

STUDY OF ROAD STRUCTURES WITH WEARING COURSE MADE OF ASPHALT MIXTURES WITH POLYMER ADDITION

PhD Thesis – Abstract

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The PhD thesis entitled „Study of road structures with wearing course made of asphalt mixtures with polymer addition” was developed based on studies and research carried out in the Laboratory of Geotechnics and Overland Communication Ways of the Civil Engineering Faculty Timisoara - Department of Overland Communication Ways, Foundation and Cadastral Survey.

The main objective of the PhD thesis is to carry out detailed comparisons between the characteristics of conventional asphalt mixtures used in the wearing course of technical class IV-V roads prepared at temperatures of about 145°C and those with recycled plastic-based polymers produced at temperatures of 180°C, in order to assess the viability of using asphalt mixtures with recycled plastic-based polymers under the traffic and climatic conditions in Romania.

The study includes the analysis of design and modeling of some flexible road structures frequently used on roads of technical class IV-V in Romania, using as wearing course asphalt mixtures whose deformability characteristics (e.g. dynamic modulus of elasticity) were determined in the study. This approach is essential to understand the long-term behavior of the mixtures and to optimize the design of road structures integrating these innovative materials.

The study also evaluates the environmental impact of the technical solutions used to integrate recycled plastic compared to traditional technology.

Asphalt mixes with recycled plastic-based polymers, although produced at higher temperatures, offer a significant advantage in terms of resistance to permanent deformation compared to conventional asphalt mixtures.

The **first chapter** makes a literature review on the international knowledge on the production of asphalt mixtures with the addition of plastomeric polymers and on the need to implement such technologies based on the general concept of sustainable development.

Freight and passenger transportation is growing worldwide, much of it attributable to motor vehicles which often have a serious impact on human health and environmental quality. Heavy traffic is changing urban development patterns, road conditions and road safety standards. Increasingly, developed and developing countries are looking for strategies to guarantee individual mobility while at the same time trying to improve environmental and social conditions. Sustainable development is increasingly adopted as a framework for the design and implementation of such strategies and road transport issues are of particular importance in this context [1].

The term „sustainable development” is increasingly used in the road industry as well. Over the last decade, numerous policies and strategies have been developed around the world on the sustainability of road transport to meet the needs of current generations without compromising the ability of future generations to meet their own needs according to the most accepted definition of sustainable development [2].

In recent years, sustainable development in the road industry has followed lines of action that consider the recycling of existing asphalt mixtures and the recycling / reuse / reintegration of certain waste materials (rubber, plastic, glass, etc.) as substitutes for the constituent materials of asphalt mixtures. The use of waste products in the production of asphalt mixtures has become increasingly widespread due to economic and environmental advantages. In particular, the use of recycled waste plastics in binders and asphalt mixtures is becoming increasingly investigated due to the impressive amount of the existing waste [3].

According to a 2018 study (Figure 1) presented by the European Parliament [4], only 32.5% of the total plastic waste collected across the European Union countries was recycled. The remaining 42.6% was used in the production of energy or heat, i.e. 24.9% of the total plastic waste was landfilled.

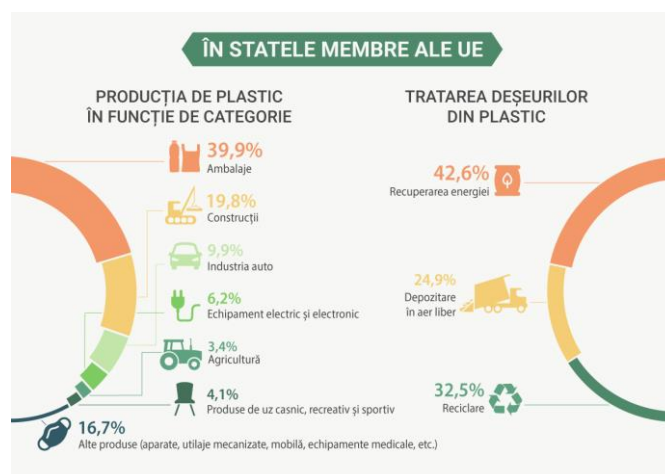


Figure 1. Plastic waste generation and treatment in the Member States of the European Union [4]

The first use of waste plastics in asphalt mixtures dates to the 1990s, when plastics in the form of fibers were used [5]. Since then, the inclusion of certain types of plastics (waste and polymer) has been investigated by various researchers [6]. The most used forms of waste plastics are high density polyethylene (HDPE), low density polyethylene (LDPE), polypropylene (PP), polyethylene terephthalate (PET), ethylene vinyl acetate (EVA), polyvinyl chloride (PVC) [7], polyethylene (PE) [8] and polyethylene terephthalate (PTP) [9]. Investigations have shown that performance parameters of asphalt mixtures such as rutting resistance [9], [10], [11], [12], [13], [14], [15], [16], fatigue resistance [17], [11], [14], [18], [19] and stiffness modulus [20], [21] can be improved when waste plastics and plastic polymers are added to the asphalt mixtures mass. However, different results have been presented in the literature depending on the targeted parameters. For example, tests presented by Wu and Montalvo [22] on the effects of HDPE and PP on rutting resistance do not lead to conclusive results. There are a variety of reasons for the recorded inconsistencies, including variabilities in sample characteristics, improper mixing conditions, lack of temperature control, and experimental errors. It is also very important to understand how the waste plastics are introduced into the mixture. Different mixing methods have different effects on the performance of the resulting mixture.

The second chapter presents the laboratory tests carried out on natural aggregates and bitumen used in the production of the asphalt mixtures analyzed in the study. Asphalt mixtures must fulfill certain qualitative and technical conditions depending on the layer in which they are used. The constituent materials of the asphalt mixtures must also comply with certain quality conditions well established by the AND 605 standard [23]. In accordance with the technical standards in force, the quality of the constituent materials of asphalt mixtures is assessed at several stages, including at source, at supply, at the commissioning stage, at the acceptance of the finished works, etc.

Regarding the analyzed aggregates and the filler, all the determined characteristics are within the limits imposed by the specific regulations. The aggregates considered - sort 8-16 and sort 4-8 - showed good wear resistance, with M_{DE} coefficients well below the maximum values required by the AND 605 standard. Both the natural aggregates and the filler showed a continuous grain size, after sieving, with passes through the sieves in the ranges of values specified by the Romanian standards in force. In terms of aggregate shape, the highest percentage of aggregates

fall into the polyhedral aggregate category, with a suitable shape, which helps to ensure the compaction of future asphalt mixtures, but also to provide increased mechanical strength.

Conventional tests: penetration at 25°C, penetration index, ring and ball softening point, ductility, elastic recovery and adhesion were carried out on pure bitumen and on bitumen-polymer mixtures in the percentages mentioned. In total pure bitumen and 5 bitumen polymer mixtures were analyzed. All the above-mentioned parameters and characteristics were analyzed to show the influence of polymer on pure bitumen.

The laboratory analysis showed that the bitumen analyzed is of the 50/70 road bitumen type, whose analyzed characteristics are within the values required for this type of bituminous binder. Also, the results of the adhesion tests carried out on the aggregates coated with this binder are favorable, the binder having a very good adhesion, achieving a good anchorage. The elastic recovery test, in the first stage, was also carried out on pure bitumen, the resulting value being low, given that the tests are only carried out on modified bitumen. In this case, R_{EL} was also determined for the pure bitumen to have a comparison value with the values obtained for mixtures of pure bitumen 50/70 and polymer in various percentages of 2%, 4%, 8% and 10% respectively.

Laboratory test results show a continuous decrease in the penetration value (Figure 2) with increasing polymer percentage. For none of the analyzed cases of polymer bitumen does the penetration value fall within the limit values of pure 50/70 bitumen. Practically the polymer changes the consistency of the bitumen, leading to its hardening.

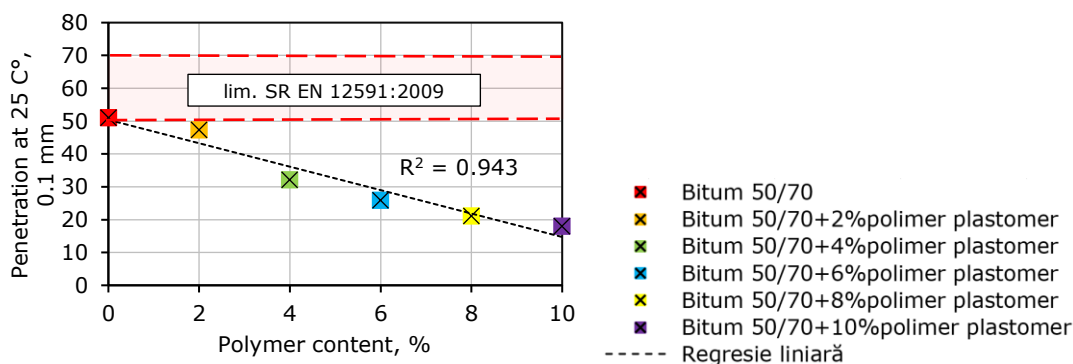


Figure 2. Results of penetration determination at 25°C as a function of polymer content

The computed values for I_P show an increase in the temperature susceptibility of the bitumen, especially in the case of the 10% polymer blend. The blends with 2% and 4% polymer keep the binder within the limit values of a 50/70 bitumen. To obtain clearer conclusions on the behavior of the analyzed bitumen and the mixtures at lower or higher temperatures, additional BBR and DSR tests would be imperatively necessary in addition to the carried out tests.

A marked hardening of the bitumen can also be observed by analyzing the ductility results (Figure 3). While for pure bitumen the ductility reached the maximum ductilometer value of 1500 mm, for the analyzed mixtures the ductility value gradually decreases up to 90% in case of the bitumen with 10% polymer.

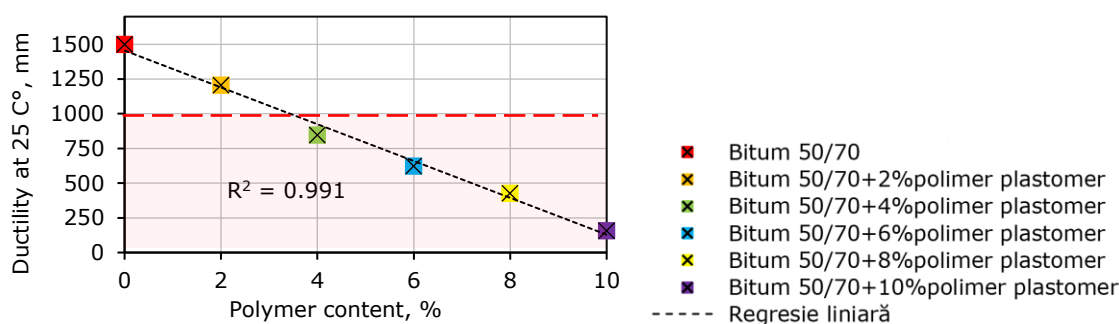


Figure 3. Test results for determining ductility as a function of polymer content

Although the polymer hardens the bitumen and increases its consistency, the adhesivity values are adequate, except for the mixture with 10% polymer for which the adhesivity value was 3% less than the minimum value required by the AND 605 standard. The highest value of adhesiveness corresponds to the mixture with 6% polymer, for which the value obtained exceeded by about 13% the minimum value of 80%.

In conclusion, the polymer has an important impact on the final characteristics of bitumen: mixtures composed with different percentages of polymer and bitumen move away from the 50/70 penetration class bitumen category. Thus, the resulting new bitumens are harder, with a higher softening point than the initial one, lower ductility, but for some lower percentages of polymer, the R_{el} value is higher, but the results are within the limits of modified bitumen's used in road engineering in Romania.

However, the aim of the analysis on bitumen with polymer content in different percentages was not to modify and obtain characteristics corresponding to a modified bitumen, but rather to evaluate the influence on the initial characteristics of pure bitumen. Based on similar studies [24], [25], [26], [27], [28], it is however expected that the modified bitumen increases the resistance to permanent deformation of asphalt mixtures.

The third chapter investigates the influence of the plastomeric polymer used in admixture with pure bitumen - based on the results presented in Chapter 2 - on the physico-mechanical characteristics of asphalt mixtures produced with different percentages of polymer. A reference asphalt mix type BA 16, a conventional hot-mixed - asphalt concrete with a maximum aggregate grain size of 16 mm - was considered as the reference asphalt mix. Based on the characteristics of the reference asphalt mix, five asphalt mixes were prepared with the addition of 2%, 4%, 6%, 8% and respectively 10% plastomeric polymer. The first part of the chapter describes in detail how the laboratory tests carried out on asphalt mixtures were performed. The second part of the chapter presents the laboratory test results for the reference asphalt mix and the third part of the chapter presents the laboratory results carried out on asphalt mixes with the addition of plastomer polymer.

The experimental design carried out on mixtures was divided into two stages to analyze the asphalt mixtures. In the first stage, 12 asphalt mixtures were prepared and analyzed, starting from three different grading curves and four binder percentages for each dosage. The first stage of research led to the establishment of an optimum binder dosage of 4.7% bitumen and an appropriate grading curve for the reference asphalt mix.

In the second stage, five asphalt mixtures prepared with different percentages of plastomer polymer (2%, 4%, 6%, 8% and 10%) were subjected to laboratory tests to study the influence of the polymer on the physical-mechanical characteristics, permanent deformation resistance and thermomechanical properties of the asphalt mixtures analyzed. The asphalt mixture of the first

stage with 4.7% bitumen percentage and grading curve number 2 was considered as the reference asphalt mix.

The Marshall characteristics have shown that increasing the percentage of polymer leads to a stiffer character of the asphalt mixtures analyzed with an increase in Marshall stability above the limit imposed by the current Romanian standard. In the case of the flow index, the trend is decreasing, but even in this case, the values fall within the minimum and maximum limits imposed by AND 605 [23], with an R^2 value of 0.792.

The stiffness modulus tests were performed by indirect tensile test at 20°C, and the experimental results (Figure 4) obtained were analyzed to highlight the influence of plastomer polymer. The conclusion of the laboratory tests indicates that increasing the percentage of polymer has an increasing effect on the stiffness values with a value $R^2=0.847$.

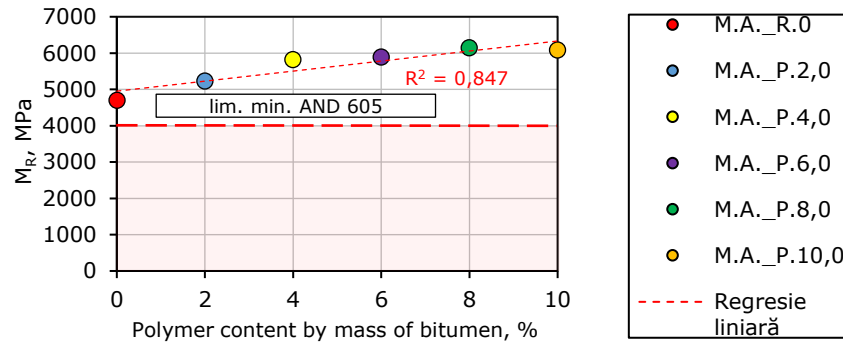


Figure 4. Stiffness modulus at 20°C - experimental values vs. limits imposed by AND 605, for asphalt mixtures of the second stage

The tests for the determination of the resistance to permanent deformation (dynamic creep), starting from the values of stiffness modulus show that the deformation values do not show a clear trend with increasing polymer percentage, the trends not showing a logical variation. However, the best behavior was observed for the asphalt mixture with 6% polymer, the comparison being made with the other mixtures with polymer addition. In contrast, the strain rate (Figure 5) shows a linear increase with a value $R^2=0.936$. Probably the temperature of 50°C in this determination leads to a decrease in the stiffness of the asphalt mixtures, hence resulting in values that show an increase in terms of strain.

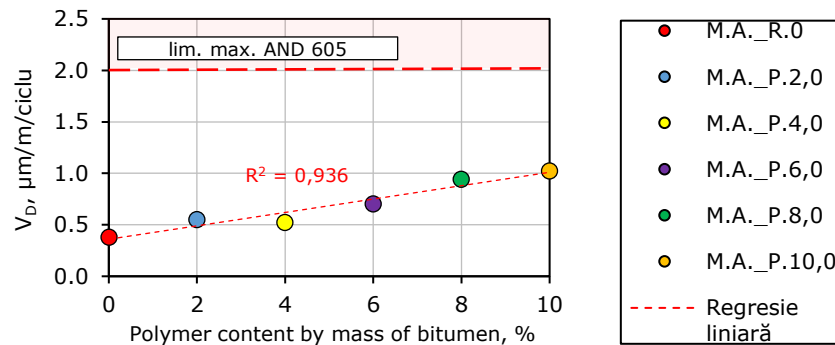


Figure 5. Deformation rate - experimental values vs. limits imposed by AND 605, for second stage

asphalt mixtures

The unfavorable effect of the polymer on the behavior of the asphalt mixtures analyzed in wet environments can be observed over a percentage of 6%, for which the water sensitivity values start to decrease, even below the minimum value imposed by the AND 605 standard for the 8% and 10% polymer percentages respectively. The decreasing trend of the water sensitivity values is similar to the results of the adhesion tests between the polymer-mixed bitumen and the natural aggregates used, the R^2 values obtained being close.

The main conclusion of the chapter demonstrates that the use of the plastomer polymer in different percentages leads to an increase in the physical-mechanical characteristics, permanent deformation resistance and on the thermo-mechanical properties of the analyzed asphalt mixtures. Increasing the percentage of polymer utilization do not always have a positive effect. For some characteristics, such as water sensitivity, flow index, void volume and water absorption, the influence of the polymer was negative, leading to a decrease in certain response values or giving inappropriate characteristics to the mixtures. Following detailed analysis, both in terms of the values obtained and in terms of the homogeneity and workability of the asphalt mix, the mix with 6% polymer (M.A.P.6.0) shows the characteristics of an asphalt mix that could be applied to road conditions in Romania.

The fourth chapter is focused on design and numerical modeling of three flexible road structures with wearing course composed of asphalt mixtures type BA16 asphalt concrete with a maximum aggregate grain size of 16 mm. Three road structures (S.R._M.A._S; S.R._M.A._R; S.R._M.A._P.6,0) with similar binder courses and a wearing course made of different asphalt mixtures were considered, two of the mixtures being analyzed in chapter 3 (M.A._R.0 and M.A._P6,0).

The design of road structures plays a major role in the development of high service life roads. The correct selection of the component materials, the choice of the appropriate thickness for each layer according to the expected traffic and climatic conditions together with the estimation of the future structure behavior, are essential to ensure high performance of the structure and to reduce not only the maintenance and rehabilitation costs, but also the vehicle operating costs [29]. For the dimensioning of flexible, mixed and rigid road structures in Romania, the standards and provisions in force are considered. The use of the "analytical method" for the dimensioning of flexible and mixed road structures is in line with the logic of standardizing the methodology for the dimensioning of road structures in European countries.

Dimensioning road structures by considering the layers perfectly linked as a multi-layer system facilitates the structure modeling and calculation process. The French method of design of flexible and mixed (semi-rigid) road structures, which is based on the elastic model used by the Alize design software, allows a perfect bond between the road layers, unbonded or with a 50% bond. The design model used by the Alize program is one of the most popular design methods worldwide. With this respect, studies carried out on specific road structures have shown that the service life of a road structure varies greatly depending on how the road layers work together [29].

In addition to "traditional" road structure design software, general finite element computation (FEM) programs, such as Abaqus, can be used to analyze road structures. FEM programs offer material-bonding models provided by the program and besides the ability to include complex constitutive material-bonding models by modifying existing or creating new options. All this opens the possibility to perform analysis for more specific problems where special material models, edge conditions and geometry are required. The sensitivity of results to input parameters, material models, geometry and edge conditions can also be investigated by FEM analysis. Because

the accuracy of finite element analysis is sensitive to the size of the discretization model, FEM analysis programs allow modification of the finite element type and the size of the discretization elements to obtain reliable analysis results.

In the study, several road structures were analyzed by comparing the results obtained by using two design software (CALDEROM 2000, Alize2) and one road structure modeling program (Abaqus/CAE 2020).

In the first part of the chapter, the road structures were analyzed using the Calderom 2000 design software, considered normative in Romania, and the Alize 2 design software, accepted as normative in France, respectively, in two design hypotheses: (i) the hypothesis of perfectly bond layers and (ii) the hypothesis of semi-bonded layers, in which case the wearing course was considered semi-bonded to the binder course, which in turn was considered semi-bonded to the upper subbase layer. For the S.R._M.A_R and S.R._M.A_P.6,0 road structures, the models of the asphalt mix component layers analyzed in the first stage considered the stiffness modulus of the wearing course (dynamic modulus of elasticity) determined in the laboratory by indirect tensile testing at 20°C. For the other layers (wearing layer) and the layers of the S.R._M.A_S structure it was considered the stiffness modulus [30] and Poisson's ratio determined according to the specifications of Indicative Norm PD 177-2001 [30]. The design traffic corresponds to a heavy traffic class according to the normative.

The results obtained with the design software for the first hypothesis of the perfectly bonded layers show that the values obtained for the specific vertical strains at the base of the bituminous layers and the specific horizontal compressive strains at the subgrade were similar, giving almost identical values for both software. Increasing the values of the stiffness modulus of the wearing course leads to a minor increase in the values of the specific strains, but the criterion of the allowable vertical specific vertical tensile strain is met. On the other hand, the values of the specific compressive strain at the foundation layer base led to linear decrease as the value of the stiffness modulus of the wear layer increases. However, for all analyzed road structures, the criteria imposed by PD 177-2001 [30] were met for the assumption of perfectly bonded layers (Figure 6).

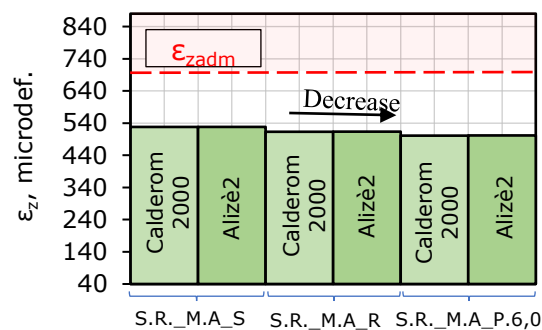


Figure 6. Specific compressive strain at the foundation - numerically determined values vs. permissible limit calculated according to [30]

In the hypothesis of semi-bonded layers in which the wearing layer is 50% bonded to the bonding layer and the bonding layer is 50% bonded to the upper foundation layer, the analysis was performed only with the Alize2 design software, the CALDEROM program not offering the possibility to modify the bonding process of the road structure layers. The reduction of the bond

between the layers of the road structure leads to higher ε_r și ε_z values. It should be noted that the ε_z value in case of S.R._M.A_R structure exceeds the ε_{zadm} value (Figura 7).

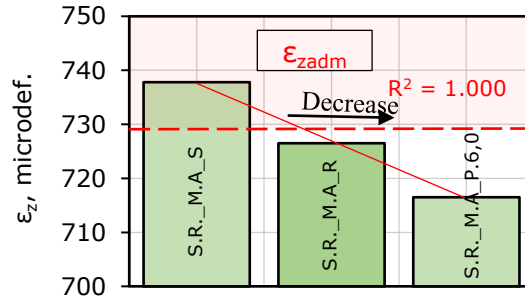


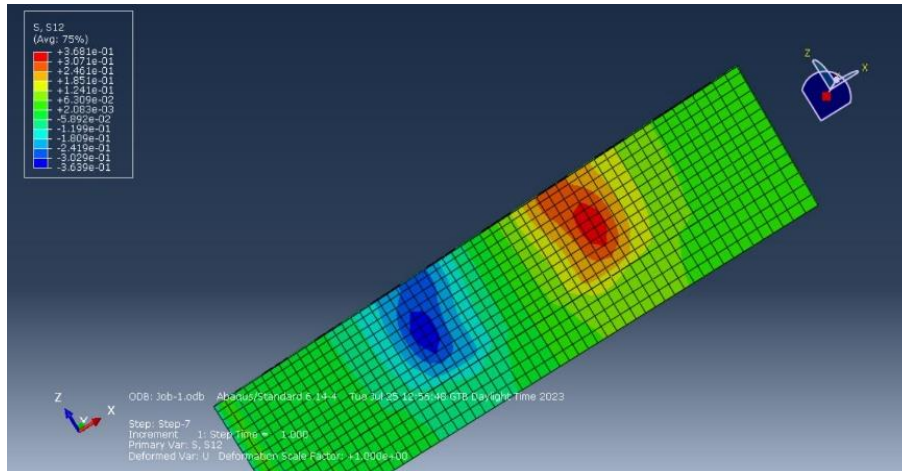
Figure 7. Specific compressive strain at the foundation - numerically determined values vs. permissible limit calculated according to [30]

For the analyzed road structures, the RDO value exceeds the admissible RDO_{adm} value required by PD 177. In this situation, only the reduction of the design traffic to an average value of half of the design traffic of 0.25 m.o.s. can lead to the verification of the criterion on the specific allowable stretch deflection at the bituminous pavement. Thus, to achieve adequate sizing, either the design traffic should be reduced, or the bituminous pavement thicknesses should be increased.

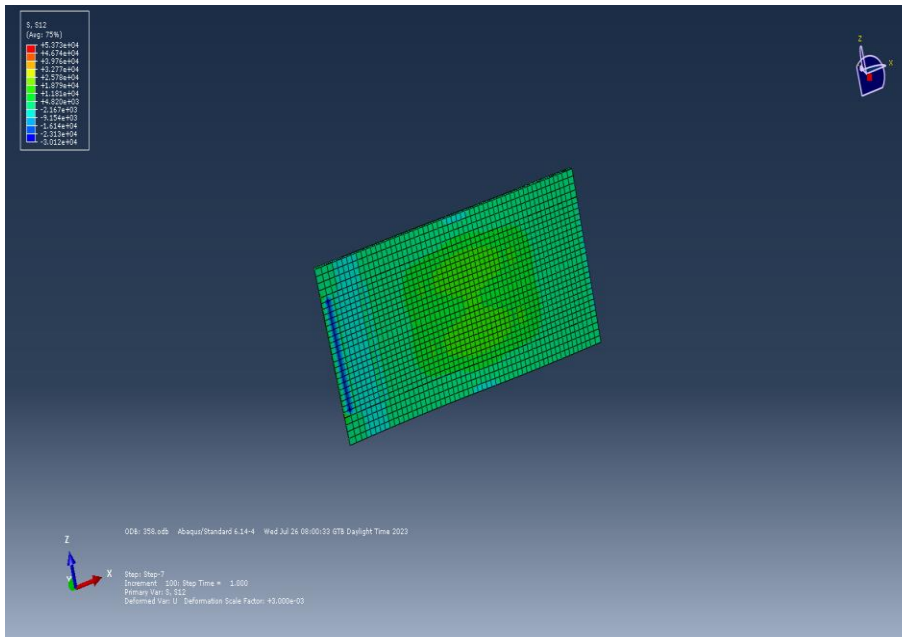
The results obtained during the design stage have shown that a road structure with bond deficiencies between the component layers cannot fully handle the design traffic considered, directly affecting the bearing capacity of the road structure and consequently their service life. As an example, the service life of road structures was initially considered to be 12 years, but this has been reduced to 6 years due to of the increase in the fatigue degradation rate and the reduction in the number of permissible stresses. In practice, a 50% partial bond between the layers of the road structure leads to a reduction of approx. 50% of the design traffic value in order to verify the dimensioning criteria of PD 177-2001.

On the basis of the design carried out with the Calderom 2000 and Alize2 software, two models of road structures with deformability characteristics and thicknesses of the component layers identical to those of the S.R._M.A._R structure were designed with the finite element program Abaqus/CAE 2020. The 3D model was validated based on the results of the design software and of the comparative results under the assumption of perfectly bonded layers. The validation results are very close to those of the design software.

In order to study the effect of different parameters, such as the effect of bonding between asphalt mix layers during a loading different from the standard static and dynamic loading, together with the effect of a braking force on the road structure, a new road structure model was created, starting from the FEM model validated on the basis of the design software. Under the hypothesis of perfectly bonded layers, the obtained values show an increasing trend of the results in terms of both normal and tangential stresses. The introduction of an additional force, such as the horizontal braking force, led to an increase in the values of tangential compressive stresses by about 85%, both at the base of the wear layer and at the surface of the bond layer (Figure 8).



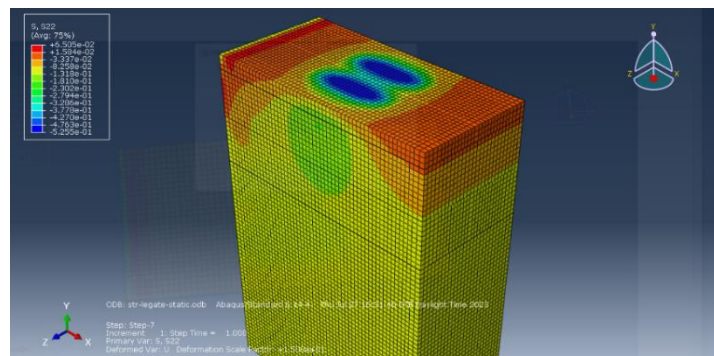
a)



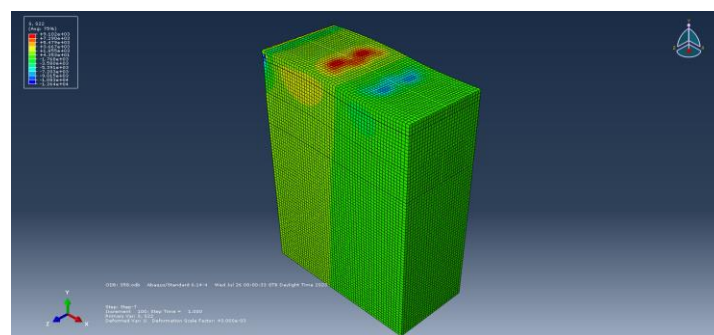
b)

Figure 8. Values of tangential stresses τ_{yz} - at the base of the wear layer: a) Static loading; b) Dynamic loading + braking force

The normal stress values show an increase of approx. 50% from the initial values (Figure 9). In addition to these increases in the values of tangential and normal stresses, the introduction of a braking force, which can practically be considered as a tangential force, also leads to the occurrence of a normal tensile stress at the surface of the bond layer. However, the values obtained are within the values specified in the literature on the values of tangential stresses and forces, indicating the favorable effect of the existence of a proper bond between the layers of the road structure.



a)



b)

Figure 9. Values of normal stresses σ_y - at the surface of the bond layer: a) Static loading; b) Dynamic loading + braking force

Chapter five presents a multi-criterial sustainability analysis of representative asphalt mixtures. The main objective of this chapter was to investigate the potential environmental impact for the production stage of one ton of asphalt mix produced according to different recipes and containing or not polymers. All materials considered in this study are specific and generally used in the Romanian road construction industry. In total, six asphalt mixtures were analysed, considering a reference mixture M.A._R.0 and similar versions with the addition of polymers in different percentages: M.A._P.2,0; M.A._P.4,0, M.A._P.6,0; M.A._P.8,0; M.A._P.10,0.

Road construction is often associated with carbon emissions from direct and indirect sources, mainly due to construction and maintenance activities. Currently, there is a lack of comprehensive Life Cycle Assessment (LCA) benchmarks for the evaluation of asphalt mixtures. Sustainable development is based on three fundamental pillars: social, economic and environmental. The social pillar aims to improve the quality of life for all citizens by promoting social justice, education, health and equity, including regulatory requirements. The economic pillar focuses on the development of an efficient and sustainable economic system, which enables long-term economic growth, secures jobs and optimizes the use of resources. The environmental pillar includes protecting ecosystems and natural resources to ensure a healthy future for the planet and future generations. While the first two pillars are easier to assess and integrate into development strategies, the environmental pillar remains an area of continuous development. While there is already a growing interest in measuring the environmental impacts of different activities, work is still ongoing to define standardized methods and develop global indicators to assess this pillar.

In recent years, several studies have been directed towards highlighting the environmental

impact of asphalt mixtures by performing life cycle assessments (LCA) and/or carbon footprint assessment through greenhouse gas (GHG) emissions [31], [32]. Environmental Impact Assessment is the process by which information is provided on the effects that the implementation of a product/process has on the environment, leading to a final environmental impact record based on the assessed emissions, categorization and aggregation of results. The decisions made are based on the interpretation of the results obtained, by evaluating their impacts, to continue/oppose or adjust the project, process, etc [33].

The manufacturing of asphalt mixtures is an energy intensive process as it releases large amounts of GHG and other pollutants into the atmosphere [34]. More than 25% of GHG emissions are caused by the intensive use of fossil fuels in road production in Europe [35]. Worldwide, the effects of GHG on the environment and hence climate change are being studied more closely, and sustainable construction technologies are being sought [36], [37], [38], [39].

Analyzing the obtained results, it can be concluded that the highest environmental impact for all six asphalt mixtures analyzed was obtained in stage A1 - the stage of procurement of component materials, followed by the stage of production of asphalt mixtures and finally their transportation.

Comparing the resulting environmental indicators, the reference asphalt mix had the lowest environmental impact compared to the results obtained for asphalt mixes with different percentages of polymer. This effect was mainly recorded due to the lower manufacturing temperature for M.A.R.0, 20°C lower than the manufacturing temperature for polymer-added asphalt mixtures. The lower manufacturing temperature leads to a reduction in the energy required for manufacturing. Compared with M.A.R.0, M.A._P.10,0 shows an increase in the climate change potential of approx. 17%. Both the production of an asphalt mix with polymer and the production of the polymer lead to higher energy use (Figure 10).

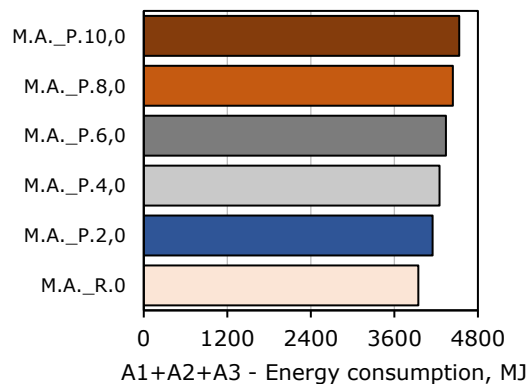


Figure 10. Energy consumption (stages A1+A2+A3)

On separate stages, the highest energy consumption can be observed in stage A1, for the asphalt mix with 10% polymer (M.A._P.10,0), with a value of approx. 13% higher than the energy consumed in the reference asphalt mix. The energy consumption values are approximately similar for all asphalt mixtures analyzed in A2.

The multi-criterial analysis was carried out considering the three criteria of sustainable development, namely economic, social and environmental impact:

- the economic criterion (30%) was considered through the cost of production;
- the social criterion (50%), integrated through the values of the most important

- normative parameter - the stiffness modulus;
- the environmental criterion (20%) through the environmental impact analysis, considered by the quantities of CO₂ emissions and energy used for the production of asphalt mixtures.

The results of the multi-criterial analysis show that the asphalt mixture with 8% polymer percentage accumulated the higher score in the multi-criterial analysis due to the score weighting method of the social criterion. Thus, the asphalt mixtures with polymer (in the case of this study asphalt mixtures with 8% polymer added) results as a better alternative in terms of durability, behaviour at higher temperatures and heavier traffic. From a total cost point of view, even if the cost for the polymer asphalt mix is slightly higher, the maintenance and repair costs of conventional asphalt mixes should also be evaluated, as they do not have a high permanent deformation resistance which most likely leads to longer maintenance intervals.

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