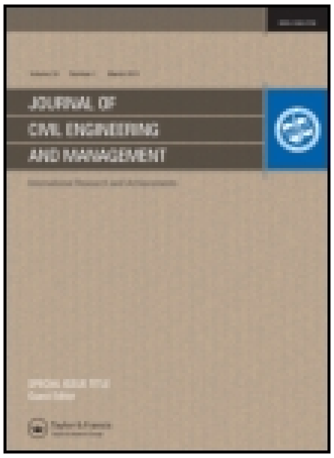

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Laboratory investigation into the effects of fibers on bituminous mixtures

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LABORATORY INVESTIGATION INTO THE EFFECTS OF FIBERS ON BITUMINOUS MIXTURES

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Abstract. The growing need for high quality bituminous mixtures in road construction, rehabilitation and maintenance is currently satisfied by means of techniques to produce polymer-modified bitumen, or by the addition of additives to mixtures during in-plant mixing operations. A rigorous rheological approach in the study of the bitumen modification process enables researchers to rationally compare different modifying agents and to evaluate their relative efficiency for specific field applications. As far as additives are concerned, the binder is not the only element involved in the evaluation; both binding mastics and bituminous mixtures must be evaluated to get a complete understanding of the characteristics. Moreover, the advantages that may stem from the use of fibers should be carefully taken into consideration since they may offer alternative strategies for the enhancement of bituminous mixtures. As a result of these observations, the authors have devised an experimental research project focused on the analysis of the effects of different types and dosages of cellulose-based fibers on the main performance-related properties of bituminous road materials: compaction properties, volumetric characteristics and mechanical performance. This paper provides an overview of the results obtained and some details of the specific protocols followed during the research project.

Keywords: bituminous mixture, fibers, compaction properties, volumetric characteristics, mechanical performance.

Introduction

The growing need for high quality bituminous mixtures in road construction, rehabilitation and maintenance is currently satisfied by means of techniques to produce polymer-modified bitumen, or by the addition of additives to mixtures during in-plant mixing operations.

A rigorous rheological approach in the study of the bitumen modification process enables researchers to rationally compare different modifying agents and to evaluate their relative efficiency for specific field applications (Bahia *et al.* 2001).

As far as additives are concerned, the binder is not the only element involved in the evaluation; both binding mastics and bituminous mixtures must be evaluated to get a complete understanding of the characteristics.

Among the wide range of additives available on the international market, fibers have been widely used as additives for bituminous mixtures. Acting mainly as thickening agents, they increase viscosity at high service temperatures, thus minimizing drain-off effects that may occur in the early phases of transportation and laying (PIARC 1998; Brown 1992; Mallick *et al.* 2000). Recently, however, spurred by the extensive use of fibers in other fields of engineering and industry, fiber technology has rapidly evolved, leading to the production of high-performance fibers that may play an important and innovative role in bituminous mixtures (Tapkin *et al.* 2009; Wu *et al.* 2008; Lee *et al.* 2005; Woodside *et al.* 2009; Hassan *et al.* 2005; Chen, Lin 2005; Mahrez *et al.* 2003, 2005; Chen, Xu 2010; Bullinger 2004; Xu *et al.* 2010; Chowdhury *et al.* 2006; Putman, Amirkhanian 2004; Sanchez-Alonso *et al.* 2011a, b; Movilla-Quesada *et al.* 2011).

Within the framework of innovation and development described above, experimental investigations were carried out in the Road Research Laboratory, Politecnico di Milano, with the aim of understanding the effects of commercially available cellulose-based fibers on bituminous mixtures for paving applications. One part of the research project focused on the effects of different types and quantities of fibers on the viscosity of bituminous mastics at working temperatures (Mariani 2010). It was shown that fibers cause changes in the viscosity of the mastics and, consequently, volumetric variations in the bituminous mixtures.

In order to better understand the mechanism by which fiber interacts with bituminous mixtures, further comparative investigations were carried out on the effects of such additives (evaluating different types and quantities of fibers) on compaction properties, volumetric characteristics and mechanical properties of bituminous mixtures. The

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Table 1. Gradation of the aggregates

Sieve size [mm]	31.5	16	12.5	9.5	8	4	2	1	0.5	0.4	0.25	0.125	0.075	0.063
Percent of passing [%]	100	86.4	73.6	62.7	57.2	40.7	29.7	23.8	16.7	13.3	8.5	6.4	5.9	5.4

Table 2. Main characteristics of fibers

Fiber	Source	Length	Diameter	Temperature Resistance
		[μm]	[μm]	[°C]
A	Cellulose	~200	~7	> 200
B	Cellulose and Glass	~200	~7	> 200
C	Cellulose and Recycled Synthetic	~200	~10	> 200

corresponding results, obtained by studying three types of fibers and three quantities, are described in this paper.

1. Materials and experimental program

1.1. Materials

The composition of bituminous mixtures included in the experimental investigation was determined in line with current specifications for pavement binder courses provided by the Italian Road and Highways Administration (ANAS and Società Autostrade). Therefore, a single particle-size distribution of aggregates and a single value of bitumen content (%B equal to 4.5% by weight of aggregates) were chosen for the preparation of the mixtures (Table 1). The key materials used in the study included natural calcareous aggregates, provided by a local contractor, a standard 50/70 penetration unmodified bitumen obtained from a refinery located in Busalla (GE) and a calcareous filler. Filler/bitumen ratio was maintained at a level equal to 1.2.

As mentioned above, fibers used in the experimental investigation (Fig. 1) are those mainly employed in the field of road pavements: Cellulose (hereinafter named Fiber A), Cellulose and Glass (Fiber B), and Cellulose and Recycled Synthetic (Fiber C).

The main characteristics of these cellulose-based fibers are shown in Table 2, in which it is possible to highlight that the fibers are of the same length, diameter (except Fiber C) and temperature resistance.

1.2. Preparation of bituminous mixtures and specimens

The preparation of the bituminous mixtures was carried out by using a heated lab mixer (mixing temperature equal to 165±5 °C, mass of each mixture 50 kg). In order to prevent lumps of filler and/or fiber and to obtain homogeneous final mixtures, an operative mixing method was developed. This method consisted of the following steps: the heating of the aggregates, filler and bitumen to the mixing temperature; insertion of the aggregates in the mixer and the addition of a set quantity of bitumen (60% by weight of the total bitumen); the mixing of all the materials until the aggregates were homogeneously covered by the bitumen; the alternate addition of fibers (5 grams at a time and previously defibered using a lab mill) and filler (10 grams at a time) while the mixer is switched on; the addition of the remaining bitumen; a final, five-minute mix.

Fig. 1. Fibers investigated

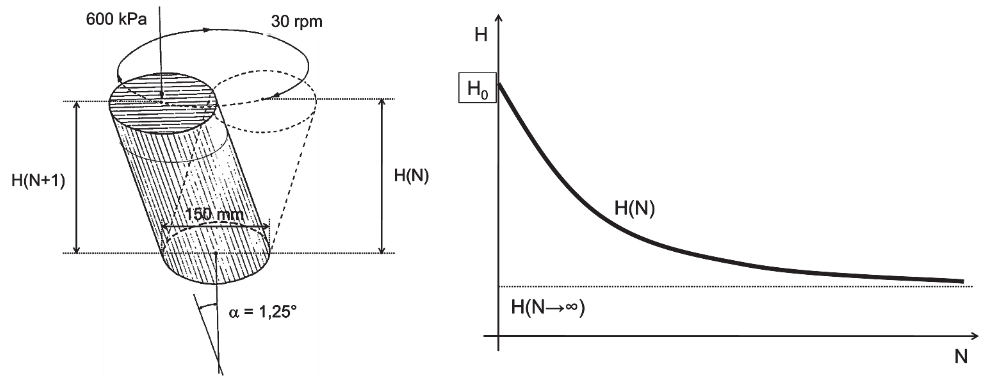
The method described above produces homogeneous mixtures, as verified by a visual inspection, as well as by both the bitumen extraction test and aggregate gradation test.

Specimens were prepared using a gyratory shear compactor (GSC) as schematically illustrated in Figure 2, and by following the protocol specifications defined within the US Strategic Highway Research Program (Cominsky *et al.* 1994) (1.25° gyration angle, 30 rev·min^{-1} gyration speed, 600 kPa vertical pressure, 150 mm mould diameter).

With regard to compaction temperatures, the preparation of specimens was carried out using different temperatures according to fiber type and quantity, on the basis of previous results obtained by the authors (Crispino *et al*. 2013; Toraldo *et al*. 2013; Toraldo, Mariani 2014). In addition, the results show that the compaction temperatures (point 4, Fig. 3) were selected in order to maintain the viscosity of the system bitumen-filler-fiber (point 3, Fig. 3) equal to the viscosity of the corresponding base mastic (point 3, Fig. 3) composed by bitumen and filler (η_{mastic} = 1238cP). The latter was obtained taking into consideration both the bitumen compaction temperature (point 2, Fig. 3) and viscosity (point 1, Fig. 3) suggested by the literature (Asphalt Institute, 2007) ($\eta_{bituminen}$ = 280cP ± 30), as described in Figure 3.

1.3. Experimental plan

The experimental investigation involved a number of tests selected to evaluate the specific performance-related



H = height of the specimen; N = GSC revolution number; H_0 = initial height of the specimen at N = 0;
H(N) = height of the specimen at the revolution N; H(N+1) = heigth of the specimen at the revolution N+1

Fig. 2. Illustration of the gyratory shear compaction and diagram of the compaction process

properties of the bituminous mixtures, useful for assessing the role of fiber as an additive. As regards the compaction properties, it was considered essential to evaluate whether the workability of the mixtures is significantly affected by the addition of cellulose-based fibers in the filler-bitumen mastic, which are characterized by a high degree of absorption. Consequently, 9 cylindrical specimens of each mixture were compacted at the temperatures showed in Table 3 using the GSC mentioned above. The number of revolutions applied to each specimen was set at 100, as previous studies show that this value leads to density levels similar to those obtained in the field by means of standard compaction equipment and procedures (Bassani*,* Santagata 2002; Cominsky *et al.* 1994).

Apparent advantages from the use of this equipment relate not only to its simulative nature, but also to the possibility of monitoring the compaction process on a quantitative basis. This is shown in Figure 4, in which the progressive compaction percentage *C* is plotted as a function of the number of revolutions *N*. As such, data points can be linearly interpolated for the evaluation of so-called self-compaction C_1 and the intrinsic workability *k*, which enables pavement engineers to quantify the compaction properties and consequently compare different mixtures, as proven by previous investigations (Bassani, Santagata 2002; Cominsky *et al.* 1994). In the compacted state, standard bituminous mixtures are three-phase composites, which can be represented in a volume phase diagram. With the addition of fibers the volume phase diagram changes as shown in Figure 5.

It should be noted that in standard bituminous mixtures, the volume occupied by aggregates V_G and bitumen V_B partially overlaps as a result of the aggregate surface absorption. Therefore, the total volume of bitumen can be divided into the absorbed portion V_{BG} and the portion which effectively acts as a binder V_{BE}. In the case of fiber-reinforced bituminous mixtures, the bituminous binder is absorbed by both the aggregate surface V_{BG} and the fibers V_{BF}. In addition, fibers occupied a portion V_F of total volume *V*. According to these observations, it is evident that fibers play an important role in the volumetric characteristics of compacted bituminous mixtures,

Table 3. Compaction temperatures of the bituminous mixtures

Fiber	Compaction temperatures [°C]			
	Fiber/Bitumen Ratio [%]			
	0	3	6	9
A	140	155	169	177
B	140	144	145	149
C	140	161	165	180

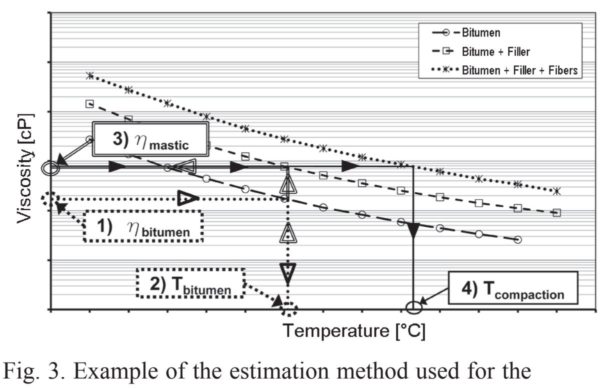


Fig. 3. Example of the estimation method used for the compaction temperatures

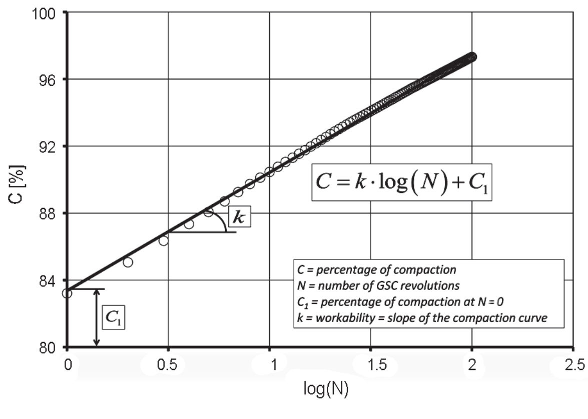


Fig. 4. Typical gyratory shear compactor test results

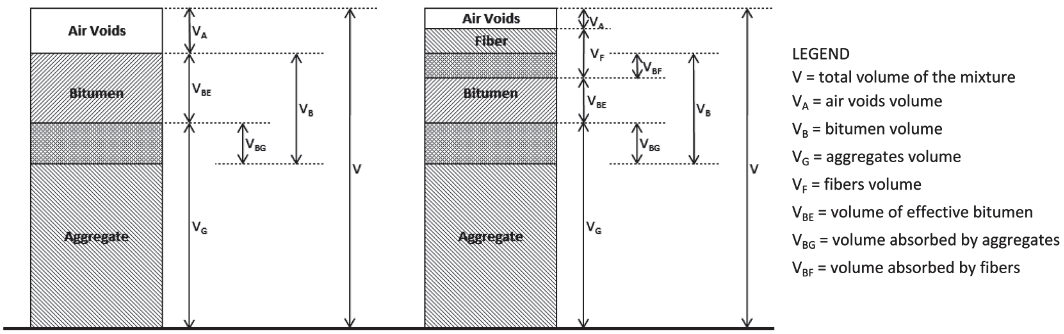


Fig. 5. Volume phase diagrams of standard and fiber-reinforced bituminous mixtures

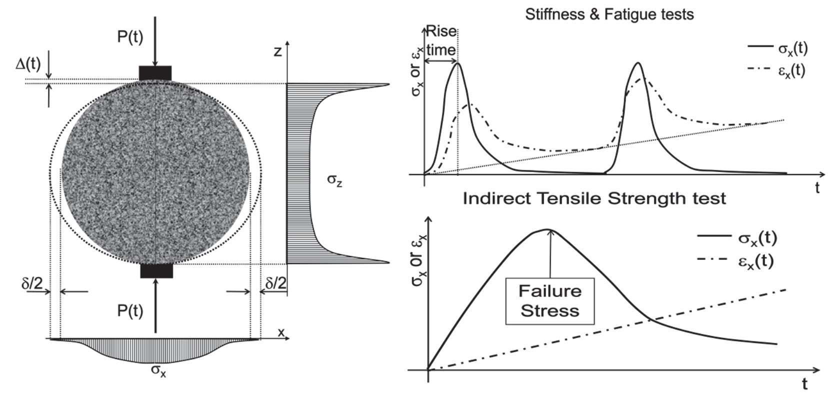


Fig. 6. Scheme of indirect tensile tests for the evaluation of elastic stiffness, indirect tensile strength and fatigue resistance

mostly because of their absorption properties due to the presence of cellulose.

Given the complexity of the internal structure of a bituminous mixture, particularly those containing additives, all GSC compacted specimens were subjected to a complete volumetric characterization. The evaluation not only provides the basis (Cominsky *et al.* 1994) for the interpretation of the results of the mechanical tests, but can also be used for mix design and quality control purposes in most pavement construction and maintenance projects (Cominsky *et al.* 1994).

By following the procedures illustrated in ASTM specifications (ASTM 2008) the authors focused on the evaluation of void content *v*, voids in the mineral aggregate (*VMA*) and voids filled with bitumen (*VFB*), which are defined by the following equations:

$$v = 100 \cdot V_A / V; \quad (1)$$

$$VMA = 100 \cdot \left(V_A + V_{BE}\right) / V; \quad (2)$$

$$VFB = 100 \cdot V_A / \left(V_{BE} / V_A\right), \quad (3)$$

where: V is the total volume of the mixture; V_A is the air voids volume; and V_{BE} is the volume of the effective bitumen (which is not absorbed by aggregates in standard bituminous mixtures and by both aggregates and fibers in bituminous mixtures with additives) as reported in Figure 5.

Specifically, it can be stated that while the void content *V* provides the measure of the degree of compaction achieved for a given mixture, being in relation to its density and permeability, the values of *VMA* and *VFB* allow for a better understanding of its internal structure: *VMA* assesses the degree of packing of the aggregate particles, *VFB* gives the degree of void filling caused by the effective bituminous binder.

Mechanical tests, as the core of the experimental investigation, were carried out to quantify both the stiffness of the mixtures, which is related to their load distribution aptitude as part of multilayered pavement structures, and their failure properties. As regards the latter, failure conditions were reached either by quasi-static loading (for the evaluation of strength) or by repetitive pulse loading (for the evaluation of fatigue resistance).

The indirect tensile configuration, obtained by subjecting a cylindrical specimen to diametrical compression (Fig. 6), was adopted to measure both the so-called elastic stiffness E and the fatigue resistance N_f by means of repetitive pulse loading. Both types of tests were carried out using a pneumatically driven asphalt tester (PAT), and in a temperature-controlled chamber.

The elastic stiffness tests were carried out at a 20 °C and 40 °C. Pulses were applied with a rise time of 60 and 120 ms and with a target horizontal deformation of the specimens equal to 7 μm (EN 12697-26 2003). The corresponding value of elastic stiffness E was calculated by means of the following expression:

$$E = \frac{P \cdot (0.273 + \nu)}{\delta \cdot h}, \quad (4)$$

where: P is the vertical peak load; h is the thickness of the specimen; ν is the Poisson ratio (assumed to be equal to 0.35); and δ is the measure of the horizontal deformation. Fatigue tests were carried out at 20 °C in the controlled horizontal stress mode (σ_h equal to 600 and 800 kPa) by applying a load pulse of a constant shape and amplitude to the specimen until its point of failure. The number of cycles before failure N_f was also recorded.

To this end, the vertical deformation of the specimen subjected to repetitive loading was monitored as a function of the number of loading pulses N_p. Typical experimental data obtained from this specific measurement are shown in Figure 7, in which three characteristic phases are highlighted. During the first phase, the vertical permanent deformation tends to increase quickly and then stabilizes at a given initial value due to local settlements of the loading platens. The second phase is characterized by a vertical permanent deformation which slowly increases as a consequence of micromechanical damage caused by the repeated pulse loads. In the third phase of testing, the damage reaches a threshold limit beyond which an almost instantaneous failure occurs for a certain number of total load applications N_f.

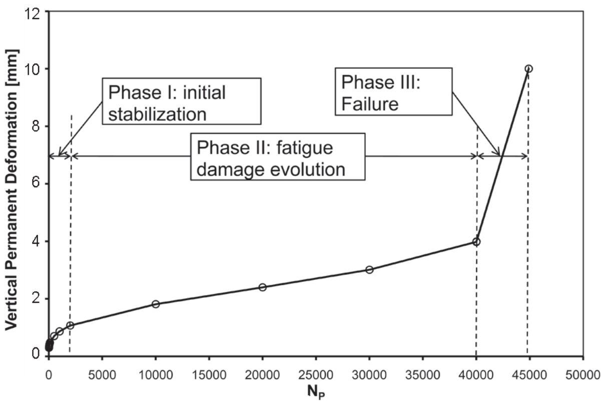


Fig. 7. Typical fatigue damage evolution during an indirect fatigue test carried out in controlled stress mode

The indirect tensile strength (ITS) was evaluated by means of the same configuration described above. However, the loading history was significantly different since, after imposing a relative constant compression speed of 0.85±0.05 mm·s^{-1} to the loading platens, the corresponding applied vertical load was recorded (Fig. 6). According to the European specifications (EN 12697-23 2003), indirect tensile strength can be calculated by the following equation:

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot h}, \quad (5)$$

where: P is the vertical peak load (at failure); D and h are respectively the diameter (150 mm) and the thickness of the specimen.

2. Results and discussion

2.1. Compaction properties

Average values of the compaction parameters C_1 and k obtained for all the bituminous mixtures investigated in the study are shown in Figure 8. It can be observed that self-compaction C_1 of the mixtures, which is related to the level of density achievable during laying in the field immediately behind the paver, is almost constant. This trend shows that the self-compaction ability of the bituminous mixtures under its own weight is not affected by the presence of fibers. It is due to the compaction method, which, changing the compaction temperature according to the type and quantity of fibers, allows an almost constant binding mastics viscosity. Mixtures with Fiber B content, however, show a slight reduction in C_1 with a medium fiber content (6%).

As far as the workability data plotted in Figure 8 is concerned, it can be stated that by adding increasing quantities of fiber to the mixture, the result is a significant reduction of workability.

Such a result is evidently due to the presence of fibers in the mixtures, which fill in the voids in the aggregate structure thus not allowing the same degree of compaction as the standard bituminous mixtures (with no fibers), via the rearrangement of the aggregates under loads. Moreover, the presence of cellulose in the additives

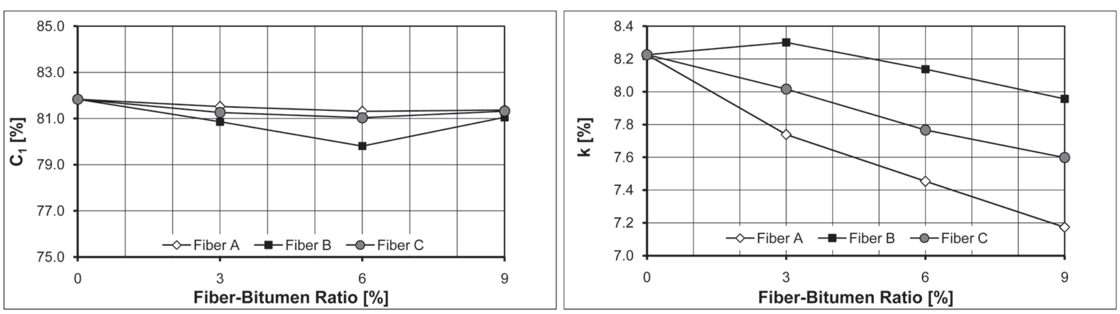


Fig. 8. Compaction parameters of bituminous mixtures

and its absorption characteristic reduces the fluidizing effect of the bitumen during the compaction process.

As can be expected, the workability data shows that the mixtures with Fiber A (pure cellulose) demonstrate the highest decrease of this parameter, whereas mixtures with Fiber B (cellulose and glass) show the lowest reduction of workability *k*. In fact, the presence of glass, characterized by its non-porous surface, reduces the fibers absorption property. Due to the presence of polymers in Fiber C, the related mixtures show an intermediate response compared to those containing Fiber A and B. Polymers, having chemical affinity with bitumen, have quite contrasting absorption properties to cellulose and aggregates.

2.2. Volumetric characteristics

Average values of void content *v*, calculated by measuring the theoretical maximum density (EN 12697-5 2010) of the mixtures and the bulk density (EN 12697-6 2009) of the corresponding specimens, voids in the mineral aggregates *VMA* and voids filled with bitumen *VFB* are plotted for each of the bituminous mixtures in Figure 9. As the three parameters are linked to each other, the interpretation of the results is quite straightforward when carried out simultaneously, enabling the evaluation of the role played by both bituminous binders and fibers in modifying the arrangement of the phases of the mixtures internal structure. By focusing on the *VMA* data, demonstrating the degree of packing of the aggregate matrix, it is possible to identify an increase of this parameter for all the tested mixtures, and especially for those with cellulose fiber content (Fiber A), as an increase in the ratio of this fiber's content in the mixture proved. This observation is coherent with the characteristic trends of compaction parameter *k* shown in Figure 8, and as the previous case seems to indicate, by increasing the percentage of fibers, the aggregate matrix proves more difficult to pack because of a decrease in the amount of effective binder, which reduces the bulk viscosity of the mixture under compaction. Results obtained in terms of void content *v* and *VFB* support the above explanations. In fact, as a consequence of the fibers' absorption characteristic, the content of bitumen acting as a binder decreases with the increase in the fiber content. Consequently the *VFB*, quantifying the degree of voids filled by bitumen, decreases. Moreover, a slight increase in the parameter relating to the air voids can be observed as a result of the fiber content increase. This behavior is due to two contrasting reasons: the fiber overfilling characteristic (which produces an increase of voids because of a reduction of the mixture's ability to obtain a high degree of packing) and the selection of a suitable compaction temperature which counteracts such phenomena.

2.3. Mechanical performance

2.3.1. Elastic stiffness

The average elastic stiffness values of each mixture, calculated after repeated load indirect tensile tests, are plotted in Figure 10 as a function of fiber bitumen ratio (0%, 3%, 6% and 9%), testing temperatures (20 °C and 40 °C) and rise times (60 ms and 120 ms).

As expected, due to the time-dependent viscoelastic properties of the bituminous binding mastic, elastic stiffness tends to increase with the increasing load application speed (rise time reduction), and to decrease with an increase in temperature.

The role of fibers is also clear; actually, it is possible to note that mixtures with Fiber A and Fiber C content show an increase in the elastic stiffness with increasing fiber-bitumen ratios, regardless of both test conditions (rise time and temperature) and the type of fiber. Mixtures with Fiber B exhibit the same behavior from 0% up to 6%. For the mixtures with 9% of Fiber B concentration, an elastic stiffness reduction is observed. This result is probably due to an increase in the quantity of bitumen acting as a binder, determined by the presence of the glass in the fibers. This bitumen surplus causes an increase in mixture deformability, as a higher quantity of viscoelastic binding mastic can deform under loading pressure. This is also proven by the volumetric results, which demonstrate an increase in *VFB* with the increase in Fiber B content, from 6% to 9%.

2.3.2. Indirect tensile strength

Some of the specimens subjected to elastic stiffness tests were used to determine the *ITS* at 20 °C. The average experimental results plotted in Figure 11 show that the addition of fibers in the mixtures causes an increase in *ITS*. However, it is important to point out that whilst in mixtures containing Fiber A and Fiber C, *ITS* progressively increases with the increase of the fiber-bitumen ratio, for mixtures with Fiber B content, a maximum value of *ITS* is observed with a fiber ratio equal to 6%. Once again, such

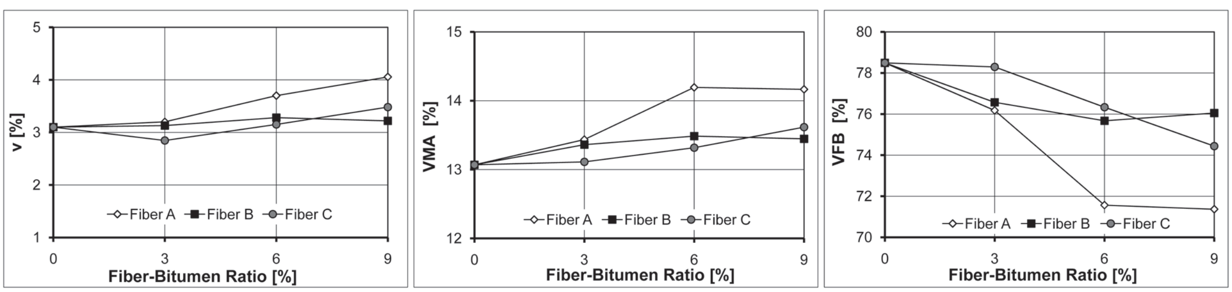


Fig. 9. Volumetric parameters of bituminous mixture

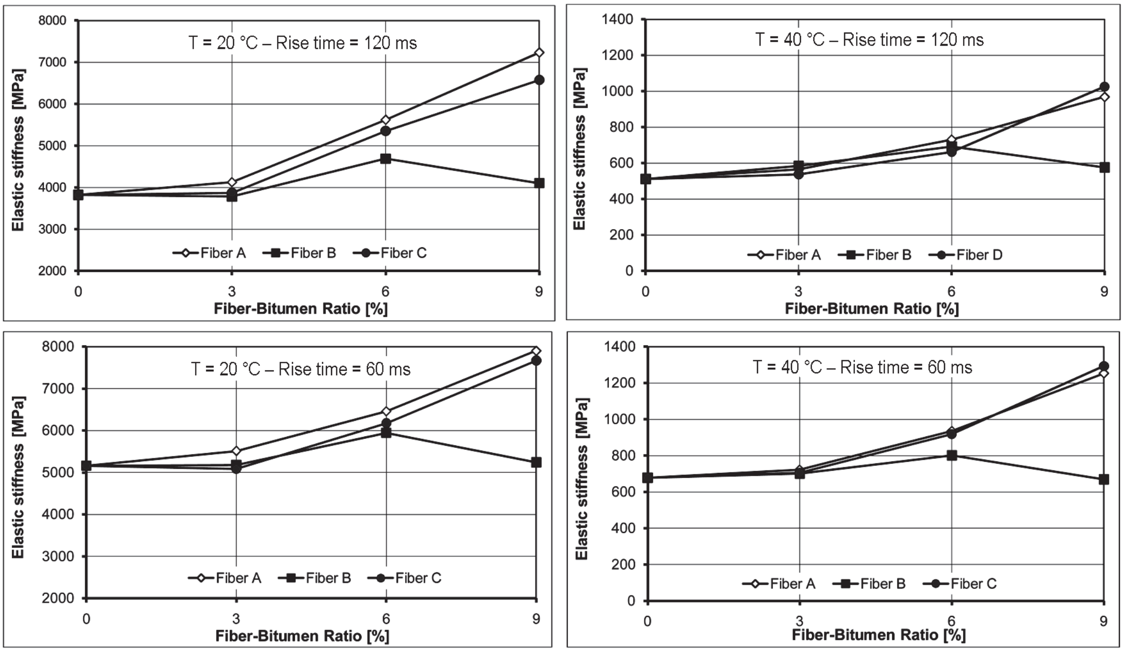


Fig. 10. Elastic stiffness of bituminous mixtures

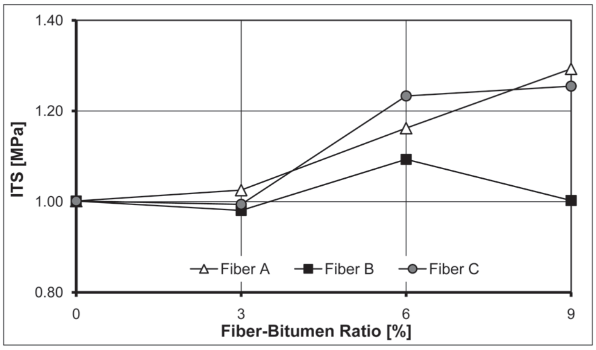


Fig. 11. Indirect tensile strength of bituminous mixtures at 20 °C

results match the *VMA* and *VFB* trends shown in Figure 9: higher tensile strength levels are reached as the aggregate structure becomes more packed, while its progressive overfilling with the bituminous binder proves to be detrimental.

2.3.3. Fatigue resistance

Fatigue test results, expressed in terms of the number of pulse applications to failure N_f are plotted in Figure 12 as a function of the fiber-bitumen ratio (0, 6% and 9%). Generally speaking, as can be expected, fatigue lifetime of the mixtures increases with the increase of the fiber-bitumen ratio. This proves to be consistent with the stiffness properties of the mixtures, since an increase in stiffness is usually considered positive in the case of tests carried out in the controlled stress mode of loading (Asphalt Institute 2007).

As far as bituminous mixtures with cellulose fibers (Fiber A) are concerned, the results obtained show a high value of N_f for the intermediate content (6%), consistent with the theoretical expectation mentioned above. Conversely, the highest content of Fiber A (9%) causes a decrease in the mixture's lifespan for fatigue. This is probably due to the increase in cellulose content, which leads to a higher absorption capacity of the bitumen content, thus reducing the quantity able to act as a binder. Moreover, this result is consistent with the volumetric characteristics described above, in which the mixture showed the least *VFB* and the maximum void content *v*.

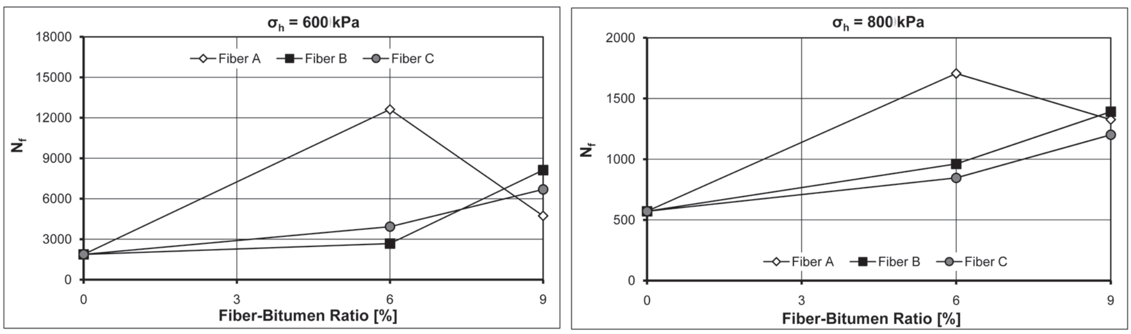


Fig. 12. Fatigue resistance of bituminous mixtures subjected to controlled stress test at 20 °C

Conclusions

Based on the experimental results reported in the paper, it can be concluded that the cellulose-based fibers investigated have a valid potential for use as a paving material as a result of three key observations.

The composition of the mixtures under scrutiny in the investigation were not formulated according to a detailed mix design procedure, on the contrary, they were derived from a straightforward sensitivity analysis which focused on the effects of two factors: type and percentage of the fibers added. Nevertheless, all the mixtures tested showed satisfactory mechanical performance-related properties, providing an encouraging set of data for further studies. Test results suggest that a closer control of both mixing and compaction procedures, and the volumetric properties, using appropriate mix design procedures including a study of the viscosity of fiber-reinforced bituminous mastics, may lead to a further enhancement in mechanical performance.

Thanks to their cellulose composition, the fibers investigated in this study demonstrated a high level of bitumen absorption. Therefore, even using small fiber concentrations, appropriate percentages of binder are necessary to reach certain target values of volumetric parameters (v, VMA and VFB). These are closely related to performance and are consequently employed for mix design and for project acceptance.

Overall, it can be stated that fibers prove to be beneficial in the context of high performance bituminous mixtures.

Future developments of the research project will include investigations focused on both cost analysis, in order to assess advantages that should derive from usage of fibers, and specific aspects of the bitumen (and bituminous mixtures) and fiber interaction which are not fully understood yet. In particular, as regards bituminous mastics, rheological performance-related tests will be developed, and moisture sensitivity studies of the bituminous mixtures will also be carried out.

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