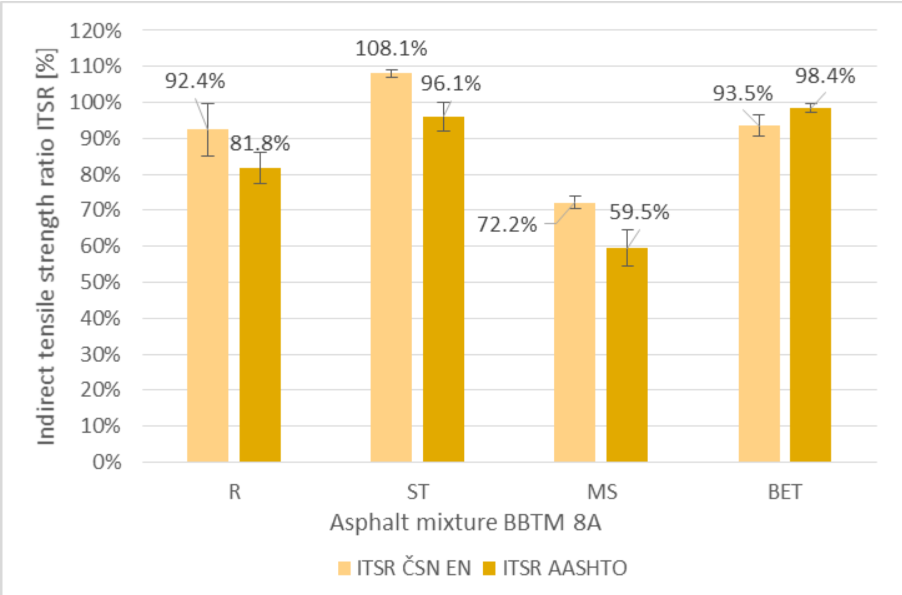

Figure 3: Determination of water sensitivity of BBTM 8A asphalt mixtures for very thin wearing courses according to the EN approach and modification of the US test method

In the case of the recycled gypsum board substitute, the ITSR value is lower than that of the reference mixture; the requirements of the standard have not been met either. This mixture demonstrates the envisaged negative effect of gypsum and its reactivity when water appears repetitively which was not eliminated from the input material during the initial disintegration, even though the material was refined significantly to facilitate superior coating by the bituminous binder. Focusing on a comparison of the individual options where the modified AASHTO method was applied, we should mention first and foremost that the for this procedure no minimum limits required for ITSR ratios are set or fixed in any standard in The Czech Republic. At the same time, there are no limits set for this alternative method of water susceptibility determination in European product standards. Let us mention that the difference between the standard employed at CTU in Prague and the US standard consists of the following aspects: (i) the compacting does not involve a gyrator, but a Marshall impact compactor with compaction specifications for the specimens as in case of the water resistance test according to ČSN EN 12697-12; (ii) the specimens compacted have 100 mm diameter; and (iii) test specimens are not compacted to a uniform voids content of 7 %-vol. However, to allow comparisons within this paper, an ITSR limit of 70 % was chosen with respect to the less favourable conditions to which the test specimens were exposed. Despite the inferior conditions of applying a single freeze cycle at -18 °C at least for 16 hours, it is apparent that the BBTM asphalt mixtures, except for the MS one, achieve values exceeding 80 %.

5.3. Stiffness Determination

Another important parameter in the asphalt mixture properties is the stiffness modulus, which was determined at four temperatures (0 °C, 15 °C, 27 °C, 40 °C), including the calculation of the thermal susceptibility ratio. The stiffness test method employed complies with the technical standard, ČSN EN 12697-26, while method "C" was chosen (non-destructive indirect tensile stress test on universal asphalt apparatus or universal tester (loading frame) on cylindrical specimens). Six test specimens were produced for this purpose and the specimens were compacted with 2x50 blows by Marshall impact compactor.

The values determining the deformation behaviour in the medium temperature range are those taken at 15 °C; this temperature is also considered the most important from the perspective of pavement structure design according to the Ministry of Transport Technical Specifications TP 170. The stiffness values measured show a positive effect of substituting the filler with blast furnace slag, when the test specimens demonstrated clearly superior test results not only at 15 °C (9 337 MPa) but at all selected test temperatures, i.e. in the low temperature range as well as higher temperature ranges when compared to the reference asphalt mixture which used the traditional limestone filler - this is a potential indicator of suitability of the slag dust for application in road construction. Comparing the results of the stiffness modulus tests at the remaining temperatures, we can see that the blast furnace slag version scored a higher stiffness modulus compared to the reference mixture at 0 °C (by 13 %), at 27 °C (by 18 %) and at 40 °C (by 2 %). The mixtures with ground gypsum board and fine-grained recycled concrete demonstrate the opposite tendency. In the case of the "BET" mixture, the stiffness modulus at 15 °C decreased by approximately 35 % compared to the reference mixture with limestone filler while the MS mixture had 11 % less. This trend is evident at the remaining test temperatures, when the substitutes (i.e. ground gypsum board and ground recycled concrete) demonstrate deteriorated deformation behaviour of the asphalt mixture for very thin wearing courses. Yet another interesting parameter, namely the thermal susceptibility indicator of the asphalt mixture in question, confirms this conclusion as well. The lower the S0/S27 stiffness ratio, the less susceptible to temperature changes the mixture can be. The mixture with blast furnace slag shows the least susceptibility while the MS and BET mixtures demonstrate the highest susceptibilities.

Table 2. Determination of indirect tensile strength and stiffness modulus of BBTM 8A mixtures

Filler Substitute	BBTM 8A	Voids content [%]	Indirect tensile strength [MPa]			Stiffness @ T °C [MPa]				Thermal susceptibility
			ITS_{dry}	ITS_{wet}	ITS_{w+f}	0	15	27	40	S_0/S_{27}
Limestone	R	10.2	1.52	1.40	1.24	17 147	9 082	3 600	1 745	4.76
Blast furnace slag	ST	10.2	1.73	1.87	1.66	19 317	9 337	4 241	1 787	4.55
Gypsum board	MS	11.4	1.58	1.14	0.94	14 300	8 045	2 703	1 181	5.29
Recycled concrete	BET	10.5	1.58	1.48	1.56	12 102	5 850	2 320	728	5.22

Due to the laboratory ageing process applied to the test specimens after the stiffness test, the thermal susceptibility indicator fell by approximately 25 % on average with the exception of the BET mixture (which achieves almost the same value as the stiffness ratio of unaged test specimens). So, we can note that in this case, the asphalt mixture most susceptible to temperature changes seems to be the mixture with micromilled recycled concrete. As indicated by the results presented in Table 3, exposure to long-term ageing means increasing stiffness modulus for all the mixtures. If we look at the crucial temperature, 15 °C, the stiffness modules of the R and ST mixtures are 12 % higher, and the MS and BET mixtures score a value even 24 % higher than the figures measured before the ageing. Based on the results we obtained, the blast furnace slag substitute appears to be a potential substitute for limestone filler in terms of the stiffness modulus values - it demonstrates the same trend as the reference asphalt mixture.

Table 3. Determination of stiffness modulus of BBTM 8A mixtures after ageing 5d @ 85 °C according to prEN 12697-52

BBTM 8A	Stiffness modulus after long-term ageing @ T °C [MPa]				Thermal susceptibility	Index of ageing @ T °C [MPa]				Thermal susceptibility
	0	15	27	40	S_0/S_{27}	0	15	27	40	S_0/S_{27}
R	17 719	10 162	4 985		3.55	0.95	1.11	1.31		0.73
ST	18 373	10 329	5 561		3.30	1.03	1.12	1.38		0.75
MS	16 262	9 859	4 293		3.79	1.14	1.23	1.59		0.72
BET	14 340	7 227	2 894		4.95	1.18	1.24	1.25		0.95

5.4. Asphalt Mixture Resistance to Crack Propagation

One of the possible approaches to the assessment of asphalt mixture behaviour in the low temperature range is testing resistance to crack propagation by means of the three-point bending test on half-cylindrical test specimens in compliance with ČSN EN 12697-44 of 2011 (actually, the values should be recalculated according to adjusted formulas according to the 2016 revision of the standard). In contrast to the basic definition given by the standard, CTU Prague has been using half-cylinder test specimens with a 100 mm diameter with a groove of the defined depth (the standard requires test specimens of 150 mm diameter, compacted by a gyrator. Since CTU Prague is the only place in the Czech Republic capable of preparing such test specimens, the application of the standard method with no modification is not encouraging for the later practical application of the method). Test specimens prepared in this way are loaded at a constant speed of 2.5 mm per minute (another deviation from the standard, which recommends a loading rate of 5.0 mm per minute. Here, the change in loading rate is justified by the fact that, besides the critical value of fracture toughness - i.e. the analogue of the strength upon maximum force – CTU Prague also assesses the fracture energy, which is determined as the area under the load-displacement diagram of the test. To allow this area to be calculated, the ALMEMO data logger is used to record the deformation force step by step, and a lower loading rate improves the precision of the log). The essential test results are the maximum stress and fracture toughness (fracture resistance) values. The test was performed at 0 °C. The critical fracture toughness values were also measured in aged specimens subjected to simulated laboratory long-term ageing according to prEN 12697-52, as in the case of stiffness modulus testing. The result is always given as the average of at least six half-cylinder specimens. In our experience, this quantity should not be any lower due to the variability of this test.

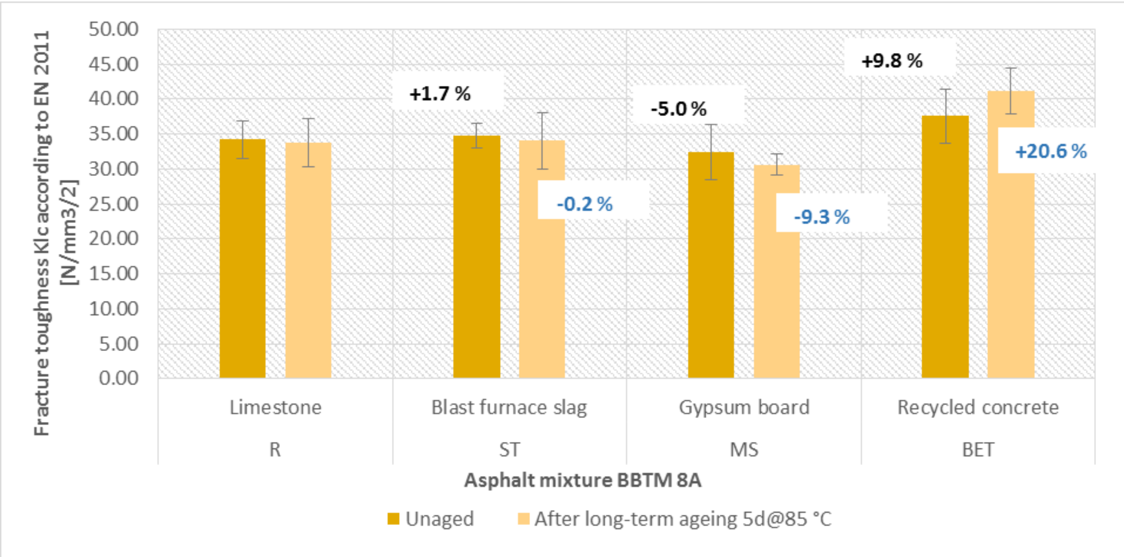

Figure 4: Comparison of critical values of fracture toughness KIc of BBTM 8A asphalt mixture according to ČSN EN 12697-44: 2011

The diagram in Fig. 4 compares the values measured for fracture toughness. For the sake of simplification, we can note that the higher the fracture toughness, the better the asphalt mixture resistance to frost cracking might be. The results show that the reference mixture with the limestone filler and the ST mixture with blast furnace slag achieve the same values, on average, while the BET mixture with recycled concrete scores the highest values (10 % more than the reference mixture); the MS mixture with ground gypsum board records the lowest values. Considering the higher strength characteristics of the aged test specimens (higher stiffness modulus) and taking into account the effect of ageing on the asphalt mixtures, a lower degree of brittle fracture resistance is expected in the low temperature range. This hypothesis is only noticeable in the results of the MS mixture; in contrast to that, the BET mixture demonstrates a 20 % increase in comparison to the reference mixture with limestone filler. The reference asphalt mixture and the mixture with limestone filler substituted by blast furnace slag achieves comparable values, not only if compared to each other, but also when compared to the unaged test specimens. Therefore, the long-term laboratory ageing applied to the test specimens of the asphalt mixtures on test does not cause any deterioration in the mechanical fracture characteristics tested in the low temperature range.

Another indicator on test is the fracture energy, the diagram in Fig. 5 shows a comparison of the above-mentioned asphalt mixtures before and after ageing in terms of fracture (deformation) energy or work required for a crack to appear. In the case of the ST mixture which scores almost the same fracture toughness values as the reference mixture, a higher deformation energy is necessary for a crack to appear than in the case of the reference mixture. This is similar for the MS mixture, in which a lower fracture toughness was measured. Unfortunately, the force and deformation data of the BET mixture before ageing is not available, so no comparison can be made in this case. If we focus on comparing the fracture energy of test specimens subject to laboratory ageing, the BET mixture with the highest fracture toughness appears to be the most resistant in terms of the deformation energy needed for cracking. In contrast to that, the post-ageing fracture energy is lower in the case of the mixture with blast furnace slag not only when compared to the reference mixture, but even after the long-term ageing simulation on asphalt mixture with MS.

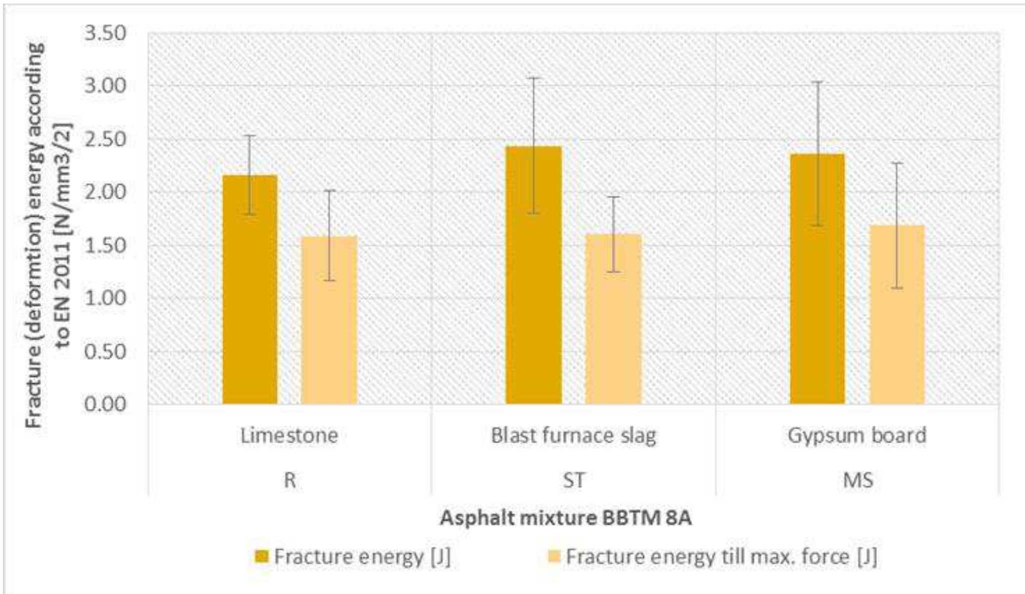

Figure 5: Results of fracture (deformation) energy of BBTM 8A asphalt mixtures according to ČSN EN 12697-44: 2011

6. CONCLUSION

This paper aims to assess BBTM 8A asphalt mixtures for very thin wearing courses with selected substitutes of the traditional fine-grained limestone filler consisting of selected waste materials or by-products, namely ground gypsum board and panel cuttings, separated recycled concrete fraction 0/2 mm from cement-concrete pavement and blast furnace slag. The results as measured suggest that the alternative solution with the best potential is the addition of blast furnace slag, which provided an improvement of the strength characteristics, higher resistance to water and freezing and, at the same time, lower thermal susceptibility. The high stiffness modulus, compared to the reference mixture, was retained even at the higher test temperature of 40 °C. In the low temperature range, the blast furnace slag substitution achieved values that are comparable to those of the limestone filler as far as fracture toughness is concerned. Equally interesting results are achieved by another waste material, which is recycled concrete that scores higher in resistance to water, including the option with a single freeze cycle. The substitution by recycled concrete and its behaviour in the asphalt mixture in the low temperature range improves resistance to crack formation and propagation (the mixture scores higher in terms of fracture toughness).

The exploitation of waste materials in the form of blast furnace slag and ground recycled concrete from the cement-concrete road pavement appears to be a potential legitimate substitute for the asphalt mixture filler, even with respect to maintaining the quality of the asphalt mixtures produced where the recycled materials behave identically to the standard materials (limestone filler, in the case at hand); in some cases, the use of such materials delivers an improvement in the asphalt mixture characteristics that are being tested.

Finally it has to be stated that we fully support the idea that an asphalt pavement is not a waste disposal. On the other hand presently it is important to turn from linear economy to circular. Existing natural resources are not unlimited and it is important to seek case by case for the best achievable value. If limestone filler actually might have a price of 25 EUR/t and the limestone quarries have to supply with this material cement industry, thermal power plants, gypsum board producers and others, and on the other hand efficiently not used existing volumes of finer fractions or particles of recycled concrete or blast furnace slag exist and can be delivered for e.g. 20 EUR/t the focus might be clear. If application in asphalt mixtures makes technically sense, it shall be used.

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