SUSTAINABLE METHODS FOR IMPROVING THE RHEOLOGICAL CHARACTERISTICS OF ASPHALT MIXTURES

PhD Thesis - Abstract

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The PhD thesis entitled „Sustainable Methods for Improving the Rheological Characteristics of Asphalt Mixtures" was developed based on studies and research conducted in the laboratories of the Civil Engineering Faculty Timisoara and the Research Institute for Renewable Energies of the Politehnica University Timișoara, during 2017-2021. An Erasmus mobility (Egletons, January-April 2019) and a Fulbright scholarship (academic year 2019-2020) provided an opportunity for additional documentation and participation in new research programs. Moreover, they allowed comparing and improving the interpretation of the results obtained in the research carried out in Romania.

The doctoral thesis is structured in five chapters, extended on 242 pages and comprising 107 figures, 66 tables and 185 bibliographic titles.

The main objective of the PhD thesis is to identify the possibilities of producing, in the climatic and traffic conditions peculiar to Romania, asphalt mixtures at lower temperatures (hereinafter referred to as warm mix asphalts - WMA), compared to the classic asphalt mixtures (called hot mix asphalts - HMA). In this regard, tests were performed to determine the optimal dosage for an asphalt concrete for use as a surface layer, to evaluate the laboratory performance of asphalt mixtures prepared at low and classical temperatures, to quantify the effect of additives (chemical additive, organic additives and synthetic zeolite) on the performance of WMA mixtures, to evaluate the physical-mechanical characteristics of the different types of WMA, to study the effects of the additives used on the mechanical characteristics of the WMA, to study the behavior of the bitumen when adding the additives and to evaluate the environmental impact of the warm mix asphalts, respectively.

The first chapter of the PhD thesis presents the synthesis of bibliographic studies on the state-of-the-art of the production of warm mix asphalts and the establishment of the need to implement such technologies based on the general concept of sustainable development.

The concept of sustainable development (sustainability) refers to all forms and methods of socio-economic development that focus primarily on ensuring a balance between social, economic and environmental aspects and the elements of natural capital. The most well-known definition of sustainable development is certainly the one given by the World Commission on Environment and Development in the report „Our Common Future", also known as the Brundtland Report: „sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. Sustainable development is not only focused on the environment but also includes three pillars: economic development, social progress, and environmental protection. Thus, in all situations, technical–economic solutions that facilitate the synergy of these three pillars should be adopted.

Generally, the classic (hot) asphalt mixes are prepared by heating the component materials (aggregates and bitumen) at temperatures of 160-180ºC, leading to the use of an important quantity of fuels and greenhouse gas emissions released into the atmosphere during the manufacturing, transportation, and construction processes. The high temperatures of HMA also create safety issues for construction workers. Hence, cold asphalt mixtures are prepared at ambient temperatures using asphaltic emulsions to solve these problems. Unfortunately, cold asphalt mixtures have lower cracking and deformation performance than HMA and are not typically used for fabricating surface layers with high durability.

Warm mix asphalt (WMA) has been used worldwide to combine the advantages of HMA and cold mix asphalt. Thus, the warm mix asphalts, which have significantly lower preparation and laying temperatures than in the case of hot mix asphalts, have been designed worldwide (preparation temperatures of about 120-150°C and laying temperatures of 100-130°C). The required workability for adequate mixing and compaction is achieved using additives (chemical or organic) or zeolites (natural or synthetic). According to a study, the application of these techniques can reduce greenhouse gas emissions by 10–50% and fuel consumption by 11–35% [2].

According to the European Asphalt Pavement Association [3], the techniques to produce WMA can be classified as follows:

- bitumen foaming techniques;
- organic additives techniques;
- chemical additives techniques.

Various foaming techniques are mentioned in the literature, such as water containing additives and water based processes [2–7]. These techniques are aimed to reduce binder viscosity during the mixing and compaction of the asphalt mixture. Several methods are used for adding small quantities of water into hot binders. When water is mixed with bitumen, the water transforms into vapor, which increases the binder volume and decreases the binder viscosity for a limited time. This behavior signifies that when the mixture cools, and the formed foam disappears, the bitumen starts to exhibit the characteristics of pure bitumen.

Organic additives are directly added to the bitumen or mixed with the asphalt mixture to reduce the bitumen viscosity. Organic additives must be selected such that their melting temperature exceeds the temperature expected for the bituminous layer to reach the field for it to have lower susceptibility to low temperatures and exhibit good performance at permanent deformations [8,9].

The chemical additives do not influence the viscosity of the bitumen; instead, they act as surfactants and reduce the friction at the binder–aggregate interface, at temperatures of 90-140°C, thus making possible the achievement of a more uniform blend between the binder and the aggregates and to compact the asphalt mixture at lower temperatures than usual [2,3,5].

The advantages of the WMA [2,3,10,11] can be summarized as follows:

- improvement in working conditions for workers owing to minimized emissions and exposure to less heated work environments;
- reduction in the emission of greenhouse gases, which are harmful to the environment;
- ability to lay bituminous layers at lower temperatures, which results in an increased construction period;
- longer haulage distances;
- easier compaction owing to improved workability;
- quicker commissioning of the bituminous layer for traffic use;
- possibility of adding large quantities of reclaimed asphalt pavement without compromising performance;
- reduction in total energy consumption during the production of bituminous layers.

In Europe, based on laboratory and field pavement performance data obtained within the last four years, WMA mixes exhibit similar or even better performance than HMA mixtures [12–15]. Similar performances have been reported in the USA between the two asphalt mixture types after two years of use [6,8,16]. However, the long-term performance of WMA mixes has not been investigated in detail owing to limited field data [11]. Based on previous research studies, some aspects of WMA mixes, such as water sensitivity, stiffness, and resistance to permanent deformation, need to be examined.

In the last decade, the road specialists are more and more concerned about finding viable technologies to reduce the fuel consumption and greenhouse gas emissions.

The study of the component materials of the asphalt mixture (Chapter 2) aimed, on the one hand, to determine the characteristics of the basic materials - natural aggregates, filler and bitumen with which it was intended to work on the design of warm mix and on the other hand, to verify the influence that different additives used on the characteristics of the pure bitumen considered.

The laboratory tests were performed within the Laboratory for Geotechnics and Overland Communication Ways of the Department of Overland Communication Ways, Foundation and Cadastral Survey, Civil Engineering Faculty Timișoara.

The used natural aggregates originate from a diorite deposit, with extremely compact rock and high mechanical strength. Laboratory tests specific to natural aggregates for roads have shown high resistance to fragmentation and wear and proper processing by crushing and sorting (granularity, particle shape). The tests carried out led to the conclusion that the sands and crushed stones investigated are suitable for use in the preparation of asphalt mixtures.

The analyzed filler revealed classic characteristics of limestone, with the granularity corresponding to the requirements imposed to be used in the preparation of asphalt mixtures.

The bitumen is a hydrocarbon binder used in road technology. Due to its easy use and its main properties (especially related to: adhesiveness, plasticity, ductility, insolubility in water and inertia to numerous chemical agents), has undergone an important development in the road and industrial fields [17–20]. Its rheological behavior is different depending on the conditions of load and temperature [21–23]. It deforms differently for normal ambient temperatures and for loads from extremely varied traffic in size and frequency of application [24,25]. Understanding bitumen flow and deformation is important for evaluating the performance of asphalt mixtures. Thus, the asphalt mixtures that deform easily are prone to rutting, and those that are too rigid are susceptible to fatigue and cracking.

Through the specific tests performed: standard penetration, softening point ring and ball, ductility, it has been shown that the binder considered is a 50/70 penetration grade virgin bitumen, suitable for the construction of asphalt concrete for the surface layer in hot climatic zones, including the Banat region in Romania. Also, the verification of the adhesion of the bitumen to the considered natural aggregates, by the qualitative test method with the spectrophotometer, led to the conclusion that the binder has a very good adhesiveness to the aggregate particles.

To highlight the rheological character of the bitumen, additional laboratory tests are required. The Bending Beam Rheometer (BBR) test was developed to facilitate the determination of the rheological characteristics of bitumen at low temperatures and the Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic behavior of bitumens at medium and high temperatures.

The second part of the investigations concerning bitumen blends with various additives (chemical additive, synthetic zeolite, classic synthetic wax, softer synthetic wax, respectively) aimed at identifying how the characteristics of pure bitumen are affected by the addition of additives. This resulted in six sets of tests of pure bitumen, respectively pure bitumen + the before-mentioned additives.

The evaluated bitumen blends are: pure bitumen, bitumen with 3% classic synthetic wax by weight of the binder (B + 3%W1), bitumen with 1.5% classical synthetic wax by weight of the binder (B + 1.5%W1), bitumen with 1.5% softer synthetic wax by weight of the binder (B

+ 1.5%W2), bitumen with 0.5% chemical additive by weight of the binder (B + 0.5%C), bitumen with 5.5% synthetic zeolite by weight of the binder (B + 5.5%Z), respectively.

By carrying out the specific tests on bitumen blends with additives, classical wax has been found to have the greatest influence on the characteristics of pure bitumen. Thus, the addition of the classic organic additive in a percentage of 3% results in the most accentuated hardening of the bitumen, which leads to non-conforming values for a 50/70 bitumen, for the penetration at 25 ºC, the softening point and the penetration index. If the synthetic wax is added in a proportion of only 1.5% then the penetration index falls within the allowable limit, however without the penetration and softening point being similar to the value of the pure bitumen.

The closest results of pure bitumen were obtained when using the chemical additive, while synthetic zeolite and soft wax lead to a small impairment of the initial characteristics. Basically, the characteristics obtained after the introduction of additives correspond to a 50/70 penetration grade bitumen.

Also, in the case of the BBR and DSR tests, as in the case of the classic bitumen tests, a hardening of the bitumen was found with the addition of wax, with the addition of conventional wax and especially in the case of a high content of 3%. The same properties were maintained in the case of the blends with synthetic zeolite or chemical additive.

The laboratory testing with the BBR device of the susceptibility to low temperatures of the binders and bituminous mastics as presented above allowed to highlight the fact that the additives considered to be used in the preparation of warm mix asphalts do not lead to significant changes in the rheology of pure bitumen, even if small influences are observed of their presence in mixtures.

The allure and the values obtained for the curves of the flexural creep stiffness and the slope m (the slope of the stiffness curve with respect to time) are close for all the tested binders. It is noticeable that the values of the slope m are very close in the case of bitumen blends, and in the case of pure bitumen, the values are higher. Lower values may indicate that the use of the considered additives leads to a lower capacity of the bitumens obtained to release the accumulated thermal stresses at reduced temperatures.

The allowed limit temperature for a certain bitumen blend represents the highest, most unfavorable temperature between the temperature corresponding to a flexural creep stiffness of 300 MPa at 60s and the temperature corresponding to a slope m of 0.30 at 60s. The allowed limit temperature has resulted for most of the samples studied depending on the temperature at which the limit value of the flexural creep stiffness is reached, and it can be deduced that it mainly controls the development of the thermal stresses. Harder bitumen leads to higher stresses than softer bitumen, independent of the slope value. However, for close values of the flexural creep stiffness, the slope m can play an important role in developing stresses at low temperatures.

The allowed limit temperature is slightly higher in the case of bitumen with wax, than in the other cases, the conclusion being that it makes it more susceptible to the temperature. The same conclusion is drawn for bituminous mastic mixes with wax.

The chemical additive is the one that leads to the lower impact on the bitumen’s characteristics, whereas the classic wax is the one that leads to the most important changes. The wax is responsible for a notable increase in softening point and limit temperature, compared to the other studied additives.

In the case of the bituminous mastics tested, the results obtained lead to similar conclusions as for the binders. However, there is an important increase in stiffness, the flexural creep stiffness being 2.5-3.0 times higher in the case of mastics than in the case of binders. Regarding the values of the slope m it is found that they are very close to those obtained on the bitumen blends. Under these conditions, a considerable increase in the allowed temperature limit is observed with the addition of the filler in the mixture in all cases, resulting in a higher susceptibility to the temperature of the bituminous mastic compared to the pure binder used.

These results are also confirmed by the literature which shows that bituminous mastic leads to increased rigidity and stability of asphalt mixtures at high temperatures. Therefore, the increase of the softening point ring and ball, respectively of the allowed limit temperature, for all binders considered, by the addition of filler, confirms a better behavior at high temperatures of the mastic, compared to the bitumen. The classic wax induces an increase in the softening point of up to 93.6 ° C (for the 3% dosage), while for the other additives and the pure bitumen the softening point reaches 56-59 ° C, which may indicate a high susceptibility to cracking of such mixtures.

The results obtained by the DSR test on bitumens and mastics converge towards the same conclusions, namely that classical wax, the higher the content of additive, leads to the impairment of the characteristics of pure bitumen. Other additives, including softer wax, behave similarly to the original binder.

The study of asphalt mixtures (Chapter 3) aimed at comparing the characteristics determined in the laboratory for warm mix asphalts mixed-compacted at various temperatures (140-120, 120-120, 120-100 °C) using additives: classic wax, soft wax, chemical additive, synthetic zeolite, with the characteristics for the same type of hot mix asphalt. It was considered an asphalt concrete dosage for the surface layer with natural aggregates with a nominal maximum aggregate size of 16 mm, widely used in the construction of Romanian roads.

In the study, the long-term performance of different types of asphalt mixtures was evaluated by comparing the test results. The evaluated asphalt mixtures were as follows: HMA, asphalt mixture mixed and compacted at WMA temperatures (HMA_LT), WMA containing 3% wax by binder weight (WMA_3%W1), WMA containing 1.5% wax by binder weight (WMA_1.5%W1), WMA containing 1.5% softer wax by binder weight (WMA_1.5%W2), WMA containing 0.5% chemical additive by binder weight (WMA_0.5%C), and WMA containing 0.3% synthetic zeolite by the weight of the mixture (WMA_0.3%Z). The binder content of the asphalt mixture was 5.2% of the total weight of the mixture. All specimen followed the same mixture design, with only additives different. The percentages of additives and synthetic zeolite were a recommendation from suppliers.

The main stages of the research were: preparation of Marshall cylindrical specimens, preparation of cylindrical specimens with the gyratory press and preparation of parallelepiped specimens with impact compactor, determination of physical-mechanical characteristics obtained on asphalt mixture samples and interpretation of results by relating them to the values recommended by the Romanian norm in force for a hot mix asphalt concrete BA 16.

For all types of asphalt mixtures considered, the bulk density, water absorption, air void content, Marshall stability and flow, stiffness modulus, resistance to permanent deformation (dynamic creep), water sensitivity and resistance to rutting were determined.

A total of 114 Marshall specimens, 213 gyratory press specimens and 14 impact compactor specimens were prepared for the laboratory tests described in this chapter.

All warm mix asphalts have significantly higher values than the asphalt mixture without additives at low temperatures and very close to the value found in the case of the hot mix asphalt for the bulk density. It should be noted that an air void content of 3-5% is achieved for a smaller mechanical compaction than in the case of hot-prepared asphalt mixture, which demonstrates a very good workability of asphalt mixtures with additives to reduce the working temperatures.

The results obtained for the WMA Marshall specimens (stability and flow) showed that WMA containing additives generally exhibited characteristics similar to those of HMA. There was a slight increase in the flow index above the value obtained for HMA, when using wax-type additives and preparing the asphalt mixture at 140 °C.

Regarding the stiffness modulus, higher values were obtained for warm mix asphalts than for hot mix asphalt, especially if wax-type additives were used. The highest values were recorded for the asphalt mixture prepared with 3% classic synthetic wax and the one prepared with 1.5% soft wax. The exception to this rule is the asphalt mixture with synthetic zeolite for which the stiffness modulus is approximately equal to that obtained for the hot mix asphalt. On the other hand, there are no significant differences between the values obtained for the same type of additive with the change of the mixing temperatures in the range of 120-140 ° C and compaction in the range of 100-120 °C, even if the values of the moduli decrease with decreasing temperatures.

For the dynamic creep the results obtained do not follow a certain rule, these being quite different both considering the additives and the temperatures used in mixing and compaction. However, there is a better performance of the WMA prepared with classic synthetic wax (contents of 1.5 and 3.0%), while the WMA prepared with softer wax (1.5% content) has a behavior inconsistent with the results obtained on bitumen and on the other warm mix asphalts. The WMAs prepared with chemical additive and synthetic zeolite have a similar behavior, and the values obtained are intermediate between those obtained on the WMA with classic wax, respectively softer wax. It should be noted that all the results obtained are within the limits allowed by the regulations for HMA, which justifies the fact that the additives used allow the production of asphalt mixtures at lower temperatures than usual.

The susceptibility to rutting is high in all the studied cases, both for the standard, hot-prepared asphalt mixture and for the warm mix asphalts. This is in line with national tests which show that the threshold of 5% of the thickness of the asphalt mixture sample at 10 000 passes is difficult to achieve even for stabilized asphalt mixtures.

Water sensitivity has led to extremely favorable results for all the asphalt mixtures analyzed, which demonstrates a good adhesion of the bitumen to the aggregates used. The results obtained are consistent with the determinations of adhesiveness performed on the bitumen and aggregates used in the research.

Another aspect of the research presented in this chapter is the way in which the bulk density and the dynamic characteristics of stiffness and creep are affected by the increase of the compaction energy of the specimens from 80 to 205 gyrations. It was found that, especially for the asphalt mixtures with additives, the increase in compaction energy of more than 80 gyrations does not lead to an obvious improvement in physical or dynamic characteristics. This demonstrates that asphalt mixtures with additives benefit from a high workability that allows them the most favorable compaction at a reduced mechanical work, even below 80 gyrations. On the other hand, the extremely high workability leading to a low air void content can be reduced by lowering the binder content, based on extensive research. In this regard, partial coating of the particles and high sensitivity to water should be avoided. This process will also lead to an increase in stiffness and a better behavior to plastic deformations.

Based on the analyses performed, it can be appreciated that the warm mix asphalt with chemical additive, prepared at 120 ºC offers the best results, the behavior being appreciated as being very good for all the tests performed.

All the results obtained from the present research lead to the conclusion that, in particular, the chemical additive can be applied in the conditions of Romania for the production of WMA. A reduction of the mixing and compaction temperature by about 40 °C can be obtained for all additives used. Thus, the best results obtained in the laboratory resulted in a mixing and compaction temperature of 120 °C.

Chapter 4 presents a different approach to the analysis that can be performed on hot mix asphalts, in general, and warm mix asphalts, in particular, according to the general Superpave methodology and the particularities imposed by the Oregon Department of Transportation (ODOT), through the technical regulations applied in this American state.

The research conducted during the Fulbright Scholarship for one academic year focused on theoretical aspects of the Superpave methodology and tests performed according to AASHTO specifications, specific to the USA, participating in teaching activities for master's and PhD students, specific Asphalt Materials Performance Laboratory testing at Oregon State University, and conducting research on a warm mix asphalt prepared with chemical additive, which also contains reclaimed asphalt mixture (RAP).

The Federal Highway Administration (FHWA) has set up an expert working group to develop an optimized Balanced Mix Design (BMD) design process [26]. The group defines BMD as "asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure."

The BMD approach proposed by Oregon State University (OSU) in the SPR 801 research project [27] is volumetric design with performance verification.

The study aimed to highlight, in addition to the tendency to find solutions to reduce the temperatures used in the preparation of asphalt mixtures, the peculiarities that underlie the design of asphalt mixtures in the two geographical areas of the world. On the other hand, the aim was to gather theoretical and practical knowledge that can create the premises for improving the design of asphalt mixture dosages and checking the quality of asphalt mixtures produced in Romania, including the justification of possibilities of including new types of tests in Romanian technical standards.

For analysis a warm mix asphalt with 30% reclaimed asphalt pavement and a chemical additive commonly used in the USA was prepared.

The test methods used in this part of the study are the Semi-Circular Bend (SCB) test to determine the crack resistance and the Hamburg Wheel Tracking (HWT) test to determine the resistance to permanent deformation (rutting).

Regarding the research carried out on the preparation of a WMA with chemical additive, the following fundamental particularities are noted in relation to the procedure applied in Romania:

- the determination of the gradation of the mineral skeleton and the binder content was performed exclusively based on the volumetric design of the asphalt mixture, starting from the maximum density curve, namely the Fuller and Thompson curve for n = 0.45. It was opted for a dense gradation of the mineral skeleton, similar to the asphalt mixture studied in Romania, with a nominal maximum aggregate size of 12.5mm compared to 16mm in Romania. Also, RAP was used, in a percentage of 30%, also with nominal maximum aggregate size of 12.5mm and a bitumen content of 5.02%;
- comparing the mineral skeleton with a similar one designed in Romania it shows that there are no significant differences between the fractions used, except for the fractions of fine parts: the fraction below 0.125 mm is higher by about 25% for the asphalt mixture designed in Romania, while the fraction 0.125-2.000 mm is about 25% higher for the asphalt mixture designed in the USA. It can also be seen that the percentage of crushed stone is similar: 67% for the asphalt mixture designed in the USA and about 71% for the one designed in Romania;
- by imposing the air void content for the design stage, an optimal bitumen content of 5.6% resulted based on the volumetric criterion, compared to 5.7% considered initially for the asphalt mixture designed in Romania. According to the volumetric design of the asphalt mixture, the voids in the mineral aggregate (VMA) fall within the range of 13.5-17.0 required for mixtures with a nominal maximum aggregate size of 12.5mm, according to the ODOT specification. The voids filled with bitumen (VFA) are also in the range of 65-75 required for level 4 asphalt mixtures in Oregon. The dust-to-binder ratio is within the limits required by ODOT, between 0.8-1.6;
- in order to verify the performance of the asphalt mixture through laboratory tests, two additional binder contents were adopted, namely bitumen contents of 5.1, 5.6 and 6.1% by mass of the asphalt mixture. For comparison, in the research presented in the previous

chapters, the binder contents were 4.8, 5.2, 5.7 and 6.1%;

- for the three bitumen contents the following samples were compacted by gyratory press: 130 mm tall cylindrical specimens with a diameter of 150 mm for the study of crack resistance and 62 mm tall cylindrical specimens with a diameter of 150 mm for the study of susceptibility to plastic deformation. The samples were prepared according to the specifics of each test. For comparison, in Romania several types of specimens were used: Marshall specimens compacted with the Marshall drop hammer, cylindrical specimens compacted with the gyratory press with a diameter of 100 mm, at 50, 80, 120 and 205 gyration, parallelepiped samples with impact compactor for determining the sensitivity of the asphalt mixtures to plastic deformations, respectively;
- for the three bitumen contents, the volumetric design was followed by a series of laboratory tests that analyze the obtained deformability performances, namely: determination of the cracking resistance, rutting and moisture damage (stripping) susceptibility respectively. In contrast to these determinations, the dosages investigated in Chapter 3 involved the determination of different mechanical characteristics: Marshall stability, water sensitivity, stiffness modulus, dynamic creep and rutting;
- the interpretation of the laboratory results obtained on the asphalt mixture with RAP and the use of balanced mix design has shown that a reduction in binder content is required in relation to the volumetric design from 5.6 to 5.3%. In the previous chapter, for the tests performed in Romania, it was concluded that it is necessary to reduce the binder content from 5.7 to 5.2% and even more as resulted from the test for plastic deformations;
- regarding the optimal binder content, comparing the results obtained in the USA and in Romania, it is found that for two asphalt concretes with quasi-identical gradation, identical binder contents are obtained, even if the attempts to determine the physical-mechanical performance are different.

Based on the two studies conducted in Romania and Oregon on asphalt mixtures, it appears that regardless of the procedure for determining the gradation of the respective mineral skeleton by the specific surface method or by complying with the Superpave requirements regarding gradation, it is necessary to reduce the initially designed bitumen content, as a result of its calibration by standardized laboratory tests, even if they differ almost entirely in Romania from Oregon. The most significant reduction in the initially designed binder content is imposed in both situations by the rutting test.

Regarding the test for determining the cracking resistance, which is not specific to Romania, it is noted that a higher binder content than the one designed on the volumetric criterion may be favorable, but cannot be accepted due to the danger of developing plastic deformations. However, the warm mix asphalts prepared with chemical additive have a better crack resistance than hot mix asphalts with the same bitumen content. This conclusion results from the analysis of the better workability for the asphalt mixture with chemical additive, which allows to obtain a higher density, with benefits associated with this performance in the long run.

The graphical analysis of the laboratory tests results, performed through the balanced mix design graph, figuratively highlights the way of analyzing the design activity for an asphalt mixture.

The last part of the study (Chapter 5) focuses on the comparative evaluation of the environmental loading for the production stage for a hot mix asphalt for the surface layer with a nominal maximum aggregate size of 16 mm and for some warm mix asphalts prepared with various organic additives, chemical additive, and synthetic zeolite in different percentages. The evaluated asphalt mixtures are: classic asphalt mixture (HMA), WMA containing 3% wax by binder weight (WMA_3%W1), WMA containing 1.5% wax by binder weight

(WMA_1.5%W1), WMA containing 0.5% chemical additive by binder weight (WMA_0.5%C), and WMA containing 0.3% synthetic zeolite by the weight of the mixture (WMA_0.3%Z). Totally, five environmental impact assessment (EIA) analyses were performed. The EIA was performed using the GaBi software [28].

The life cycle of an asphalt mixture usually consists of five main stages, namely: asphalt mixture production, construction, use, maintenance/rehabilitation and end-of-life. The presented study evaluates only the asphalt mixture production stage and was evaluated to highlight the impact of the production technology on the environment. The stage of asphalt mixture production is divided in three modules as follows:

A1. Raw materials extraction;

A2. Transport of raw materials to the asphalt mixture plant;

A3. Production of the asphalt mixture at the asphalt mixture plant.

The EIA results show that the raw materials extraction process has the greatest impact on the environment in all five cases, followed by the actual production process of the asphalt mixture and the transportation of the materials.

Comparing HMA and WMA, it was observed that the overall impact of WMA is generally smaller than the global impact of HMA with 10–15%. The WMA with the lowest impact is the one produced with a chemical additive. However, in the case of the WMA with synthetic zeolite, an increase in the environmental impact was noticed for all the studied categories. For the other three types of WMA, the impact was slightly lower than for HMA. The WMA with the lowest impact is the one produced with chemical additive.

Regarding the actual production process of the asphalt mixture, the impact of WMA was about 20% lower than the impact of HMA, due to the reduction of the manufacturing temperature. However, the impact of the raw materials extraction process was slightly higher in the WMA case when using additives: about 4% in the case of the organic additive and about 2% in the case of the chemical additive. For synthetic zeolite there is an increase of about 30% in the raw materials extraction process. Thus, for this case, the benefits of reducing the manufacturing temperature of WMA, inherently with the reduction of energy consumption at this stage, are partially nullified due to the impact on the environment caused by the production and transport of the used additive. Consequently, the total impact of the asphalt mixture with synthetic zeolite was greater than the environmental impact of the classic asphalt mixture.

In the case of WMA with chemical additive, organic additive respectively, there was a decrease in the impact on the environment compared to HMA. The impact reduction was mainly attributed to the decrease in manufacturing temperature which led to a minimization of the energy required.

It should be noted that one of the main advantages of WMA is represented by the possibility of using a higher amount of reclaimed asphalt pavement due to the increased functionality of WMA compared to HMA. The improved performance of the asphalt mixture prepared at a lower temperature, with a lower aging of the binder, counteracts the stiffer binder in the RAP. Various studies have reported that a percentage of up to 50% RAP can be used in the production of asphalt mixtures. Considering the whole technological process and the impact of the additives used, the advantages offered by the decrease of the production temperature are diminished. However, besides the environmental advantages, there are additional social benefits that should be considered. One of these refers to the working conditions in the factory or at the site of the asphalt mixture, giving the workers the opportunity to work in the vicinity of less hazardous (hot) materials, to inhale less smoke and gas and wear lighter protective equipment.

The behavior of asphalt mixtures, over time, at low or high temperatures, remains a subject of further research, including by conducting field testing.

The studies carried out allowed the publication of over 20 articles by the candidate in journals and the volumes of national and international conferences. Out of these, 11 are ISI indexed, 4 are published in ISI journals (of which three are in journals with an impact factor greater than 3), and 5 are BDI indexed.

References

[1] World Commission on Environment and Development (Comisia Mondială pentru Mediu și Dezvoltare), Our common future (Viitorul nostru comun), Oxford University Press, USA, 1987.

[2] J. D'Angelo, J. Cowsert, D.D. Newcomb, Warm-Mix Asphalt: European Practice, 2008.

[3] European Asphalt Pavement Association, The Use of Warm Mix Asphalt. EAPA position paper, (2014). http://www.eapa.org/ (accessed May 26, 2018).

[4] S.D. Capitão, L.G. Picado-Santos, F. Martinho, Pavement engineering materials: Review on the use of warm-mix asphalt, Construction and Building Materials. 36 (2012) 1016–1024. https://doi.org/10.1016/j.conbuildmat.2012.06.038.

[5] M.C. Rubio, G. Martínez, L. Baena, F. Moreno, Warm mix asphalt: an overview, Journal of Cleaner Production. 24 (2012) 76–84. https://doi.org/10.1016/j.jclepro.2011.11.053.

[6] G.C. Hurley, B.D. Prowell, Evaluation of Aspha-Min® Zeolite for Use in Warm Mix Asphalt, (2005). https://trid.trb.org/view/787746 (accessed April 13, 2020).

[7] M.R. Mohd Hasan, Z. You, X. Yang, A comprehensive review of theory, development, and implementation of warm mix asphalt using foaming techniques, Construction and Building Materials. 152 (2017) 115–133. https://doi.org/10.1016/j.conbuildmat.2017.06.135.

[8] G. Hurley, B. Prowell, Evaluation of Sasobit® for use in warm-mix asphalt, 2005.

[9] R. Bonaquist, Mix Design Practices for Warm-Mix Asphalt, National Academies of Sciences, Engineering, and Medicine, Washington, DC, 2011.

[10] R. Mallick, J. Bergendahl, A laboratory study on CO2 emission from asphalt binder and its reduction with the use of warm mix asphalt, International Journal of Sustainable Engineering. 2 (2009) 275–283. https://doi.org/10.1080/19397030903137287.

[11] N. Bower, H. Wen, S. Wu, K. Willoughby, J. Weston, J. DeVol, Evaluation of the performance of warm mix asphalt in Washington state, International Journal of Pavement Engineering. 17 (2016) 423–434. https://doi.org/10.1080/10298436.2014.993199.

[12] C. Raab, I. Camargo, M.N. Partl, Ageing and performance of warm mix asphalt pavements, Journal of Traffic and Transportation Engineering (English Edition). 4 (2017) 388–394. https://doi.org/10.1016/j.jtte.2017.07.002.

[13] A. Topal, B. Sengoz, B.V. Kok, M. Yilmaz, P. Aghazadeh Dokandari, J. Oner, D. Kaya, Evaluation of mixture characteristics of warm mix asphalt involving natural and synthetic zeolite additives, Construction and Building Materials. 57 (2014) 38–44. https://doi.org/10.1016/j.conbuildmat.2014.01.093.

[14] A. Vaitkus, D. Čygas, A. Laurinavičius, Z. Perveneckas, Analysis and evaluation of possibilities for the use of Warm mix asphalt in Lithuania, Baltic Journal of Road and Bridge Engineering - BALT J ROAD BRIDGE ENG. 4 (2009) 80–86. https://doi.org/10.3846/1822-427X.2009.4.80-86.

[15] A. Vaitkus, D. Čygas, A. Laurinavičius, V. Vorobjovas, Z. Perveneckas, Influence of warm mix asphalt technology on asphalt physical and mechanical properties, Construction and Building Materials. 112 (2016) 800–806. https://doi.org/10.1016/j.conbuildmat.2016.02.212.

[16] A. Ali, A. Abbas, M. Nazzal, A. Alhasan, A. Roy, D. Powers, Effect of temperature reduction, foaming water content, and aggregate moisture content on performance of foamed warm mix asphalt, Construction and Building Materials. 48 (2013) 1058–1066. https://doi.org/10.1016/j.conbuildmat.2013.07.081.

[17] A. Nikolaides, Highway Engineering: Pavements, Materials and Control of Quality, CRC Press, 2014.

[18] J.-F. Corté, H.D. Benedetto, Matériaux routiers bitumineux : Tome 1, Description et propriétés des constituants, Hermes Science Publications, France, 2004.

[19] G. Lucaci, I. Costescu, F. Belc, Construcţia drumurilor, Editura Tehnică, Romania, 2000.

[20] J.C. Petersen, Binder characterization and evaluation, Strategic Highway Research Program, National Research Council, Washington, D.C., 1994.

[21] D. Lesueur, Rhéologie des bitumes: Principes et modifications, Rhéologie. 2 (2002) 1–30.

[22] M. Marasteanu, T. Clyne, J. McGraw, X. Li, R. Velasquez, High-Temperature Rheological Properties of Asphalt Binders, Transportation Research Record. 1901 (2005) 52–59. https://doi.org/10.3141/1901-07.

[23] D. Lesueur, The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification., Advances in Colloid and Interface Science. 145 (2008) 42–82. https://doi.org/10.1016/j.cis.2008.08.011.

[24] C. Romanescu, C. Răcănel, Reologia lianților bituminoși și a mixturilor asfaltice, Romania, 2003.

[25] K. Peterson, B. Bury, C. Duininck, D. Holt, A. Johnson, D. Johnson, R. Kjonaas, M. Marasteanu, M. Marti, J. Quade, G. Skok, D. Van Deusen, R.O. Wolters, Asphalt Paving design guide, Minnesota Asphalt Pavement Association (MAPA), USA, 2014.

[26] R. West, C. Rodezno, F. Leiva, F. Yin, Development of a Framework for Balanced Mix Design, Project NCHRP 20-07/Task 406, National Cooperative Highway Research Program, USA, 2018.

[27] E. Coleri, S. Sreedhar, I.A. Obaid, Development of a Balanced Mix Design Method in Oregon, Oregon Department of Transportation and Federal Highway Administration, USA, 2020.

[28] GaBi software, n.d. http://www.gabi-software.com/international/index/.