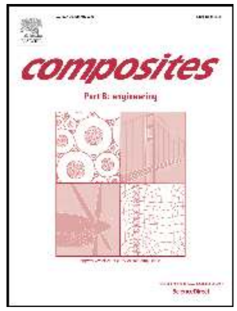
Accepted Manuscript



The effects of fibers on the performance of bituminous mastics for road pavements

Cristina Bonica, Emanuele Toraldo, Luca Andena, Claudia Marano, Edoardo Mariani

PII: S1359-8368(16)30157-3

DOI: 10.1016/j.compositesb.2016.03.069

Reference: JCOMB 4170

To appear in: *Composites Part B*

Received Date: 30 July 2015

Revised Date: 8 March 2016

Accepted Date: 25 March 2016

Please cite this article as: Bonica C, Toraldo E, Andena L, Marano C, Mariani E, The effects of fibers on the performance of bituminous mastics for road pavements, *Composites Part B* (2016), doi: 10.1016/j.compositesb.2016.03.069.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

The effects of fibers on the performance of bituminous mastics for road pavements

Cristina Bonica[a], Emanuele Toraldo[a]*, Luca Andena[b], Claudia Marano[b], Edoardo Mariani[a]

[a]Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy. Email: cristina.bonica@polimi.it; emanuele.toraldo@polimi.it; edoardo.mariani@polimi.it

[b] Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy. Email: luca.andena@polimi.it; claudia.marano@polimi.it

*Corresponding author: Tel: +39 02 2399 6618, email address: emanuele.toraldo@polimi.it

Abstract

The experimental investigation herein described is aimed at understanding the effects of cellulose-based fibers on the mechanical properties of bituminous mastics for paving applications. Three bitumen (two of which modified with SBS polymers), a calcareous filler and four different types of fiber with varying content were used to prepare the investigated mastics. The filler to bitumen ratio was maintained constant. The laboratory investigations were focused on empirical tests (Needle Penetration and Ring and Ball - R&B - Temperature) and dynamic-mechanical tests, the latter performed in a wide range of temperatures. Results suggest that fibers improve the

behavior of mastics for hot mix asphalts, particularly with respect to the prevention of rutting phenomena at high service temperatures.

Keywords: A. Bituminous mastics; A. Fibers; B. Rheological properties; C. Dynamic Mechanical Analysis.

1. Introduction

Hot Mix Asphalts (HMAs) are the materials most used for road pavements through the world. They are composed of aggregates, bitumen and filler [1]; different types of additives are also frequently used for both processing and performance purposes. Aggregates, generally deriving from rock quarries, are the skeleton of a HMA. Bitumen and filler together form the so-called mastic which, when mixed with the aggregates, acts as an effective binder for the lithic skeleton. Thus mastics have a crucial role in the HMAs' performance during a pavement service life [2-5] because they have to bear both traffic loads and climatic changes.

Polymers and natural or synthetic fibers are often used as HMAs' additive to improve their performance in the field. They can be added either to the bitumen (modified bitumen) or directly to the final HMAs; the latter option is of particular interest in areas of the world in which bitumen modification plants are not available or too far from the construction site.

The main effects of an additive on the HMA's behavior are related to its interaction with the mastic: this is true for both a polymer-based additive, due to its affinity to the bitumen, and an additive based on fibers, whose specific area is significantly higher than that of typical aggregates.

ACCEPTED MANUSCRIPT

Consequently, the role of fiber-based additives on preventing failure in the HMA pavements, such as rutting or thermal cracking [6-8], can be more easily studied at a small scale on the bituminous mastics rather than on the complete asphalt system (standard, porous, or other HMA compositions).

Short fibers are often used as reinforcement of HMA for road applications. In this context several studies have been conducted, as demonstrated by recent scientific literature review papers [9, 10]. In particular, some recent papers focused on the use of both natural (i.e. coir) [11, 12] or waste/recycled (i.e. textiles, tires, carpets) [13, 14] fibers into HMA. Several studies have addressed the use of fibers to improve the HMAs performance: a few of them focused on the specific performance related to environmental, water and temperature effects [15, 16], while other experimentations were carried out to highlight HMAs' mechanical performance, e.g. stiffness [17], fatigue [18] and rutting [19]. Another line of research has been devoted to investigate the whole performance of fiber-reinforced HMAs [20, 21], their mix-design [22], or their performance related to the effects of fibers during compaction [23].

In this context, few researches have been focused on binder reinforcement due to fibers, taking into account the specific interaction with the bitumen. These researches concern the study of rheological properties [24, 25] and fiber dispersion into the bitumen blends [26], not considering the effect of filler which, in turn, is crucial to determine the mastic's final behavior.

Given this scenario, the main goal of the research described in this paper is to study, through laboratory tests, the effect of fiber addition on the mechanical behavior of bituminous mastics. The mastics considered in this research are composed by bitumen (three different bitumen were considered, two of them modified with the addition of a

Styrene-Butadyene block copolymer, SBS), a calcareous filler (a single ratio of filler to bitumen was considered in this research) and a short- cellulose fiber-based compound (four different types of compound were used). Different contents of the reinforcing fiber additives were considered. As for the mechanical tests, both empirical measurements (Needle Penetration and Ring and Ball tests) and dynamic-mechanical analyses (DMA) were carried out [27-32]. Temperature sweep DMA tests were carried out in a range of temperatures (which reproduce the typical climatic conditions of Mediterranean countries) to investigate the associated changes in bitumen stiffness. In particular, the research was focused on the role of mastics in preventing high temperature rutting phenomena and low temperature cracking that typically occur in road pavements during their service life.

Finally, the paper describes some details of the specific protocols developed during the research project and it provides an overview of the obtained results.

2. Materials, experimental plan and test methods

The basic constituents of the materials used in the research described in this paper are summarized in Table 1 and more details about bitumen and fibers are given in Table 2 and Table 3 respectively.

The bitumen and the fiber compounds used in this work are commercial products available on the Italian market. As for the fiber compounds (in Figure 1 their general appearance is shown), their exact composition has not been disclosed by the producer. Data shown in Table 3 were taken from the supplier’s technical data sheets.

Starting from these basic constituents, 67 combinations of fiber reinforced mastics were prepared in the laboratory, using a filler-bitumen ratio equal to 1.20 by weight, as required by the most common Italian Standard Technical Specifications (filler

ACCEPTED MANUSCRIPT

bitumen ratio between 0.8 and 2.0; ANAS and Società Autostrade). Fibers compounds were first grinded and then added into the base mastics, composed by bitumen and filler, in different quantities. The mixing operations were carried out using a laboratory mixer and following the procedures described by Toraldo et. al. [21].

The final fiber content ranged between 1.5%wt and 12%wt of the bitumen, as suggested by the fibers' supplier and following typical road applications practices. Only for the fiber compound indicated as Fiber C, having a woolen-appearance, the maximum content was 9%wt because of difficulties arising during mixing at higher fiber contents, which were responsible for a loss of mastic homogeneity. The fiber-added mastics will be referred to as reinforced mastics in the remainder of this paper.

Both bitumen and mastics were subjected to a set of tests in order to assess their mechanical behavior in a wide range of temperatures. Both empirical tests and DMA were performed.

As for the empirical tests, Penetration and Ring & Ball tests were carried out according to EN 1426/2007 and EN 1427/2007 standards, respectively.

DMA tests were carried out using a Rheometrics System Analyzer produced by TA instruments. All tests were performed using a parallel plate (diameter 25mm) compression configuration. For this purpose, cylindrical samples (22 mm in diameter and 6 mm in height) were prepared. The procedure developed to produce these samples (Figure 2) can be summarized as follows:

- the bitumen and the mastics were first heated and stirred (by the same laboratory mixer used to produce them) to achieve a low viscosity;

ACCEPTED MANUSCRIPT

- they were then cast in a Polytetrafluoroethylene (PTFE) mold (the edges and the bottom of which were covered with a polyester film, in the same manner described in the SHRP specifications to produce samples for Bending Beam Rheometer tests [33]) and then the excess material was removed using a pre-heated cutter;
- the mold was maintained for 24 hours at -10 °C, to promote the separation between the polyester film and the samples;
- finally, the samples were removed from the mold and stored in a freezer until testing in order to preserve their shape.

A suitable testing protocol had to be devised in order to characterize the temperature-dependent mechanical behavior of the investigated materials while avoiding experimental issues due to the following phenomena:

- gravity flow at high temperature;
- creep under load;
- thermal expansions with fixed plate gap;
- local inhomogeneity of composition at low temperatures.

The selected dynamic loading conditions consisted in a sinusoidal compressive strain with 0.1% amplitude at a frequency of 1 Hz. A static force was initially applied at room temperature to flatten the surface of the samples. This force was then continuously adjusted during the test so as to exceed by 40% the dynamic load induced by the harmonic oscillation, in order to ensure good contact between the sample and the compression plates. The samples were cooled down to -20°C and let rest for a few minutes to reach thermal equilibrium; after that, dynamic loading was applied while

ACCEPTED MANUSCRIPT

the temperature increased at a constant rate of 5°C/min up to 60°C. At least three samples for each material were tested.

The harmonic strain excitation at a given angular frequency ω, $\varepsilon(t)=\varepsilon_0\sin(\omega t)$, gives rise to a steady-state stress, measured during DMA:

$$\sigma(t)=\sigma_0\sin(\omega t+\delta) \qquad (1)$$

with $\delta(\omega)$ being the (positive) phase angle shift observed for all viscoelastic materials. The material characteristic response can be described by the complex tensile modulus, $E(\omega)$:

$$E(\omega)=(\sigma_0/\ \varepsilon_0)[\cos\ \delta + \mathrm{i}\ \sin\ \delta] \qquad (2)$$

where the real and imaginary parts represent the elastic (conservative) and viscous (dissipative) components of the material's response, respectively. The magnitude of the complex modulus, $E^*=|E(\omega)|$, is the dynamic rigidity which will be considered as an indication of the material's stiffness in this study.

In Figure 3 a typical plot of the dynamic rigidity (E^*) is given as a function of the test temperature (T). Data at the lowest and highest temperatures in the range investigated are not reliable, due respectively to the material becoming frozen or displaying excessive softening; accordingly, only data in the temperature range between -10°C and +50°C were considered. As shown in Figure 3, E^*-T curves are characterized by an initial plateau from -10 °C to +15 °C followed by a fairly linear decreasing trend between +25 °C and +50 °C.

To evaluate the effect of bitumen type and type /content of fiber compound on the dynamic rigidity of the mastics, three parameters were considered as representative of the E^*-T curves:

ACCEPTED MANUSCRIPT

- the dynamic rigidity in the low temperature range (from -10 °C to +15 °C), herein named E^*_{LT};the dynamic rigidity at 50 °C, herein named E^*_{50};
- the slope of log E^* plotted versus T (α_{HT}), in the temperature range between +25 °C and +50 °C.

The first parameter represents the material stiffness in cold conditions, in which thermal cracking phenomena could occur during the pavement service life. The latter two parameters are able to describe the materials behavior at high temperatures (approximately from +25 °C up to +50 °C), at which rutting phenomena could occur.

3. Results and discussion

3.1 Empirical tests

Figure 4 and Figure 5 show the results of the empirical tests (Needle Penetration and R&B Temperature) for each bitumen and the relevant mastics.

It can be observed that, as expected, the unmodified bitumen has a Needle Penetration higher than those of the two modified bitumen. Moreover, the Needle Penetration of the base mastics (bitumen and filler) is lower than the neat bitumen. This result is more evident in the case of unmodified bitumen (B1) which does not benefit from the inherently higher stiffness granted by the added polymers. The addition of fiber further reduces the mastic Needle Penetration; this effect is larger in the case of the Fiber C compound. Generally speaking, a decrease of the investigated parameters can be observed as the content of the fiber additive increases.

ACCEPTED MANUSCRIPT

Similar effects of material composition on the R&B Temperature tests were observed (Figure 5). For each mastic, its R&B Temperature is higher than that of the constituent bitumen: this result indicates, again, that the bitumen stiffness increases due both to the addition of the filler (bitumen compared to the base mastics) and of the fibers (base mastics compared to fiber containing mastics). The higher values of the R&B Temperature measured for mastics made of modified bitumen are related to the presence of polymers. As for the fibers' effects, the increase in the investigated parameter due to fibers addition is slightly dependent on fiber content. This dependency is stronger in the case of Fiber C when compared to Fiber A and B compounds which, instead, behave similarly; moreover, the highest values of the R&B Temperature were attained with Fiber C.

These results are consistent with those from the Needle Penetration tests.

3.2 DMA

In Figure 6 the average value of the low temperature dynamic rigidity, E^{*}_{LT}, is reported as a function of the fiber-bitumen ratio for the different materials.

A first observation is that E^{*}_{LT} of both unmodified bitumen (B1) and 4% SBS modified bitumen (B3) is lower than that of the corresponding base mastics. This is not true for 2% SBS modified bitumen (B2): in fact, bitumen and mastic have almost the same value of E^{*}_{LT}. As far as the effect of the fibers is concerned, it can be observed that: (i) the investigated parameter seems to be not significantly influenced by fibers type and content, irrespective of the bitumen used; (ii) only for the mastics based on 4% SBS modified bitumen the addition of fibers brings about a decrease of E^{*}_{LT}. In all cases, the contribution of fibers appears not to be detrimental for road construction uses. In

ACCEPTED MANUSCRIPT

fact, at cold temperatures a lower stiffness can be a positive factor in preventing cracking phenomena, as reported in the literature [16].

Figure 7 shows the average values of E^*_{50} and α_{HT}, defined at the end of section 3, plotted as a function of the fiber-bitumen ratio.

Analyzing the graphs of E^*_{50}, the increase in stiffness due to the filler is noticeable for all the investigated bitumen, even if it is more appreciable for the unmodified one (B1), which as noticed previously already possesses an inherently lower dynamic rigidity.

The effect of the fibers addition depends on the type of bitumen used to prepare the mastics. In particular, mastics made of B1 bitumen show a slight increase of the stiffness with increasing fibers content. On B2 mastics, the effect is more appreciable although relatively independent of the actual fiber content. In the case of B3 mastics the dynamic rigidity is not affected by the addition of fibers.

As for the effect of the specific fiber type, no definite trends can be found.

It is more difficult to analyze the E* versus temperature slope, α_{HT} parameter, due to the significant scatter of the data, particularly for the mastics based on bitumen B1 and B2: in these cases it is not possible to observe a well-defined trend in the plot of α_{HT} versus the fiber content. Instead, for the mastics based on bitumen B3, a decrease in α_{HT}as the fiber content increases is appreciable, irrespective of fiber type.

To conclude, it is possible to point out that fibers have a beneficial effect on the mastics stiffness at high service temperatures, especially on conventional (i.e. unmodified) bitumen. Results in term of the α_{HT} parameter also show that the temperature sensitivity is reduced, meaning that the increased level of stiffness can be retained at higher temperatures. These observations support the data obtained from empirical tests and confirm that referring to the performance required to the mastics when used as binder in Hot Mix Asphalts (HMA) for road pavements, fibers play a positive role in preventing rutting deformations in the field as a consequence of high temperatures and traffic loads.

4. Conclusions

The laboratory investigation described in this paper focuses on the effects of the addition of fibers on the mechanical behavior of bituminous mastics for road pavements. To this end, the investigation was carried out performing empirical and DMA tests.

As for empirical tests (Needle Penetration and Ring and Ball), the obtained results show that both filler and fibers addition improve the materials' performance: specifically, a decrease of both Needle Penetration and Ring and Ball temperature were obtained after the addition of filler and fiber based compounds.

As for DMA tests, laboratory results confirm that fibers improve mastic performance, particularly at high service temperatures, playing a positive role in preventing rutting phenomena in the field.

The obtained results suggest that fibers could be used to improve the mechanical performance of HMAs, based on both standard (unmodified) and modified bitumen. These findings are important considering that modified bitumen, which is an unstable material, cannot be easily transported or stored; this rules out the use of these binders in those areas of the word in which bitumen modification plants are far from the road construction sites. In these areas, it is possible to use fibers and standard bitumen to increase HMA performance.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Acknowledgments

The research was partially supported by Advanced Manufacturing Lab (AMALA) of Politecnico, Milan. The authors thank Mr. Oscar Bressan for help in performing DMA tests.

ACCEPTED MANUSCRIPT

References

[1] The Asphalt Handbook, Asphalt Institute 2007; MS-4. 7th edition.

[2] Delaporte B, Di Benedetto H, Chaverot P, Gauthier G. Linear viscoelastic properties of bituminous materials: from binders to mastics (with discussion). Journal of the Association of Asphalt Paving Technologists 2007, 76.

[3] Moon K H, Falchetto A C, Park J Y, Jeong J H. Development of high performance asphalt mastic using fine taconite filler. KSCE Journal of Civil Engineering 2014; 18(6): 1679-1687.

[4] Delaporte B, Di Benedetto H, Chaverot P, Gauthier G. Effect of ultrafine particles on linear viscoelastic properties of mastics and asphalt concretes. Transportation Research Record: Journal of the Transportation Research Board 2008; 2051(1): 41-48.

[5] Hesami E, Birgisson B, Kringos N. Numerical and experimental evaluation of the influence of the filler–bitumen interface in mastics. Materials and Structures 2014; 47(8): 1325-1337.

[6] YE Q, WU S. Rheological Characteristics of Polyester Fiber Modified Asphalt Mastic [J]. Journal of Highway and Transportation Research and Development 2009; 9, 007.

[7] Bo P E N G, Zhi-yong D, Jing-liang D. Road performance comparison of different asphalt mastics. Journal of Traffic and Transportation Engineering 2007; 3, 012.

[8] Chen J S, Lin K Y. Mechanism and behavior of bitumen strength reinforcement using fibers. Journal of Materials Science 2005; 40(1): 87-95.

ACCEPTED MANUSCRIPT

[9] Abtahi S M, Sheikhzadeh M, Hejazi S M. Fiber-reinforced asphalt-concrete–a review. Construction and Building Materials 2010; 24(6): 871-877.

[10] Abiola O S, Kupolati W K, Sadiku E R, Ndambuki J M. Utilisation of natural fibre as modifier in bituminous mixes: a review. Construction and Building Materials 2014; 54: 305-312.

[11] Lokesh Y, Kulkarni H, Ponnappa K J, Reddy T. Study on Effect of Coir Fibres on SdbC Grade- 2 Mix. International Journal of Scientific Research 2014; Vol : 3.

[12] Subramani T. Experimental investigations on coir fibre reinforced bituminous mixes. Strain 2012; 2: 4-5.

[13] Gordon G, Holmquist D, Kennedy T. Use of Recycled and Waste Fibers in Asphalt Concrete. Proceedings of the 2nd Recycling of Fibrous Textile and Carpet Waste Conference, Georgia, Institute of Technology, 1997.

[14] Putman BJ, Amirkhanian S N. Utilization of waste fibers in stone matrix asphalt mixtures. Resources, conservation and recycling 2004; 42(3): 265-274.

[15] Xu Q, Chen H, Prozzi J A. Performance of fiber reinforced asphalt concrete under environmental temperature and water effects. Construction and Building materials 2010, 24(10), 2003-2010.

[16] Tasdemir Y, Agar E. Investigation of the low temperature performances of polymer and fiber modified asphalt mixtures. Indian J Eng Mater Sci 2007;14: 151-157.

[17] Moreno-Navarro F, Sol-Sánchez M, Rubio-Gámez M C, Segarra-Martínez M. The use of additives for the improvement of the mechanical behavior of high modulus asphalt mixes. Construction and Building Materials 2014; 70: 65-70.

[18] Ye Q, Wu S, Li N. Investigation of the dynamic and fatigue properties of fiber-modified asphalt mixtures. International Journal of Fatigue 2009; 31(10): 1598-1602.

[19] Xu T, Wang H, Li Z, Zhao Y. Evaluation of permanent deformation of asphalt mixtures using different laboratory performance tests. Construction and Building Materials 2014; 53: 561-567.

[20] Wu S, Ye Q, Li N, Yue H. Effects of fibers on the dynamic properties of asphalt mixtures. Journal of Wuhan University of Technology-Mater. Sci. Ed. 2007; 22(4): 733-736.

[21] Toraldo E, Mariani E, Malvicini S. Laboratory investigation into the effects of fibers on bituminous mixtures. Journal of Civil Engineering and Management 2015; 21(1): 45-53.

[22] Ye Q, Wu S. Rheological properties of fiber reinforced asphalt binders. Indian Journal of Engineering and Materials Sciences 2009; 16(2): 93.

[23] Crispino M, Mariani E, Toraldo E. Assessment of fiber-reinforced bituminous mixtures' compaction temperatures through mastics viscosity tests. Construction and Building Materials 2013; 38: 1031-1039.

[24] Wu S, Chen Z, Ye Q, Liao W. Effects of fibre additive on the high temperature property of asphalt binder. Journal of Wuhan University of Technology-Mater. Sci. Ed. 2006; 21(1): 118-120.

[25] Ye Q, Wu S. Rheological properties of fiber reinforced asphalt binders. Indian Journal of Engineering and Materials Sciences 2009; 16(2): 93.

[26] Chen H, Xu Q. Experimental study of fibers in stabilizing and reinforcing asphalt binder. Fuel 2010; 89(7): 1616-1622.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

[27] Dos Santos S, Partl M N, Poulikakos L D. From virgin to recycled bitumen: A microstructural view. Composites Part B: Engineering 2015; 80: 177-185.

[28] Rinaldini E, Schuetz P, Partl M N, Tebaldi G, Poulikakos L D. Investigating the blending of reclaimed asphalt with virgin materials using rheology, electron microscopy and computer tomography. Composites Part B: Engineering 2014; 67: 579-587.

[29] Shu X, Huang B. Micromechanics-based dynamic modulus prediction of polymeric asphalt concrete mixtures. Composites Part B: Engineering 2008; 39(4): 704-713.

[30] Zhu X Y, Yang Z X, Guo X M, Chen W Q. Modulus prediction of asphalt concrete with imperfect bonding between aggregate–asphalt mastic. Composites Part B: Engineering 2011; 42(6): 1404-1411.

[31] Rossi C O, Spadafora A, Teltayev B, Izmailova G, Amerbayev Y, Bortolotti V. Polymer modified bitumen: Rheological properties and structural characterization. Colloids and Surfaces A: Physicochemical and Engineering Aspects 2015.

[32] Ortega F J, Navarro F J, García-Morales M, McNally T. Thermo-mechanical behaviour and structure of novel bitumen/nanoclay/MDI composites. Composites Part B: Engineering 2015; 76: 192-200.

[33] AASHTO T 313-06: Standard test method for determining the Flexural Creep Stiffness of Asphalt.

ACCEPTED MANUSCRIPT

Figure captions

Figure 1. General appearance of investigated fibers compounds

Figure 2. Laboratory mixer (a); PTFE mold (b) and (c); a mastic sample (d)

Figure 3. Example of the DMA test result on a base mastic sample made of unmodified bitumen (B1) (see table 1). The figure also shows how E^*_{LT}, E^*_{50} and α_{HT} parameters were determined.

Figure 4. Effect of fiber type and content on the Needle Penetration for the mastics based on unmodified bitumen, B1 (left plot) and modified bitumen B2 and B3 (central and right plots). The different symbols refer to the different fiber compounds used.

Figure 5. Effect of fiber type and content on the R&B Temperature for mastics based on unmodified bitumen, B1 (left plot) and modified bitumen B2 and B3 (central and right plots). The different symbols refer to the different fiber compounds used.

Figure 6. Effect of the filler type and content on the dynamic rigidity measured at low temperature, E^*_{LT}, for mastics based on unmodified bitumen, B1 (left plot) and modified bitumen B2 and B3 (central and right plots). The different symbols refer to the different fiber compounds used. Average values are reported for each mastic with error bars representing standard deviation.

Figure 7. Effect of the filler type and content on the dynamic rigidity at high temperature (above), E^*_{50}, and corresponding slope, α_{HT}, for mastics based on unmodified bitumen, B1 (left plot) and modified bitumen B2 and B3 (central and right plots). The different symbols refer to the different fiber compounds used. Average values are reported for each mastic with error bars representing standard deviation.

ACCEPTED MANUSCRIPT

Tables

Table 1. Summary of the materials investigated in the present research work

Bitumen	Bituminous mastics	Fiber-reinforced bituminous mastics (fiber content in %wt)			
		A pure cellulose	B cellulose+glass	C cellulose+ polymer	D cellulose+recycled polymer
B1 (unmodified)	B1+F	B1+F+A (1,5-3-6-9-12)	B1+F+B (1,5-3-6-9-12)	B1+F+C (1,5-3-4-5-6)	B1+F+D (1,5-3-6-9-12)
B2 (2%wt SBS)	B2+F	B2+F+A (1,5-3-6-9-12	B2+F+B (1,5-3-6-9-12)	B2+F+C (1,5-3-4-5-6)	B2+F+D (1,5-3-6-9-12)
B3 (4%wt SBS)	B3+F	B3+F+A (1,5-3-6-9-12	B3+F+B (1,5-3-6-9-12)	B3+F+C (1,5-3-4-5-6)	B3+F+D (1,5-3-6-9-12)

ACCEPTED MANUSCRIPT

Table 2. Main characteristics of the three investigated bitumen

Test	Standard	B1	B2	B3
Needle penetration [dmm]	EN 1426	51.3	40.3	35.2
Ring and Ball [°C]	EN 1427	46.5	58.8	61.7
Rotational Viscosity [cP]	ASTM D4402	116	342	424

ACCEPTED MANUSCRIPT

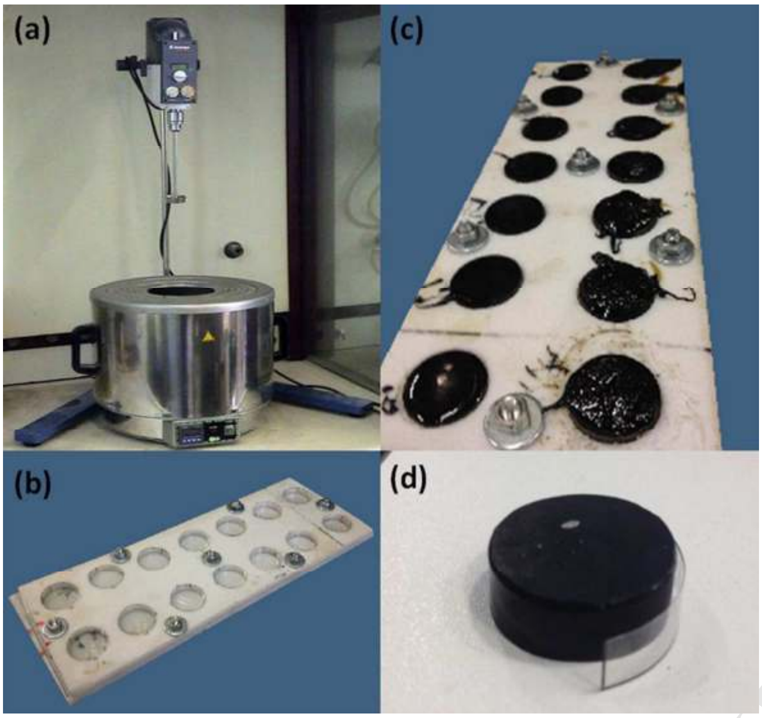
Table 3. Main characteristics of investigated fiber types

Fiber compound	Length [mm]	Diameter [µm]	Maximum service temperature [°C]
Fiber A	~0.2	~7	>200
Fiber B	~0.2	~7	>200
Fiber C	~6	~20	>200
Fiber D	~0.2	~10	>200

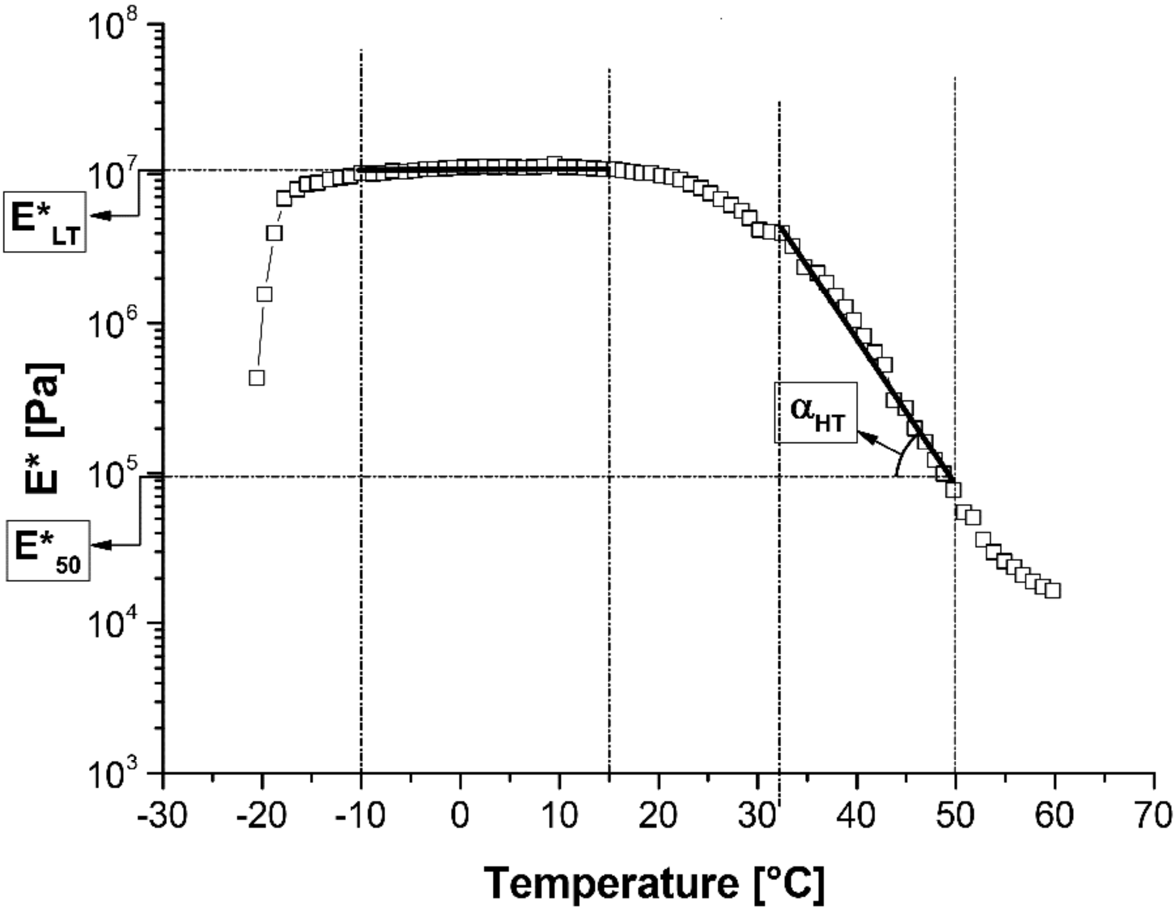
ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

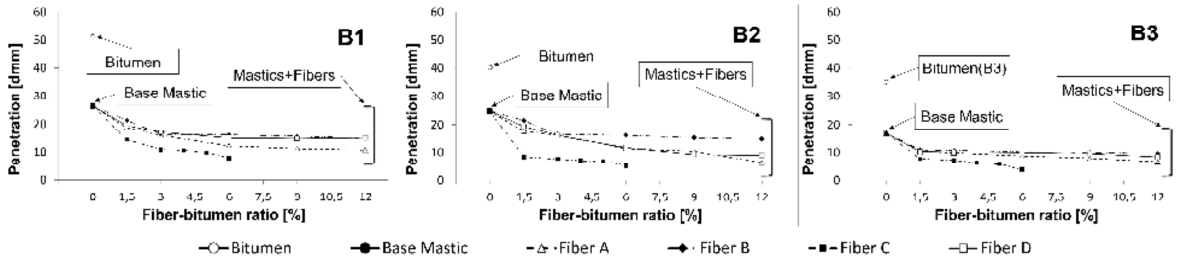


ACCEPTED MANUSCRIPT

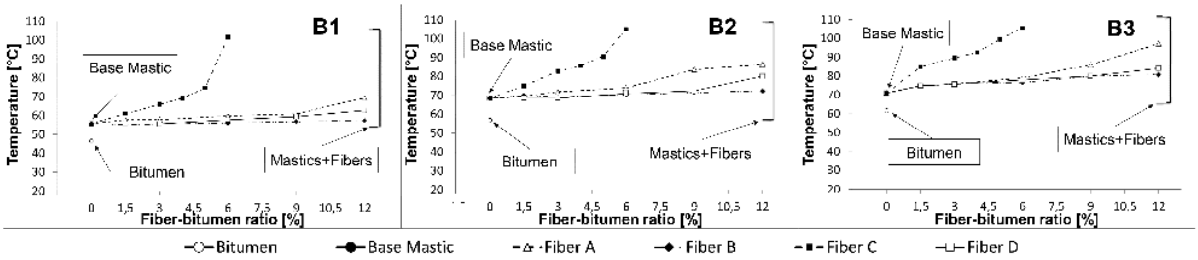


ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

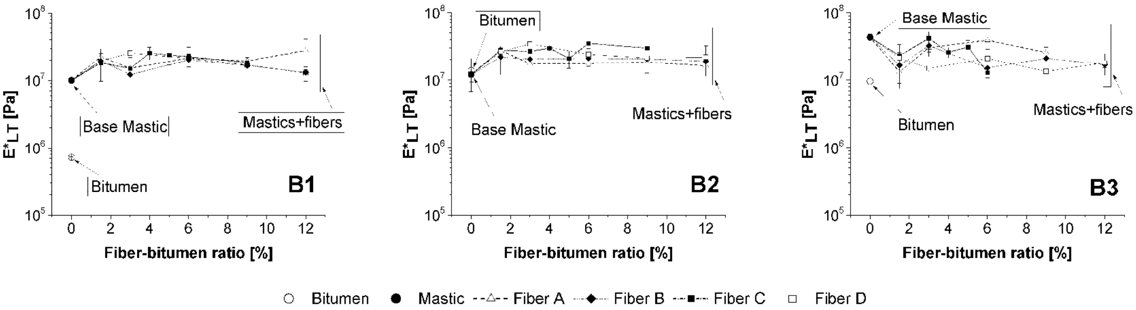


ACCEPTED MANUSCRIPT

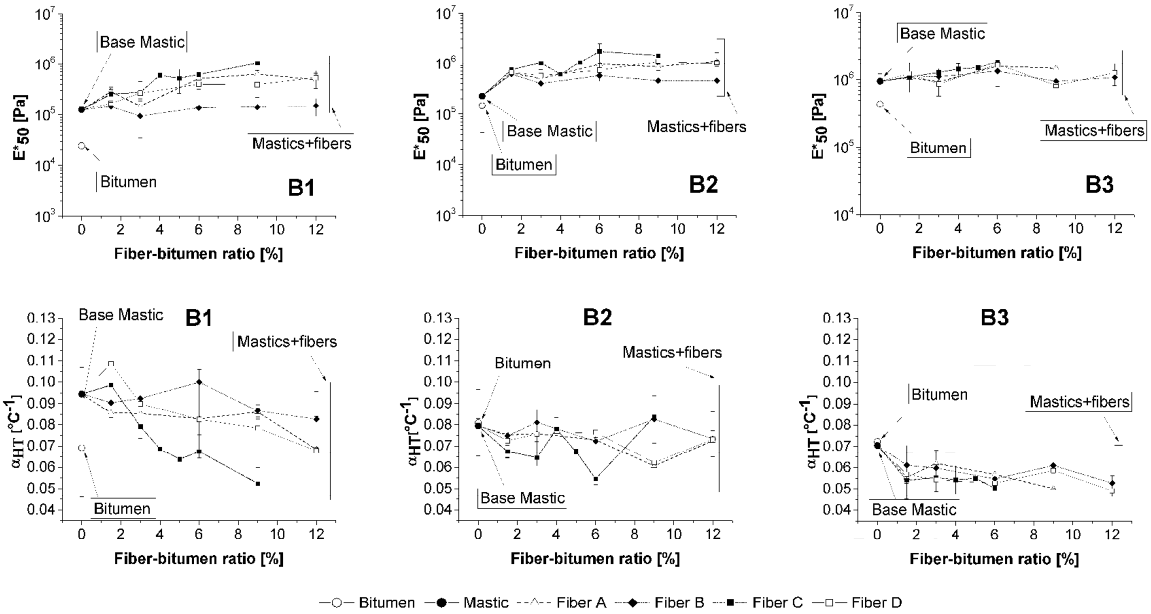


ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT