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BEHAVIOR OF ASPHALT MIXTURES MANUFACTURED WITH RECYCLED MATERIALS AND THEIR *IN SITU* PERFORMANCE LEVEL

Nicoleta-Adaciza IONESCU[1], Daniela DOBRE[1, 2]

[1]National Institute for Research and Development in Construction,
Urban Planning and Sustainable Spatial Development - URBAN-INCERC,
266 Pantelimon Road, District 2, 021652, Bucharest, Romania
[2]Technical University of Civil Engineering of Bucharest,
122-124 Lacul Tei Blvd, District 2, 020396, Bucharest, Romania

Corresponding author email: adaionescu2002@yahoo.co.uk

Abstract

In the context of several solutions that can be used to improve the performance of asphalt mixtures during their service life, the paper presents a case study in which asphalt mixtures are manufactured using some recycled materials such as glass, plastic and rubber. The level of performance will be quantified both by the rheological properties measured by conventional tests (viscosity, permanent deformation etc.), but also by some tests that take into account the change in response over time and that lead to variation curves for the stiffness modulus, yielding and fatigue resistance etc. Asphalt mixtures with different percentages of recycled materials will be studied and the results obtained from dynamic and rheological tests before and after the aging process will be compared and interpreted. Determining the degree of influence of recycled materials on the aging resistance of modified asphalt mixtures and characterizing the dynamic and rheological properties can lead to optimizing the percentages of additions and choosing the most advantageous solution based on multi-criteria analyses in different climatic and stress conditions.

Key words: *asphalt mixtures, performances, recycled materials, service life.*

INTRODUCTION

In the context of reducing the irrational use of resources and reducing the level of pollution, the use of waste or secondary materials instead of natural materials can have great benefits, of an economic and environmental nature, with a relatively low energy consumption (Gheorghe et al., 2008; Croitoru, 2016; Dobrescu et al., 2016; Radu et al., 2017; Dobrescu & Calarasu, 2019; Petcu & Racanel, 2024; Saca et al., 2023; 2024).

The choice of materials used for asphalt mixtures depends on the traffic and climate conditions for which the respective asphalt mixture is designed. When designing the asphalt mixture recipe, it is important to consider the ways in which the raw material can affect the performance of asphalt mixtures during the exploitation period, as well as how it will affect the performance of the mixture and the service life of the road structure.

In order to obtain durable, cheap, high-quality asphalt mixtures, with physical-mechanical and dynamic characteristics comparable to those of existing asphalt mixtures, consideration will be given to improving the qualities of bitumen, as well as the use of recyclable materials (glass, recycled mixture, slag aggregates, recycled plastic, recycled rubber, industrial waste, oils), which will replace part of the quantity of aggregates and fillers.

The following research directions outline the development of solutions and formulations incorporating specific dosages of recycled materials.

Use of industrial waste powders in asphalt mixtures

By using power plant ash in asphalt mixtures, the Marshall stability determined for temperatures higher than the test temperature by 10°C, respectively 20°C, due to the higher conductivity and specific heat for the asphalt mixture containing a significant percentage of ash in the mixture (7.5%, 10%), decreases by approximately 5% compared to 30% for the mixture containing limestone filler in the mixture (Paul Marc, 2011).

Use of bio-oil as a substitute for bituminous binder in asphalt mixtures

Replacing 25% bitumen with bio-oil, at the current production price of the asphalt mixture, will result in a production saving of 5%. If the reduction of mixing and compaction temperature are taken into account, the economic opportunity in using this technology is greater (Perlata, 2013).

Use of bituminous binders modified with industrial waste and bio-oil in asphalt mixtures

Regarding the fatigue behavior of asphalt mixtures with polymer-modified bitumen, the fatigue resistance of the studied asphalt mixtures highlights the fact that the working temperature in the laboratory must be correlated with the *in situ* atmospheric temperature. An increase in temperature by 10°C corresponds to an increase in specific deformation by almost 280% (Burlacu & Răcănel, 2014).

Use of crushed glass in asphalt mixtures

In the study on the performance of asphalt mixtures (paving asphalt), in which a finely divided aggregate is replaced by crushed glass, it was found that the performance of the aggregate is not affected for crushed glass percentages of up to 30% of the aggregate mass, a combination of 3% rubber polymer plus 2% glass powder can considerably improve the mechanical properties of the asphalt mixture and that asphalt mixture layers containing 10-15% ground glass in surface mixtures performed satisfactorily (Issa, 2016).

Use of recycled construction aggregates in asphalt mixtures

Asphalt mixtures containing recycled construction aggregates (roads, concrete) have the problem of high bitumen absorption. The effects of glass on bitumen absorption and volumetric properties of asphalt mixtures containing 25% and 50% recycled aggregates are demonstrated through laboratory investigations. Three glass contents of 0%, 10% and 20% in terms of the total weight of fine aggregates are used in the mix design to prepare 100 mm diameter samples containing 0%, 25% and 50% recycled aggregates, under 120 rotation cycles. The results indicate that waste glass can be a viable material for improving the problem of high bitumen absorption of asphalt mixtures containing recycled aggregates (Tahmoorian et al., 2018).

The use of compounds obtained by processing industrial waste in ecological asphalt mixtures

The partial replacement of quarry mineral aggregates with steel mill slag considerably influences the physical-mechanical characteristics of the asphalt mixture. The addition of certain materials derived from industrial waste can bring benefits to the quality of the asphalt mixture, e.g. the behavior of adding power plant ash as a substitute for the usual limestone filler that leads to the stiffening of the asphalt mixture, giving it properties that can be compared to the use of polymers/elastomers in the composition of the bituminous mixture (Lixandru et al., 2018).

Use of aggregates from recycled asphalt mixtures

These mixtures were prepared with two filler additives, steel mill slag and silica fume, at four different percentages of the aggregate weight. A total of 234 mixtures were tested. The laboratory results indicated the effectiveness of using such additives as fillers. Marshall stability showed an improvement for mixtures prepared with steel slag ranging from 11.73 to 32.73 kN as the dosage of recovered asphalt aggregates increased; high stability was recorded for a dosage of 75% recovered asphalt pavement aggregates with a mixture of 50% steel slag. On the other hand, silica fume showed variations in its strength, however the maximum load value of 31.02 kN was for a dosage of 75% recovered asphalt aggregates with 100% silica fume (Naser et al., 2023).

Finite element modelling of asphalt mixture

An advanced area of research and testing aims to assess deformations and stress distributions under specific static and dynamic loading conditions for asphalt mixtures, both homogeneous and inhomogeneous. This approach incorporates the use of recyclable materials and employs modelling through the finite element method within a multidisciplinary framework that includes chemistry, engineering, and finite element analysis (Ionescu et al., 2024).

MATERIALS AND METHODS

Testing the physical and mechanical properties according to normative standards

Given the importance of asphalt mixtures' performances, this paper highlights the behavior of classic asphalt mixtures, as well as those modified by introducing a recycled material, used in the base, binding and wear layers.

The physical-mechanical characteristics of the asphalt mixtures were determined on Marshall specimens made from the asphalt mixture prepared in the laboratory to establish the optimal dosages of materials: aggregates, filler, bitumen and fiber (according to the requirements of Normative AND 605).

To prepare the asphalt mixtures in the laboratory, all materials were heated to a temperature of 180°C in an oven. After that, they were mixed for homogenization for 5 minutes in the laboratory mixer. Marshall samples were compacted at 170-180°C using an impact hammer stand (Marshall press), by applying a compaction effort on each side of the specimen 50 blows or 75 blows (for SMA).

The following physical and mechanical characteristics were determined on the specimens made with the Marshall press:

- apparent density, according to SR EN 12697-6;
- Marshall stability, at 60°C, according to SR EN 12697-34;
- flow index, at 60°C, according to SR EN 12697-34;
- void volume, according to SR EN 12697-8;
- water sensitivity, according to SR EN 12697-12;
- water absorption, Normative AND 605:2016;

After obtaining the optimal bitumen dosage, the following tests were performed:

- on specimens made with a rotary press;
- modulus of rigidity, SR EN 12697-26;
- fatigue resistance, SR EN 12 697-24;
- resistance to permanent deformations by cyclic compression (dynamic creep), SR EN 12 697-25;
- resistance to permanent deformations (tracking), SR EN 12697- 22.

RESULTS AND DISCUSSIONS

Experimental data analysis for different classic asphalt mixtures

To highlight the behavior of mixtures with different percentages of bitumen (behavior of interest in the case of the action of external agents such as traffic, or atmospheric phenomena), some representations will be presented based on the results of the tests carried out (Figures 1, 2 and 3), for the following types of asphalt mixtures:

- wear layer:
  - asphalt mixture with high mastic content using modified bitumen with a maximum grain size of 16 mm - SMA 16 (bitumen PmB 45/80-80);
  - asphalt mixture with high mastic content using simple bitumen type 50/70 with a maximum grain size of 16 mm - SMA 16 (bitumen 50/70);
  - asphalt concrete with crushed gravel with a maximum grain size of 16 mm - BAPC 16 (Bitumen 50/70);
  - asphalt concrete with a maximum grain size of 11.2 mm - BA 11.2;
  - asphalt concrete with crushed gravel with a maximum grain size of 8 mm - BAPC 8;
  - asphalt concrete with a maximum grain size of 8 mm - BA 8;
  - asphalt concrete with crushed gravel with a maximum grain size of 31.5 mm - BAPC 31.5.
- binder layer:
  - asphalt concrete with modified bitumen and a maximum grain size of 22.4 - BAD 22.4 (Bitumen PmB45/80-65)
- base layer:
  - bituminous asphalt with a maximum grain size of 31.5 mm - AB 31.5;
  - bituminous asphalt with a maximum grain size of 22.4 mm - AB 22.4.

Bitumen is part of an asphalt mixture in a proportion of 5-7% of its mass and the optimal dosage must be chosen depending on the physical and mechanical characteristics considered.

High stability for approx. 5.3 % percentage of bitumen is shown in Figure 1.
An inverse dependence, i.e. bitumen content increases, water absorption decreases, is observed in Figure 2.
In Figure 3, density is mainly influenced by the source of aggregates (i.e. their density).
The characterization of asphalt mixtures through dynamic laboratory tests is presented in Figures 4, 5 and 6.

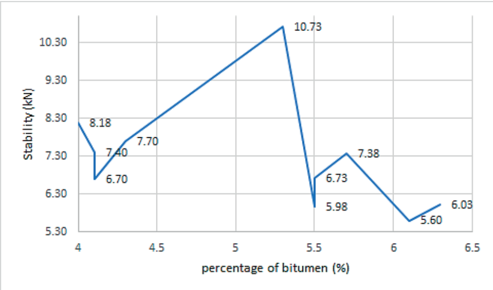

Figure 1. Graphical representation of Stability - the percentage of bitumen

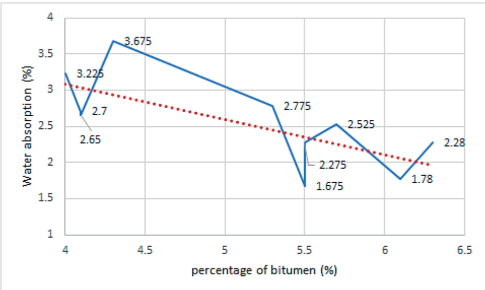

Figure 2. Graphical representation of water absorption - percentage of bitumen

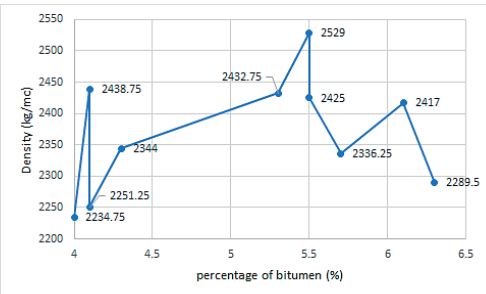

Figure 3. Graphical representation of Density-percentage of bitumen

The modulus of rigidity is higher for asphalt mixtures used in base layers (Figure 4).

The lower the dynamic creep, the more resistant the mixture is under traffic (Figure 5). It is important that the tracking resistance is below 5 min. cycles to cracking at 15°C to avoid undulations under traffic (Figure 6).

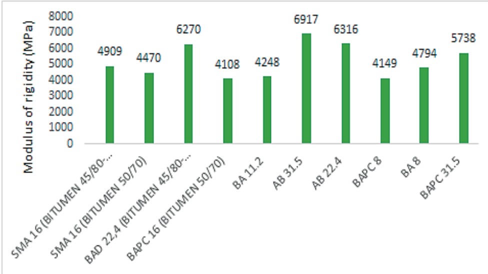

Figure 4. Graphical representation of the modulus of rigidity

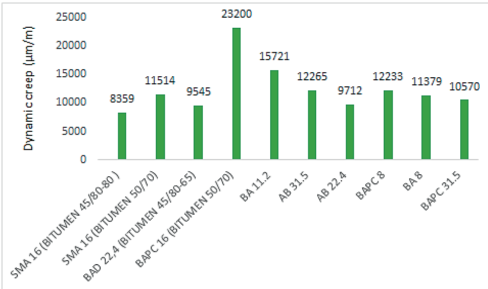

Figure 5. Graphical representation of the resistance to permanent deformations – dynamic creep - deformation at 50°C, 300 kPa and 10000 impulses

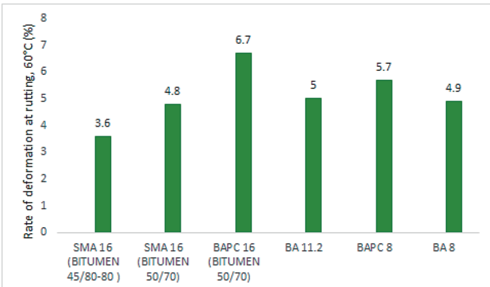

Figure 6. Graphical representation of the rate of deformation at tracking at 60°C

Description of different types of asphalt mixtures, including those with recycled materials

As a case study, the asphalt mixture type SMA 16 is presented, prepared in two variants in which different conventional raw materials and recycled materials were used:

- asphalt mixture prepared with quarry aggregates, filler, fibre and road bitumen type 50/70 modified with 15% recycled rubber (MA1);
- asphalt mixture prepared with recycled asphalt mixture, quarry aggregates, filler, fibre and bitumen PmB45/80-50 (MA2).

The two asphalt mixtures were designed in accordance with the requirements of the documents: Normative AND 605:2016 and SR EN 13108-5:2016.

Bitumen modified with a polymer (in our case recycled rubber) and which consists of two distinct phases, can be considered in three situations (Brule, 1993; Dony, 2014):

• The polymer content is low (below 4%), the bitumen constitutes the continuous phase of the system in which the polymer phase is dispersed (Figure 7a). The dispersed polymer phase improves the properties at high service temperature and at low temperatures.

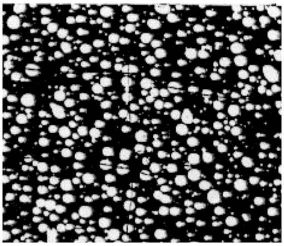

Figure 7a. The polymer phase is dispersed (Dony, 2014)

• The polymer content is high (above 7%), the polymer phase constitutes the matrix of the system (Figure 7b). In this case the polymer is plasticized by the oils in the bitumen in which the heavy fractions of the initial binder are dispersed. The properties of this system are fundamentally different from those of a bitumen and depend largely on the properties of the polymer.

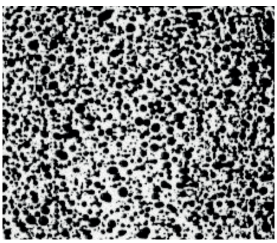

Figure 7b. The polymer is plasticized by the oils in the bitumen (Dony, 2014)

• The polymer content is around 5%, microstructures are obtained in which the two phases are continuous and interpenetrated (Figure 7c). However, this system presents stability problems, being difficult to control.

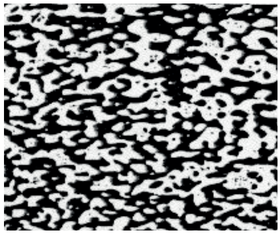

Figure 7c. Microstructures are obtained in which the two phases are continuous and interpenetrated (Dony, 2014)

The rheological properties of modified bitumen are strongly influenced by the polymer content (Tudose, 1982). For a low polymer content (3%) the behavior of modified bitumen remains close to that of plain bitumen, and for modified bitumen with a high polymer content (e.g. higher than 6%) the rheological behavior changes fundamentally. These rheological properties are highlighted in (Background of SUPERPAVE asphalt binder test methods, 1994), which selects the measurement of the bitumen's contribution to improving the resistance to permanent deformation. This methodology demonstrates that the bitumen must have both a high complex modulus and high elasticity at the maximum temperature that the asphalt pavement can withstand.

Dynamic shear and bending tests on plain and modified bitumen have revealed the dynamic shear modulus (G, Pa), and the phase angle (δ, deg). For a given complex shear modulus, low values of the phase angle are found, so better resistance to permanent deformations and better fatigue resistance (Tudose, 1982). There is an influence of the styrene-butadiene-styrene type polymer (rubber) on the complex modulus and the phase shift angle (Tudose, 1982), a decrease in the phase shift with the increase in the values of the complex shear modulus.

The graphical representation of Complex shear modulus-temperature shows a plateau with a high modulus that varies little with temperature (low temperature susceptibility), resulting in good resistance to permanent deformation (Tudose, 1982).

In Figure 8, two asphalt mixtures used for thewear layer are presented in comparison: MA1-asphalt mixture (prepared with bitumen type 50/70 modified with 15% rubber powder) and MA2-asphalt mixture (prepared with modified bitumen type PmB45/80-50). The results for the tracking test by monitoring are the deformation rate at 50°C, 300 kPa and 10000 pulses (mm/10000 cycles) and the rut depth % of the initial thickness of the sample.
Bitumen modified with rubber powder is obtained in bitumen modification installation or laboratory, by introducing a recycled material into the bitumen mass, in this case recycled rubber.

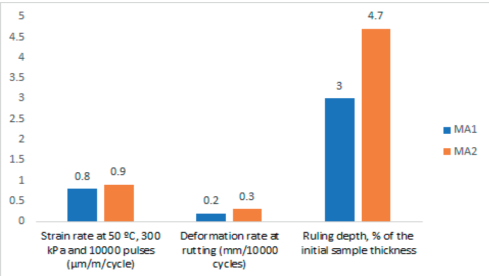

Figure 8. Comparative representation of MA1 and MA2

The performance of the two asphalt mixtures MA1 and MA2 in operation was also monitored, by performing *in situ* tests on two road sections, 6 months after laying (Table 1).

Table 1. Results of *in situ* tests

Determined characteristics	Values			Test method
	Obtained		Imposed by Normative AND 605	
	MA1	MA2		
Roughness (with SRT pendulum), SRT units at 1 m from axis at 3 m from axis	90 87	83 81	min. 80	SR EN 13036-4
Roughness (volumetric method), mm at 1 m from the axis at 3 m from the axis	1.6 1.5	1.3 1.2	min. 1.2	SR EN 13036-1
Resistance to permanent deformation at 60°C (tracking) determined on cores taken from the road: -rut depth, mm/% of the initial sample thickness -tracking deformation rate, mm/10000 cycles	3.56 0.23	4.87 0.35	max. 5 max. 0.5	SR EN 12697-22 +A1

The behavior of the two mixtures in terms of roughness and deformations can be compared using Figures 9 and 10. The asphalt mixture with recycled rubber shows greater roughness but also a high resistance to permanent deformation at 60°C, as illustrated in Figure 10.

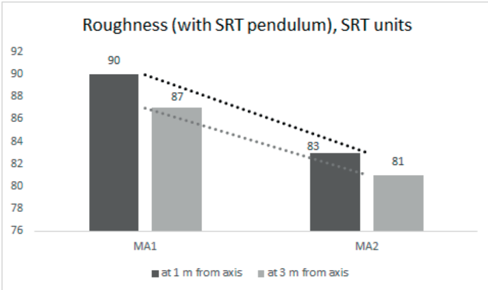

Figure 9. Variation of roughness between asphalt mixtures (MA1 and MA2)

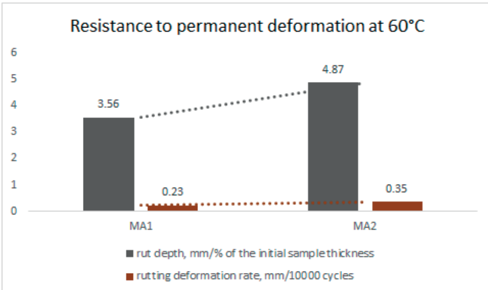

Figure 10. Variation of resistance to deformations between asphalt mixtures (MA1 and MA2)

CONCLUSIONS

The service life of road structures is very important, starting from the date of execution and commissioning until the decision to rehabilitate or reconstruct is made.
From the presented study it can be concluded that recycled materials used in the preparation of asphalt mixtures can have better performance compared to classic asphalt mixtures, important for the road's service life. To carry out durable and high-performance works, it is important to test the physical-mechanical and dynamic characteristics of the resulting asphalt mixture. It is also important to declare the performance of asphalt mixtures under the requirements of Regulation (EU) No. 305/2011 and the harmonized European standards (often referred to as "CE marking").

The trend of studying the potential of some additions of animal waste and agro-industrial by-products for use in the construction field should be sustained at the level of exploratory research also in the direction of additions in asphalt mixtures (only for temporary roads, no heavy traffic) (Popa et al., 2021; 2023).

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