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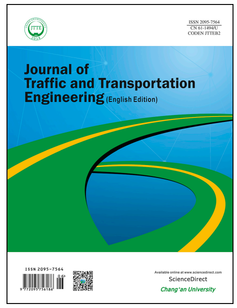

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Original research paper

Recycling of reclaimed fibers from end-of-life tires in hot mix asphalt

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Highlights

- Use of fibers from end-of-life tires in hot mix asphalt (HMA) to improve its performance.
- The fibers are composed of transparent polyester and include fine rubber particles.
- After failure, end-of-life tires (ELT) fibers sew the crack edges and contrast the fracture opening.
- ELT fibers determine a noticeable increase in the resistance to fatigue of HMA.

Abstract

Nowadays, the disposal of end-of-life tires (ELT) is worldwide one of the major concerns for the environment as well as for public health. Crumb rubber and steel wires, the main by-products (in terms of weight) deriving from the ELT processing, can be recycled in several ways. However, the textile fiber, representing about 10% of the waste by weight, is typically not reused and ends up in landfills or incinerators. The present paper deals with the use of reclaimed fibers from ELT in hot mix asphalt (HMA), with the aim to improve its performance. The study included the preliminary characterization of the fiber through microscope observation and Fourier trans form infrared (FTIR) spectroscopy and then the investigation of the mechanical properties of HMA containing ELT fibers, in comparison with an ordinary HMA with no fibers. In particular, indirect tensile strength (ITS), indirect tensile stiffness modulus (ITSM), semi-circular bending (SCB), three point bending (3PB) and indirect tensile fatigue (ITF) tests were carried out. The results showed that the use of ELT fibers does not reflect in a significant improvement in terms of strength and stiffness properties. However, the ELT fibers determine a noticeable increase of the HMA resistance to fatigue, probably related to the ability of the fibers in sewing the micro-crack edges and contrasting the macro-crack opening.

Keywords:

Road engineering; Hot mix asphalt; End-of-life tire; Fiber; Fatigue; Recycling.

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1 Introduction

In recent decades, the number of vehicles has considerably increased, causing a significant growth in the number of end-of-life tires (ELT) all around the world. According to a report by ETRMA (2017), about 3.9 million tons of waste tires were discarded every year in Europe. In the sole Italy, 400 thousand tons of ELT was produced in 2016 (Ronchi et al., 2018). Therefore, the amount of waste tires represents worldwide one of the major concerns for the environment as well as for public health.

In Europe most of ELT, about 3.4 million tons per year, are destined to energy production or material recovery (EASME, 2015), with several benefits both from economic (reduction of the cost for new raw materials, energy requirements and waste management) and environmental (reduction of the amount of landfill material and pollutant emissions) point of view. Clearly, the most profitable option deals with the recycling of the materials derived from ELT, namely rubber, steel wires and textile fibers.

Rubber is the first by-product from ELT in terms of weight (about 70%) and it is recycled in several engineering fields. As reported by Shu and Huang (2014), it can be used in asphalt paving mixtures, Portland cement concrete, crash barriers, bumpers, artificial reefs or as light-weight filler. For what concerns the road field, crumb rubber can be included in hot mix asphalt (HMA) as part of the aggregate matrix (dry process) or as elastomeric modifier for the bitumen (wet process) (Caltrans, 2003; Lo Presti, 2013). The first technique does not currently find many applications because of the issues related to the reduced compactability of the HMA and the consequent raveling (Moreno-Navarro and Rubio-Gamez, 2012; Subhy et al., 2017; Yu et al., 2014). Recently, a modified dry process was introduced, in which the crumb rubber is much finer (100% passing at 0.6 mm sieve) than usual (Feiteira Dias et al., 2014; Hernandez-Olivares et al., 2009; Picado-Santos et al., 2019; Rodríguez-Fernández et al., 2019). If in the traditional dry process the crumb rubber acts as an aggregate, in this method an interaction between the bitumen and the rubber occurs during the time that these components come into contact. In fact, the rubber particles are finer and the contact surface with bitumen is higher, so rubber digestion happens more quickly. This allows a certain modification of the binder, which reflects in an increase of the elastic properties, improving resistance to fatigue and rutting (Hassan et al., 2014; Moreno-Navarro et al., 2015).

In the second technique (wet process), the crumb rubber is blended with asphalt to produce the so-called rubberized asphalt, which is being adopted in many parts of the world, especially in the United States and in Europe, as an alternative to polymer-modified HMA. According to the processing conditions (blending temperature and time, amount and dimensions of the crumb rubber), different crumb-rubber modified asphalts can be obtained, typically defined as “asphalt rubber” and “terminal blend” (Harvey et al., 2001; Lo Presti, 2013). According to ASTM D6114, asphalt rubber consists of bitumen and 15% of crumb rubber blended at about 200 ℃ for approximately one hour. This allows the crumb rubber particles to swell, determining a significant increase of the binder viscosity. In the terminal blend, the crumb rubber particles are finer (passing 0.3 mm sieve) and the content is about 10% by asphalt weight. Moreover, the terminal blend processing conditions are pushed to higher temperatures (200 ℃–300 ℃) and shear stresses, allowing the crumb rubber to degrade and making the binder enough stable to be handled as an ordinary asphalt binder. Many studies demonstrated that the use of crumb rubber in HMA through wet process determines significant performance benefits in terms of reduction of the low temperature brittleness (Eskandarsefat et al., 2018), increase of the resistance to fatigue and rutting (Pasquini et al., 2011; Zhou et al., 2014) and decrease of the rolling noise (Licitra et al., 2015).

Steel wires, which approximately represent 15% by weight of the material deriving from ELT treatment, find many possibilities of reusing. For instance, Portland cement concrete, whose mechanical behavior is characterized by high brittleness along with low tensile strength and strain capacities, can be improved with the addition of steel wires from ELT (Abbass et al., 2018; Pilakoutas et al., 2004). Moreover, high volumes of steel wires partially coated with crumb rubber from ELT can be used as aggregate in Portland cement concrete for acoustic purposes (Flores Medina et al., 2016).

The textile fibers, third by-product from ELT processing (about 5%–10% by weight), is typically not reused and ends up in landfills or incinerators (Landi et al., 2018). However, recent studies have identified some applications for this waste. For instance, Maderuelo-Sanz et al. (2012) showed that the use of the textile residue from ELT in sound absorber products allows good acoustic properties at low and high frequencies to be achieved. Moreover, Abbaspour et al. (2019) proved that waste ELT fibers may be used as highly efficient reinforcement materials in all geotechnical projects with granular soils, bearing no excessive cost. Marconi et al. (2018) demonstrated the possibility to reuse the tires textile fibers as reinforcement in plastic compounds instead of bringing it to the landfill. Banaszkiewicz and Badura (2019) proposed the use of recycled fibers for tires as a low-cost sorbent for benzene, toluene, ethylbenzene and xylene (BTEX) compounds in soils treated with cement. The review paper by Uriarte-Miranda et al. (2018) identified the industries of artificial grass, shoe soles and clothing as fields for the reuse of the fibers from ELT.

In HMA, different types of fibers are actually used with various purposes. Mainly, cellulose and mineral fibers are used in porous asphalt mixtures and stone mastic asphalt (SMA) mixtures to avoid bitumen drain down (Hansen et al., 2000). According to the review work by Slebi-Acevedo et al. (2019), synthetic fibers as polypropylene, polyester, aramid or polyacrylonitrile can improve strength and resistance to repeated loads of the HMA. Abiola et al. (2014) observed that natural fibers (such as jute, coconut, sisal and hemp) allow enhancing the material strength, fatigue characteristics and at the same time, increasing the ductility of the composite. Luo et al. (2019) proved that lignin fibers can improve the resistance to fatigue low temperature cracking in HMA while glass fibers increase the high temperature performance and water stability. Serin et al. (2012) and Morova (2013) tried to use steel and basalt fibers in HMA, denoting a positive impact for stability but a damaging effect on vehicle tires. Recently, some authors (Abdelaziz et al., 2003; Park et al., 2015) proposed the use of fibers in HMA as reinforcing materials, with the aim to provide additional tensile strength and increase the amount of strain energy that can be absorbed during the fatigue and fracture process of the mix. However, this practice has not significantly widespread, mainly because of economic issues.

Only few studies investigated the opportunity to reuse the textile fibers from ELT in road pavement engineering. Putman and Amirkhanian (2004) stated that waste tire and carpet fibers can be viable options as stabilizing additives in SMA mixtures. Differently, Moreno-Navarro et al. (2014) used the carcass ply and steel belts layers of ELT (that also contain the textile component) to produce an anti-reflective cracking system within the pavement structure and demonstrated their efficiency against fatigue cracking.

At the light of the above-made considerations, the present research aims at evaluating the possibility to recycle the textile fibers derived from waste tires in HMA for binder layers, with the scope to increase the mechanical performance of the mixture.

2 Objective

The objective of this research was to profitably reuse the fibers from waste tires in HMA. In particular, the effect of the reclaimed fibers was analyzed in a mixture for binder course, where no fiber is typically included, in order to assess the opportunity to both recycle this by-product and enhance the HMA mechanical and performance properties.

To this aim, the preliminary part of the experimental program dealt with the characterization of the fiber, through microscope observation and Fourier transform infrared (FTIR) spectroscopy in order to define the fiber dimensions and composition. Then, the main part of the study regarded the mix design and the analysis of the mechanical behavior of HMA including reclaimed fibers, in comparison with an ordinary HMA with no fiber. In particular, indirect tensile strength (ITS) test, indirect tensile stiffness modulus (ITSM) test, semi-circular bending (SCB) test, three-point bending (3PB) test and indirect tensile fatigue (ITF) test were performed.

3 Materials

The HMA tested in this study was a dense-graded binder course mix, with 16 mm nominal maximum size. The mix was produced in the laboratory using two fractions of basalt coarse aggregate (8/16 G_C 90-15 and 4/12 G_C 90-10 according to EN 13043), two fractions of limestone fine aggregate (Limestone 2/4 G_G 85-15 and 0/4 G_F 85) and limestone filler, adequately proportioned by volume in order to obtain a regular gradation curve complying with the specifications by the main Italian Highway Authority (Fig. 1).

The binder was a 50/70 paving grade bitumen with a penetration of 55 × 0.1 mm and a softening point of 62 ℃. The properties of the base bitumen are summarized in Table 1.

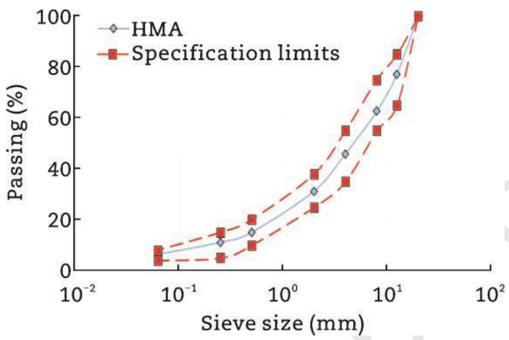


Fig. 1 Gradation curve of HMA.

Table 1 Characteristics of the bitumen.

Property	Method	Typical value
Penetration at 25 ℃ (0.1 mm)	EN 1426	55
Softening point (℃)	EN 1427	62
Dynamic viscosity at 160 ℃ (Pa • s)	EN 13702-1	0.18
Flash point (Cleveland)	EN 12593	305
Properties after RTFOT EN 12607-1		
Weight loss (%)	EN 12607-1	0.31
Penetration at 25 ℃ (% original)	EN 1426	68
Increase in softening point (℃)	EN 1427	8

The fibers recovered from waste tires are shown in Fig. 2. The material has a dark gray color and includes filaments and crumb rubber particles, with dimensions approximately lower than 1 mm.

Through an industrial process, the fibers are grouped into pellets by adding 10% by weight of paraffin wax, in order to facilitate the filament dispersion in HMA during the mixing phase in the asphalt plant. The content of fibers in the asphalt concrete was 0.3% by mix weight.

Fig. 2 Fibers reclaimed from waste tires.

4 Specimen preparation

The HMA was produced in the laboratory at 150 ℃ using a planetary mixer. The HMA components were added in this order: coarse and fine aggregates, fibers (when present), bitumen and filler. After the addition of each component, the blend has been mixed for 30 s in order to allow obtaining an adequate homogeneity.

The specimens for mix design and testing (ITS, ITSM, ITF and SCB tests) were prepared with a shear gyratory compactor (SGC), according to the European standard EN 12697-31. The compaction protocol provided a pressure of 600 kPa, a speed of 30 rpm, an angle of inclination of 1.25° and a number of gyrations of 100. The specimen diameter was 100 mm for ITS, ITSM and ITF tests and 150 mm for SCB tests. After cooling, the 150 mm diameter cylinders were sawed to obtain the specific shape for SCB tests.

The specimens for 3PB tests were obtained from HMA slabs compacted with a roller compactor, using a vertical pressure of 3 bar and a number of passages equal to 25. Each 305 × 305 × 50 mm^3 slab was cut in order to obtain 3 beams with dimension 305 × 100 × 50 mm^3.

5 Test methods

ITS was measured at the temperatures of 25 ℃ by means of an electro-mechanical press, imposing a constant rate of deformation of 50 ± 2 mm/min until specimen failure occurred (EN 12697-23). Three repetitions for each mixture were provided.

ITSM test was carried out at 20 ℃ through a servo-pneumatic machine by applying repeated load pulses with a rise time of 124 ms and a pulse repetition period of 3 s. For each specimen, the load was adjusted using a closed-loop control system in order to achieve a target horizontal (diametral) deformation of 3 μm (EN 12697-26, Annex C). ITSM measurements were repeated along two diameters, and an average value was calculated for each specimen.

SCB test was performed according to EN 12697-44 at 10 ℃. By means of an electro-mechanical press, a constant rate of deformation of 5.0 ± 0.2 mm/min was applied on the specimen until the crack propagated from the notch to the edge of the specimen. The fracture toughness (K), i.e., the maximum stress at failure multiplied for a geometric factor, and the specific fracture energy (G), i.e., the ratio between the area under the load-vertical deformation curve and the specimen middle section were evaluated.

3PB test was carried out at 10 ℃ by means of an electro-mechanical press, imposing a constant rate of deformation of 5.0 ± 0.2 mm/min until specimen failure occurred. The test allowed measuring the moment (M) at failure in the middle of the beam, the maximum tensile stress (σ_{max}) at the bottom of the beam, the vertical strain (ε_{peak}) in correspondence of the maximum stress and the total fracture energy (E_{tot}), i.e., the area under the load-vertical deformation curve. Three repetitions for each mixture were provided.

The resistance to fatigue was analyzed in indirect tensile configuration according to EN 12697-24. Test temperature was set at 20 ℃ and three horizontal stress amplitudes were fixed in order to obtain a fatigue life between one hundred and one million cycles. During the test, the servo-pneumatic machine applied a pulse load with 0.1 s loading time and 0.4 s rest time and vertical deformations was runtime recorded. The fatigue failure of the specimen N_f was assumed in correspondence to the number of load applications when the sample broke and the vertical crack completely separated it into two halves.

The details of the test parameters are summarized in Table 2.

Table 2 Experimental program and test parameters.

Test	Standard	Parameter	Repetition
ITS	EN 12697-23	T = 25 ℃; deformation rate = 50 mm/min	3
ITSM	EN 12697-26	T = 20 ℃; rise time = 124 ms; horizontal deformation = 3 μm	4
SCB	EN 12697-44	T = 10 ℃; deformation rate = 5 mm/min	4
3PB	–	T = 10 ℃; deformation rate = 5 mm/min	3
ITF	EN 12697-24	T = 20 ℃; horizontal stress = 250 kPa, 300 kPa, 350 kPa	4

6 Characterization of the fibers from waste tires

The fiber filaments (collected before the industrial processing for the pellets manufacturing) were analyzed by means of FTIR spectroscopy in order to define their chemical nature. Spectral data were obtained with a Perkin-Elmer Spectrum GX1 FT-IR, in transmission on NaCl plates. The spectral resolution was 4 cm^{-1}. Baseline (two-points linear fit) was performed in all cases, while the second derivative, Fourier self deconvolution and low Gaussian character (LGC) curve fitting procedures were used. For data handling, Spectrum v.6.3.1 (Perkin-Elmer) and Grams AI (Galactic Corp.) software packages were used.

The FTIR spectroscopic analysis proved that the filament of the fibers is composed of polyester (Fig. 3), with a correspondence of 99.6%. When isolating the filament for the test, it was observed that the fiber is actually transparent. Indeed, the dark gray color is due to the presence of black rubber powder that is stuck to the filaments. In fact, the FTIR spectrum presented two significant bands at 2909 cm^{-1} and 3299 cm^{-1} wave numbers, respectively, representing the -CH2 functional group due to carbon black stick to ELT-fibers and the O-H group attached with rubbery products.

This issue was confirmed through the observation of the fiber from waste tires with the optic microscope. In fact, the images in Fig. 4 clearly show that the filaments are effectively translucent and that there are many black rubber particles grabbed to the threads.

Additionally, a digital image analysis allowed estimating the fiber dimensions. The filaments showed a diameter ranging between 5 and 40 μm and a length ranging between 1 and 2.5 mm.

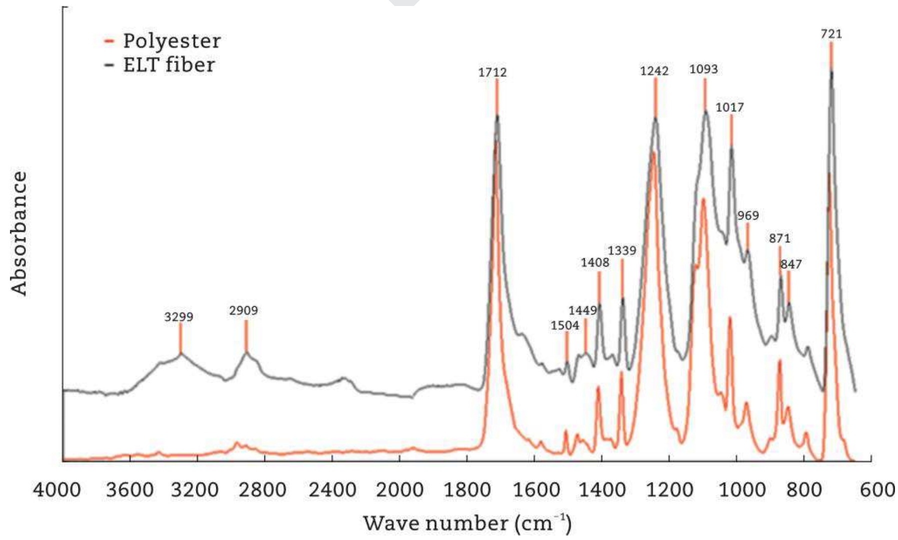


Fig. 3 FTIR analysis on the filament.

(a) (b)

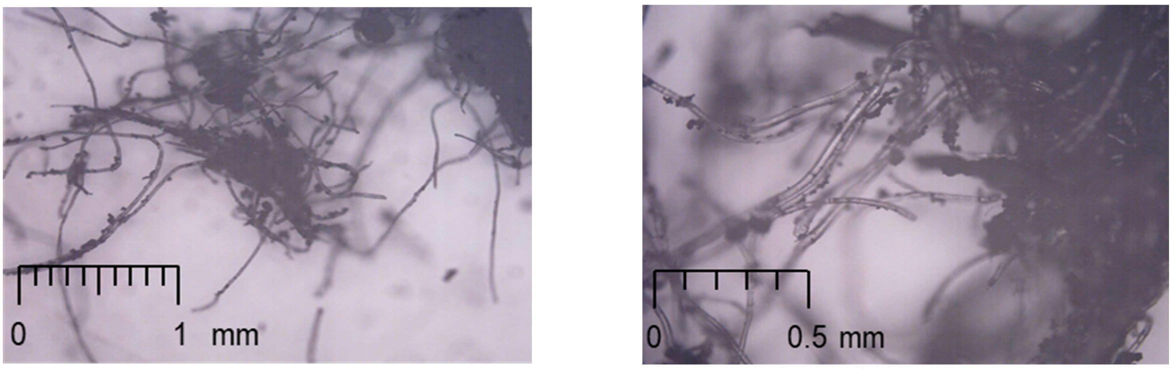


Fig. 4 Microscope photo of the fibers. (a) 5× enlargement. (b) 10× (right) enlargement.

7 Results of the mix design study and discussion

The job mix formulas for the preparation of the HMA with/without fibers have been optimized through a mix design study. For the reference HMA without fibers, the analysis provided the laboratory manufacturing of 4 mixtures including different amounts of bitumen (specifically 4.80%, 5.05%, 5.30% and 5.55% by mix weight), with the content of added filler equal to 2% by aggregate weight. Whereas, for the HMA containing the fibers, the mix design study involved 3 bitumen contents (4.70%, 4.95% and 5.20% by mix weight) and 2 filler contents (2% and 4% of added filler by aggregate weight). According to Italian specifications, the optimum bitumen content is the one that allows reaching 4% of air voids after 100 gyrations of SGC. In addition, for this bitumen content, the air voids at 10 and 180 gyrations must match the acceptability range, respectively 12%–15% and ≥ 2%. The results for the two HMA mixtures without and with fibers, afterwards indicated with the codes HMA and HMA-F, are shown in Table 3 and Fig. 5.

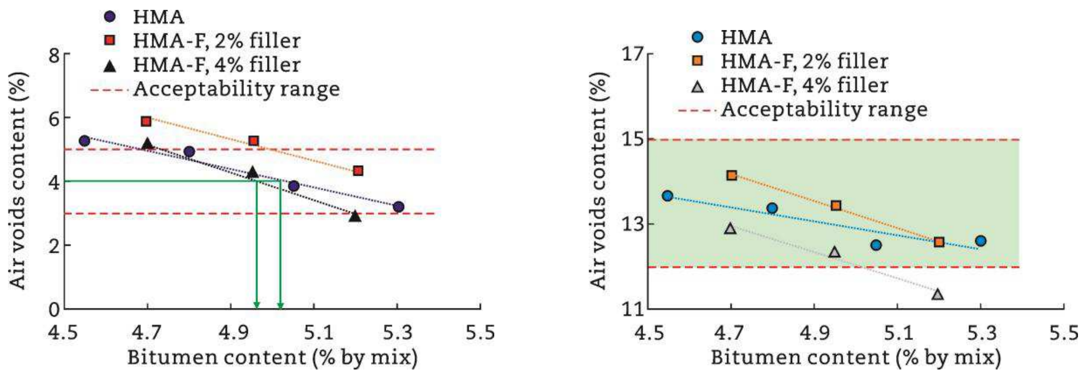
From the graphs it can be observed that air voids content obviously decreased when increasing bitumen content and compaction energy. Moreover, for HMA-F it can be noticed that, when 2% of filler was used (the same amount used in the mix HMA), the air voids content at 100 gyrations could not reach 4% for bitumen contents up to 5.20% (Fig. 5(a)). However, when filler content was raised to 4%, the volumetric properties improved (lower air voids at all bitumen contents and compaction energies) and resulted comparable with the mixture HMA.

Due to the increase of the filler, the gradation of the two mixtures is slightly different, mainly in the zone of fine particles. In particular, the passing at 0.063 mm sieve is 6.5% and 7.7% for HMA and HMA-F, respectively. The variation of the gradation curve for HMA-F is shown in Fig. 6.

Table 3 Air voids content at different compaction energies for HMA and HMA-F mixtures.

Property	Value (%)			
HMA				
Bitumen content (by mix)	4.55	4.80	5.05	5.30
Air voids content after 10 gyrations	13.7	13.4	12.5	12.6
Air voids content after 100 gyrations	5.3	5.0	3.9	3.2
Air voids content after 180 gyrations	3.2	2.8	1.7	1.0
HMA-F				
Added filler content (by aggregate)	2.0	2.0	2.0	
Bitumen content (by mix)	4.70	4.95	5.20	
Air voids content after 10 gyrations	14.2	13.5	12.6	
Air voids content after 100 gyrations	5.9	5.3	4.3	
Air voids content after 180 gyrations	4.0	3.2	2.4	
Added filler content (by aggregate)	4.0	4.0	4.0	
Bitumen content (by mix)	4.70	4.95	5.20	
Air voids content after 10 gyrations	12.9	12.3	11.4	
Air voids content after 100 gyrations	4.6	4.2	2.9	
Air voids content after 180 gyrations	2.6	2.5	1.2	

(a) (b)



(c)

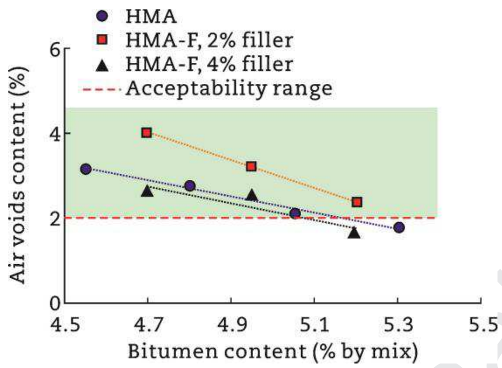


Fig. 5 Variation of the air voids content with bitumen and filler contents at different compaction energies. (a) 100 gyrations. (b) 10 gyrations. (c) 180 gyrations.

From Fig. 5(a), the same optimum bitumen content of 5.0% by mix weight could be approximately identified. This result denotes that the presence of the fibers reduces the mix compactability and a higher content of filler is necessary to increase the volume of the bituminous mastic and thus decrease the air voids content.

As it can be observed from Fig. 5(b) and (c), the optimum bitumen contents allowed acceptable air voids contents at 10 and 180 gyrations to be achieved. In particular, the mix HMA at a bitumen content of 5.0% showed air voids contents at 10 and 180 gyrations of about 13% and 2.4%, whereas the mix HMA-F with 4% of filler at a bitumen content of 5.0% showed air voids contents at 10 and 180 gyrations of about 12.2% and 2.2%.

Table 4 summarizes the job mix formulas adopted in the production of the mixtures for the following mechanical tests.

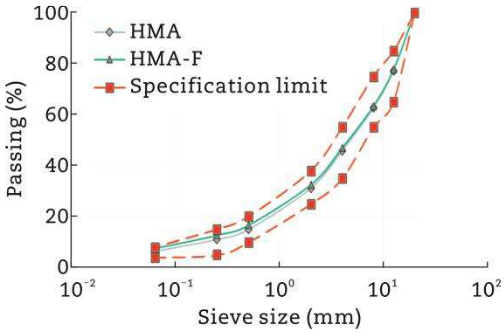


Fig. 6 Gradation curve of HMA-F compared with that of HMA.

Table 4 Job mix formulas of the asphalt concretes for mechanical tests.

Component	Content (% by mix)	
	HMA	HMA-F
Basalt 8/16 G_C 90-15	31	30
Basalt 4/12 G_C 90-10	21	21
Limestone 2/4 G_G 85-15	10	10
Limestone 0/4 G_F 85	31	30
Filler	2	4
Fibers from waste tires	0	0.3
Bitumen	5	5

8 Results of the mechanical tests and discussion

8.1 ITS at 25 ℃

Fig. 7 shows the results from ITS tests carried out at 25 ℃. In the histograms, the bars represent the average value for each group of specimens tested at the same conditions, whereas the black lines indicate the data dispersion.

The graphs clearly show that the HMA with and without fibers had comparable ITS values at 25 ℃, which match the acceptability range defined by Italian Highway Authority. Moreover, the data scattering was very low and the results can be considered reliable. As it can be observed from Fig. 7(b), HMA-F mixture showed a slightly higher fracture energy E_{tot} (calculated as the integral of the vertical force versus vertical displacement curves plotted in Fig. 8) with respect to HMA mixture. This denotes that the contribution of the fibers is not significantly appreciable on the mixture strength but it is more remarkable in terms of mix ductility. In fact, the specimens probably had a similar mechanical behavior until they failed; after that instant, the fibers started working, by sewing the crack edges and contrasting the fracture opening. However, the effectiveness of this phenomenon is limited because of the high deformation rate during the test (50 mm/min).

In addition, it should be considered in the analysis that the increase in filler content (2% and 4% of added filler, 6.5% and 7.7% of particles passing at 0.063 mm sieve for HMA and HMA-F, respectively) can influence the mix stiffness and strength properties (Diab and Enieb, 2018). Nonetheless, the slight difference in ITS and the contemporary significant increase in E_{tot} denote that the effect of the fibers is more relevant than the effect of the higher filler content.

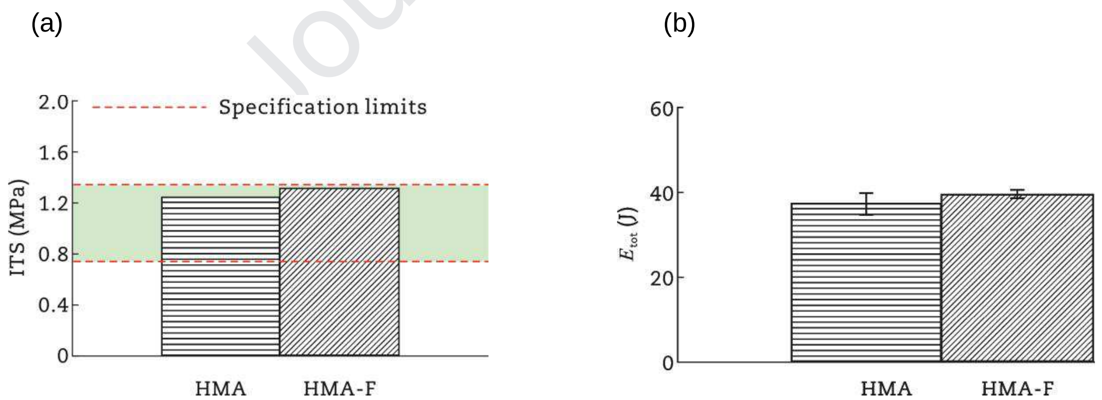


Fig. 7 Results from ITS test at 25 ℃. (a) ITS. (b) E_{tot}.

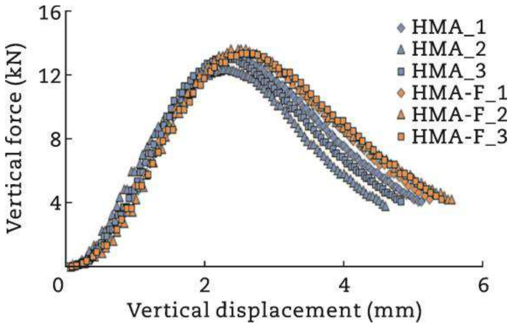


Fig. 8 Vertical force versus vertical displacement curves.

8.2 ITSM at 20 ℃

Fig. 9 shows the results from ITSM tests carried out at the temperature of 20 ℃. The graph highlights that the ITSM values were comparable between the two mixtures. This indicates that the presence of the fibers does not rise or penalize the material stiffness. This behavior is likely, as the stiffness modulus, under the same volumetric properties of the specimen, related to the characteristics of the bituminous mastic (bitumen and filler), which are not influenced by the fibers or by the small amount of rubber powder that they contain. Moreover, the ITSM values confirms that the increase in filler content for HMA-F mix has not determined any significant stiffness increase, as well.

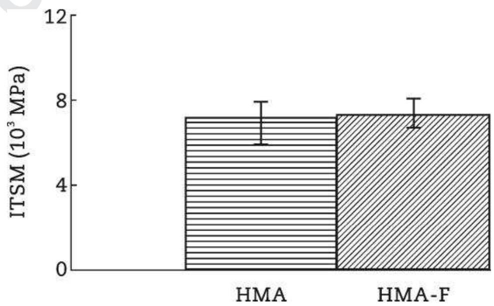


Fig. 9 Results from ITSM tests at 20 ℃.

8.3 SCB at 10 ℃

Fig. 10 shows the results from SCB tests carried out at 10 ℃ in terms of fracture toughness (*K*) and specific fracture energy (*G*). For HMA-F mix a slightly higher *K* (+10%) and lower *G* (–10%) were observed with respect to HMA mix, on average, but a relevant data scattering was present. So, *t*-test by

Student (two-tailed distribution, heteroscedastic) was used to assess the statistical significance of the results. The α-values (probability associated that a sample of the first group is higher than a sample of the second group) were 0.34 and 0.81 for K and G, respectively. Therefore, the average K and G values obtained can be considered equal from a statistical point of view (α > 0.05). This denotes that the presence of the fiber, as well as the higher filler content, does not determine any relevant change in the mix strength properties at low/intermediate temperatures.

(a) (b)

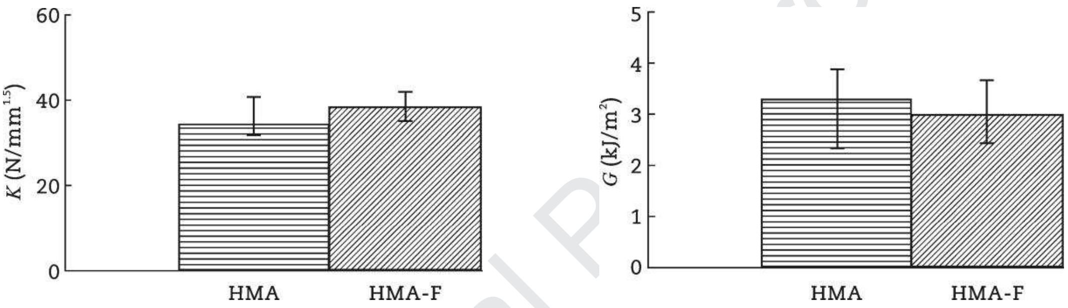
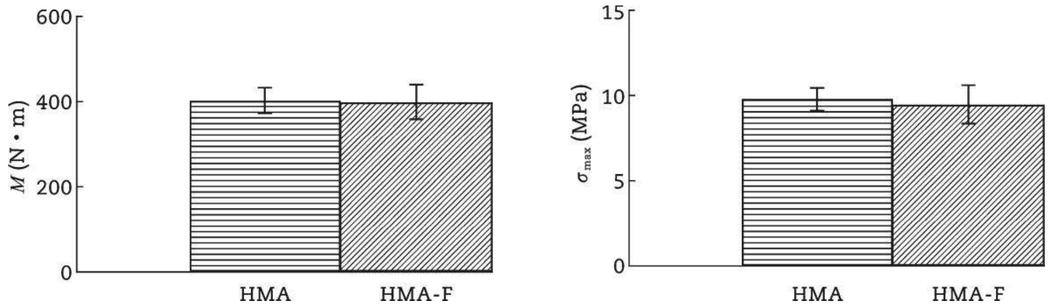


Fig. 10 Results from SCB tests at 10 ℃. (a) K. (b) G.

8.4 3PB at 10℃

Fig. 11 shows the results from 3PB tests carried out at 10 ℃. In particular, the graphs from (a) to (d) depict the average values and dispersion ranges of moment at failure (M), maximum tensile stress (σ_{max}), vertical strain (ε_{peak}) and total fracture energy (E_{tot}). The results indicate that the mechanical behavior of the HMA mixtures with and without fibers is similar, as comparable values of M, σ_{max}, ε_{peak} and E_{tot} were registered. This is corroborated by the outcome from t-test, that showed α-values of 0.84, 0.62, 0.85 and 0.19 for M, σ_{max}, ε_{peak} and E_{tot}, respectively.

(a) (b)



(c) (d)

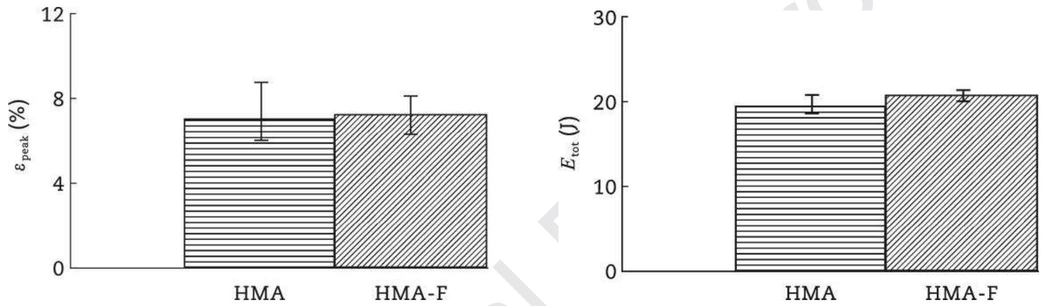


Fig. 11 Results from 3PB tests at 10 ℃. (a) *M*. (b) σ_{max}. (c) ε_{peak}. (d) E_{tot}.

Therefore, as in the case of SCB tests, 3PB tests confirmed that the contribution of the fibers at low/intermediate temperatures, observed is not significant. If the fibers contrast the fracture opening after specimen failure, as hypothesized from ITS test results, their effectiveness is negligible when the bituminous mastic is very stiff and the specimen quickly breaks.

Moreover, SCB and 3PB tests allowed denoting that the paraffin wax carried by the ELT fibers (10% by fiber weight means 0.03% by mix weight, i.e., 0.6% by bitumen weight) does not determine any significant brittleness in the mixture HMA-F at 10 ℃.

8.5 ITF at 20 ℃

Fig. 12 depicts the results from ITF tests at 20 ℃ in terms of horizontal stress (Fig. 12(a)) and initial horizontal strain (Fig. 12(b)) as a function of the cycles at failure. The initial horizontal strain is the ratio between the horizontal stress and the indirect tensile stiffness modulus of the specimens.

(a) (b)

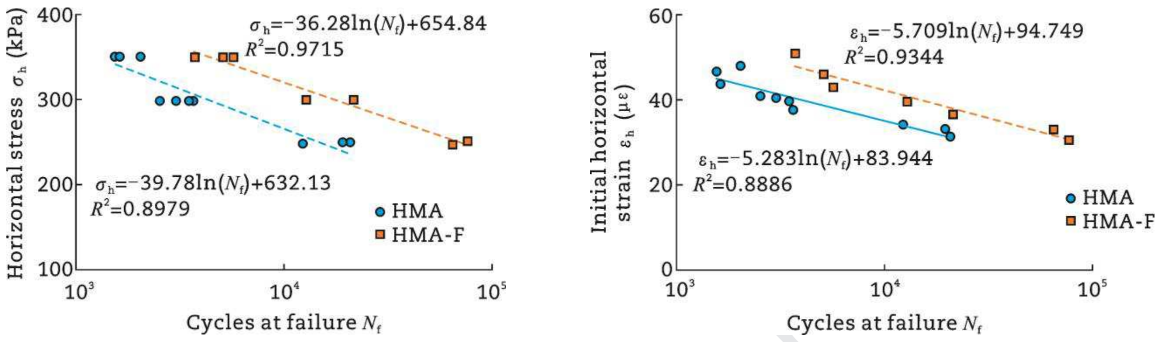


Fig. 12 Results from IFT tests at 25 ℃. (a) σ_h versus N_f. (b) ε_h versus N_f.

The graphs clearly show that the presence of the fibers determines a noticeable increase in the resistance to repeated loads. In particular, the average number of cycles at failure obtained at each stress level for HMA-F specimens was about 2.5, 5.5 and 4.5 times of those obtained for HMA specimens. This result is probably related to the ability of the fibers in maintaining the micro-crack edges close and thus opposing the micro-crack evolution into a macro-crack. If in ITS, SCB and 3PB tests the efficacy of the fibers was not evident because of the high loading rates or low specimen temperature, in ITF tests (at 25 ℃ and with lower stress levels compared to strength tests) the contribution of the fibers is always relevant, but increases when reducing the horizontal stress. Thus, the benefits related to the use of the fibers are more marked when they are included in HMA mixtures for deep layers (base and binder layers), where the stresses are lower.

Finally, it has to be highlighted that, despite the ITF tests were carried out in control-stress configuration, the improvement can be observed also in the ε_h versus N_f plot, as the stiffness of the two mixtures was comparable (Fig. 9). This denotes that the fibers and the crumb rubber they bring do not determine any fragile behavior of the mixture.

9 Conclusions

The present paper deals with the reuse of textile fibers from waste tires in HMA mixtures with the aim to improve its performance. The investigation, which included the characterization of the fiber derived from ELT processing and the testing of HMA containing ELT fibers in comparison with a reference mix with no fibers, showed the following results.

- The filaments of the fibers, whose dimensions range between 5–40 μm in diameter and 1–2.5 mm in length, are composed of transparent polyester. Fine rubber particles are grabbed to the threads.
- The presence of the ELT fibers reduces HMA compactability; so, an increase of filler content (about 2% by weight) is recommended to raise the volume of the bituminous mastic and thus decrease the air voids content.
- The contribution of the ELT fibers to the mechanical performance of HMA is not significantly appreciable on the mix strength (ITS, SCB, 3PB) and stiffness (ITSM), but the fibers start working after material failure by sewing the crack edges and contrasting the fracture opening. However, the effectiveness of this phenomenon is limited when HMA exhibits a stiff and brittle behavior (low temperatures, high loading rate).
- The use of ELT fibers in HMA determines a noticeable increase in the resistance to fatigue, probably related to the ability of the fibers in opposing the micro-crack evolution into a macro-crack.
- The beneficial effect of the ELT fibers in terms of improving HMA resistance to fatigue increases when reducing the horizontal stress.

In conclusion, the laboratory study demonstrated that the application does not only allow recycling a material, ELT fiber, that currently ends up to landfill or incinerators, but can be a resource to increase the performance of HMA mixtures. The promising results encourage continuing the research with a full-scale validation, in order to assess the real feasibility and profitability of the technique.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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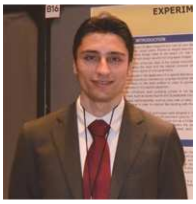

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