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COMPARATIVE STUDY ON USING THERMOPLASTIC POLYMERS TO IMPROVE ASPHALT MIXTURES CHARACTERISTICS

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Abstract

Asphalt mixtures are composite building materials consisting of a mineral skeleton mixed with a bituminous binder, following a recipe which may also include fibres and/or polymers. The natural aggregates sustain the mixture structure, but adequate bitumen behaviour under various temperature and mechanically-induced stresses is also essential for the structural durability. Much research effort was directed towards improving the asphalt mixtures' resistance to permanent deformation, implying an increase in mixture stiffness. At the same time, the mixture must exhibit enough low temperature cracking resistance. Six reference asphalt mixture samples were prepared and tested: mixtures M1 and M2 for base and binder courses respectively, as well as four mixtures for wearing courses (two asphalt concrete - AC1 and AC2, a stabilised mixture SMA containing fibres, and a porous mixture - PM). A 50/70 penetration grade bitumen was used to prepare all mixtures. In some cases, the obtained results did not meet the standard requirements. Bitumen or mixture modification is commonly performed by adding thermoplastic or elastomeric polymers, to improve the asphalt mixture behaviour. In this study, the effects of four thermoplastic polymers on the stiffness modulus, dynamic creep and fatigue resistance were studied. All tested polymers were introduced as grains during mixture preparation. Polymer addition led to a 31 % to 104 % increase in mixture stiffness modulus. A 220 % average increase in fatigue resistance was observed for mixtures M1 and M2. For the wearing course mixtures, creep resistance is expressed through a 99 % reduction in deformation speed and a 50 % to 80 % reduction in rut depth. The obtained results met the standard requirements. Using grain polymers is currently an effective alternative to polymer-modified bitumen, because of several technological and economical advantages. Polymer quality is essential to obtain adequate mixture characteristics.

Keywords: asphalt, thermoplastic polymer, stiffness, deformation, fatigue

1 Introduction

Asphalt mixtures are composite building materials consisting of a mineral skeleton mixed with a bituminous binder, following a recipe which may also include fibres and/or polymers, in order to improve the mixtures' behaviour in operation [1, 2]. The natural aggregates sustain the mixture structure, but adequate bitumen behaviour under various temperature and mechanically-induced stresses is also essential for the structural durability. Much research effort was directed towards improving the asphalt mixtures' resistance to permanent deformation, implying an increase in mixture stiffness at high temperatures. At the same time, the mixture must exhibit workability and enough low temperature cracking resistance. Modified bitumens are binders whose rheological properties have been modified by adding one or

several modifying chemical agents, in certain dosages, to improve the bitumen's viscoelastic properties and behaviour [3-6].
Polymer-modified bitumen (PMB) is produced in specially designed refineries or units consisting of quality and performant equipment. Its production and distribution costs are rather high. Furthermore, technological difficulties (e.g. segregation) when applying or using PMB can be encountered, especially in developing countries. Therefore, a technological alternative was developed, addressing the improvement of asphalt mixtures' properties instead of bitumen modification, by adding grain polymers directly during asphalt production [3-4, 7]. This material is also known as polymer-modified asphalt (PMA).
The polymers currently employed in the business can be divided in two main categories: elastomers (with the ability to regain their initial shape after an action) and plastomers (forming a rigid tridimensional network in the asphalt mixture, capable to reduce/limit deformations under increased actions).
Thermoplastic polymers (plastomers) become soft and ductile when heated at certain temperatures. Afterwards, when temperature decreases, they become rigid and maintain their shape. These polymers do not exhibit elastic properties in ordinary thermal conditions, as their molecular chains' ability to move and recover their original position is limited. They increase the mixture's stiffness, however they do not significantly influence the bitumen elasticity or Fraass breaking point.
The main plastomers used for bitumen modification are: ethyl-vinyl-acetate (EVA), polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), ethylene-methyl-acrylate (EMA) and ethylene-butyl-acrylate (EBA) [3].

2 Materials

The polymers' efficiency and their influence on asphalt properties were the primary purpose of this study. Therefore, to perform a relevant comparison between different polymers, the analyses started by preparing and testing six reference asphalt mixture samples. Two of them, M1 and M2, were designed for bituminous base and binder courses, respectively. The rest of the mixtures were designed for wearing courses. Tests were performed on two asphalt concrete mixtures (AC1, AC2), as well as on a stabilised mixture (SMA) and a porous one (PM). All materials used to prepare the asphalt mixtures were tested according to the European regulations.
A 50/70 penetration grade bitumen was used to prepare all mixtures. Its properties follow the standard requirements. The natural aggregates used to prepare all the tested mixtures were extracted from a medium-density, slightly acid and porous dacite. The performed tests for aggregates' mechanical and physical properties indicated the following results, according to EN 13043 [8]: LA_{15} resistance to fragmentation, MDE_{15} resistance to wear, SI_{20} shape index.
The reference asphalt mixtures consisted of: natural aggregates (fine and coarse), bitumen, mineral filler, as well as cellulose fibres in the case of SMA. Mixtures M2, SMA and especially PM had high contents of 8/16 coarse aggregates fraction. 90 % of aggregates used to prepare the porous mixture (PM) were coarse. This mixture had the lowest content of fine aggregates of the six tested mixtures. SMA had a 22 % content of fine aggregates, while the rest of them contained 30-35 % fine aggregates.
The main physico-mechanical properties of the reference mixtures are indicated in Table 1 and Table 2. Shaded table cells indicate values outside the recommended standard intervals. Allowable values are shown where results were unsatisfactory.

Table 1 Reference mixtures' properties

Ref. mix.	Characteristics							
	Bitumen content [%]	Stability (S)[kN], 60 °C	Flow (F) [mm]		S/F [kN/mm]		Water abs. [%]	
			tests	limits	tests	limits	tests	limits
M1	4.7	9.8	3.2	≤ 3.0	3.1	≥ 6.0	5.8	≤ 5.0
M2	4.8	11.6	3.3		3.5		1.8	
AC1	5.7	11.4	3.3	≤ 3.0	3.5	≥ 4.0	2.5	
AC2	5.7	10.4	3.6	≤ 3.0	2.9	≥ 4.5	2.1	
PM	4.3	10.5	2.8	≤ 2.5	3.8	≥ 5.0		

Table 2 SMA reference mixture properties

Ref. mix.	Characteristics					
	Bitumen content	Binder drainage [%]		Void content [%]	Voids filled with bitumen [%]	Water sensitivity [%]
		test	limit			
SMA	5.9	1.1	≤ 0.2	3.6	79.3	89

Mixture recipes design have shown that the best laboratory results are obtained using a low bitumen content, compared to the standard recommended values: 4.5 % for M1/M2, 5.7 % for AC, 4.0 % for PM and 5.9 % for SMA. PM reference void content was 18.1 %. All mixtures passed the stability requirements, with all reference values extracted from the Romanian standard applicable at the time of study. This latter aspect shows that the obtained flow values exceed the maximum allowable ones with up to 10-20 %, except mixture M2 for the binder course.

Thermoplastic grain polymers consist of small and flexible grains which are added during the preparation of hot bituminous mixtures in order to improve their physico-mechanical properties, mainly their stiffness and their resistance to permanent deformations. They can be added directly in the mixer during production, after the aggregates and before the bitumen. In this study, the effects of four thermoplastic polymers (P1, P2, P3, P4) on the stiffness modulus, dynamic creep and fatigue resistance of bituminous mixtures were analysed. All tested polymers were introduced as grains during mixture preparation. Product P4 was added only to mixture AC1. The main properties of the thermoplastic polymers used in this study are presented in Table 3.

Table 3 Thermoplastic polymers properties

Properties	Polymers			
	P1	P2	P3	P4
Composition	low-density PE, EVA	low-density PP, PE	low-density polymers	low-density polymers
Aspect / colour	gray, 1.5-4.0 mm soft grains	black powder / grains	brown, soft grains	transparent, soft grains
Soft. point [°C]	150-160	150	160	100
Melt. point [°C]	180	155-170	180	120
Density at 20 °C [kg/m^3]	900-980	900-980	550-650	550-650
Dosage [% of bitumen]	4-6	4-6	4-8	4-8

3 Methodology and results

3.1 Stiffness modulus

Under normal loading conditions, asphalt mixtures show a viscoelastic behaviour, therefore the fundamental elastic modulus used for linear elastic materials does not apply. Asphalts are characterised by the stiffness modulus, where the stress-strain relation depends on the temperature and loading rate, unlike the fundamental Young's modulus. The commonly used stiffness modulus is the dynamic one, where the applied load is dynamic (short loading rate) [3]. The stiffness modulus is determined according to EN 12697-26 [9]. Indirect tensile tests, bending tests or direct uniaxial tests can be performed. In this study, indirect tensile tests on cylindrical specimens were performed at 20 °C, under controlled strain conditions.

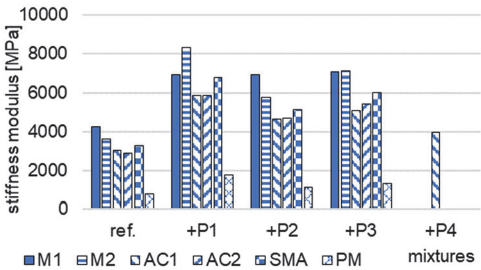

Figure 1 Stiffness modulus

Adding thermoplastic grain polymers clearly improves the mixtures' stiffness moduli (Figure 1). On average, polymer addition led to a 31 % (P4) to 104 % (P1) stiffness improvement. Since P4 was only used for mixture AC1, its relevance is limited. The largest increase was obtained with polymer P1, which doubled every mixtures' stiffness, except M1. Adding any of the tested polymers to mixture M1 improved its stiffness modulus with 65 %. Mixture M2 has shown the highest average stiffness increase (+95 %). The lowest improvement was obtained using polymer P2, which increases the mixture stiffness with 55-60 % on average.

3.2 Permanent deformation

The permanent deformation of an asphalt mixture is closely related to its low-stiffness response (i.e. response at high temperature and long loading time). It depends on the aggregate and bitumen volume, grading, shape, texture and hardness, as well as on the degree of interlocking and compaction. The mixture deformation and strain quickly increase during the beginning of the loading time, and become quasi-constant afterwards. The total deformation is partially recovered instantaneously (elastic deformation) when removing the applied load. Another fraction of the total deformation is recovered gradually (viscoelastic deformation), whereas the rest cannot be recovered (permanent deformation). The latter represent the mixture rutting [3].

3.2.1 Cyclic compression tests

Testing a bituminous mixture's resistance to permanent deformation by cyclic compression with confinement is described in EN 12697-25 [9]. The creep test is conducted under dynamic loading and allows ranking various mixes or checking the acceptabiity of a given material. They do not provide the possibility to predict field rutting from a quantitative point of view. In this study, method B was used, testing the mixtures by means of the triaxial cyclic compression test. This method is usually employed to develop and evaluate new mixture types. The confining stress is induced by vacuum as the mixture specimen is subjected to a cyclic axial stress. Mixtures M1 and M2 were tested at 40 °C, with a 200 kPa axial stress. The other mixes were tested at 50 °C and 300 kPa, being designed for the wearing course. The deformations recorded after 10,000 loading/unloading cycles are synthesised in Figure 2.

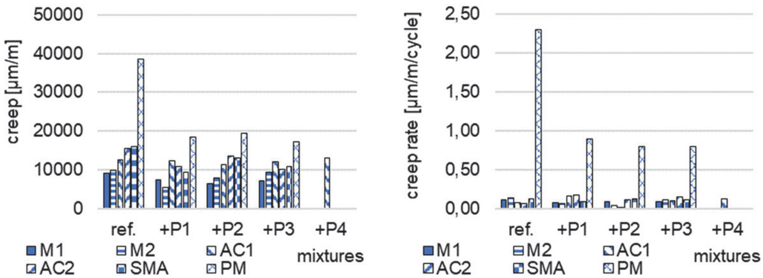

Figure 2 yclic compression tests: creep (left) and creep rate (right)

Tested polymers reduce creep for all mixture specimens on average with 23 % (P2) to 31 % (P1). A significant effect is observed on the PM porous mixture. Its reference creep of almost 40,000 µm/m, as well as its creep rate of 2.30 µm/m/cycle, exceed the standard allowable values. However, adding thermoplastic grain polymers reduces creep by half and creep rate by two thirds. Although creep is reduced by adding polymers, in some cases (i.e. asphalt concrete mixes AC1 and AC2) creep rate increases at the same time.

3.2.2 Wheel tracking tests

The purpose of the wheel-tracking test is to determine the asphalt susceptibility to permanent deformation under a moving load. The test procedure is described in EN 12697-22 [9]. It is performed in a controlled environment, simulating real conditions. In this study, rectangular specimens were prepared in the laboratory and tested using a small-size device, procedure B, testing in air. The applied load is fixed, whereas the table with the specimen's mould is repeatedly moving forwards and backwards. Tests were performed at 60 °C, on mixtures designed for wearing courses.

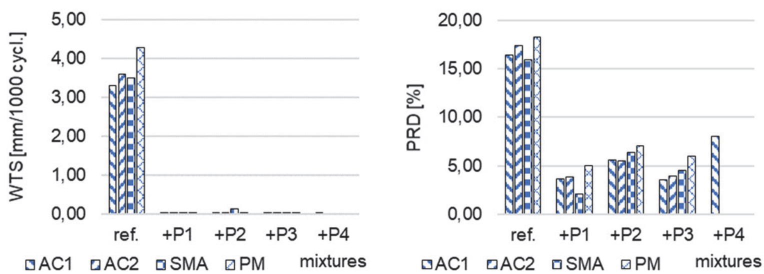

Figure 3 Wheel tracking tests: WTS (left) and PRD (right)

The wheel-tracking slope (WTS) is the average value of the tested specimens (two in each case). While the values obtained for the reference mixtures exceed the allowable limits, adding grain polymers substantially improves WTS (Figure 3). The proportional rut depth (PRD [%]) is determined by dividing the vertical specimen displacement after 10,000 cycles to the initial specimen height. In this study, the reference mixtures' PRD values were three times the recommended limits. Asphalt mixtures including P1 or P3 polymers exhibit improved PRD with 75 % to 80 % on average. The results (PRD ≤ 5,00 %) indicate these mixtures could be used on almost any type of road. Polymers P2 and P4 improve the PRD with 50 % to 65 % on average. However, the obtained values (5.5 % to 8.0 %) recommend those asphalt mixtures for secondary roads only.

3.2.3 Resistance to fatigue

In this study, the resistance to fatigue tests were performed on cylindrical specimens of M1 and M2 hot mix asphalts, according to EN 12697-24 [9]. This standard indicates five alternative test methods: an indirect tensile test on cylindrical specimens and four bending direct tensile tests on prismatic and trapezoidal specimens. In this case, the indirect tensile test on cylindrical specimens was used.

The resistance to fatigue may be used to rank asphalt mixtures or as a pavement performance indicator to estimate/evaluate its structural behaviour. The conventional failure criterion is the number of load application when the mixture's complex stiffness modulus decreases to half its initial value.

The laboratory-prepared specimens were 40 mm thick and 100 mm in diameter. After ageing, they were conditioned and tested at 15 °C. Three specimens were tested at each of the three constant stress levels of pulse.

The reference mixtures performed poorly, with values as low as 30 % from the minimum allowable number of loads. As Figure 4 shows, adding thermoplastic grain polymers significantly improved the tested mixtures' resistance to fatigue: 140 % average increase for mixture M1 and 300 % for mixture M2. The obtained results exceed the minimum allowable values with 5 to 20 %.

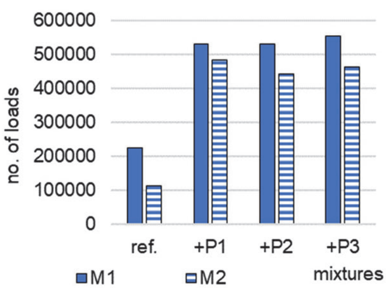

Figure 4 Resistance to fatigue

4 Discussion and conclusions

This study, as well as others [7-12], have confirmed that thermoplastic polymers, added as PMB components or as grains during PMA production, increase the asphalt stiffness and its resistance to deformations. Therefore, these agents are recommended to limit or eliminate common pavement distresses such as rutting. However, a careful and rational approach must be ensured in order to obtain the required results without negatively affecting other characteristics.

PMAs provide equilibrium between asphalt properties, ensuring both stiffness under high temperatures as well as flexibility at low temperatures. This is a useful method to extend the pavement lifespan and reduce maintenance costs [5]. Using grain polymers is currently an effective alternative to PMB, because of several technological and economical advantages. Polymer quality is essential to obtain adequate mixture characteristics.

Remark

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