PERFORMANCE EVALUATION OF FOAMED BITUMEN BOUND MIXTURES MADE WITH RECYCLED AND ARTIFICIAL AGGREGATES AND FIBERS

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ABSTRACT

The paper describes a research aimed at analysing the performance of mixtures for road base and sub-base layers, made with foamed bitumen, cement, recycled and artificial aggregate as well as different types of fibres, used in order to enhance adhesion and structural properties of the mixes. Reclaimed Asphalt Pavement (RAP), Electric Arc Furnace (EAF) steel slag, foundry sand and fly ash were used in the experiment as alternative secondary aggregates. A control mixture prepared with quarried natural aggregate (limestone) was also studied for comparison purposes. Such Cement-Bitumen Treated Mixtures (CBTM) were manufactured using 70/100 pen foamed bitumen and CEM I 32.5 R Portland cement. Three types of fibres were also alternatively added to the mixtures: structural, polypropylene and cellulose/glass fibres. The comparative mechanical characterization was based on fatigue resistance (EN 12697-24), indirect tensile strength (EN 12697-23) stiffness (EN 12697-26) and water susceptibility (EN 12697-12). The research permitted to recognize the overall positive, but different, contribution of fibres to the performance of mixtures, and define most appropriate fibre content and field of application. Moreover, the contribution of the different waste materials to the structural properties and durability of the studied mixes has been ascertained and new construction solutions have been proposed.

INTRODUCTION

The foamed bitumen is a cold technology used to build road pavement layers, usually the foundation and the base layers. The technology is called “cold” because the mixtures can be laid at temperature lower than the traditional one used in the case of Hot Mix Asphalt. Some researchers have studied the foaming of bitumen and the properties of the mixes manufactured with this technology (Godenzoni et al, 2018; Grilli et al, 2016; Arimilli and Jain, 2015; Hailesilassie et al, 2015; Iwański and Chomicz-Kowalska, 2013, Jenkins et al, 2012; Jenkins et al, 2007; Pasetto et al, 2004). This system has important advantages when used with the recycling philosophy: the old pavement is milled and, integrating the grading envelope with virgin (or other) aggregates, the Reclaimed Asphalt Pavement (RAP) is blended with the foam bitumen and cement and then laid to constitute the layer (Chandra et al, 2013; Godenzoni et al, 2017).

The recycling of the materials from industrial process wastes, such as fly ashes and steel slags, is a good strategy to improve the performance of the mixtures, to reuse the secondary materials and to save the environment (limitation of extraction from quarries and reduction of materials disposed to the landfills). The secondary materials can be reused to increase the performance of the hydraulic mixes for foundation or base layers in the road pavement construction.

Usually the road foundation layers (sometimes the road base layers in case of low traffic) are built using mixes blended only with cement or lime (Pasetto and Baldo, 2018; Mallick and Hendrix, 2004). The hydraulic binder quantity added to the mix is low (about 3 % – 4 % by the weight of the aggregates). In the cement-bitumen treated mixtures, the bitumen is added to the mix in a small amount, using the foaming machine. The bitumen is sprayed into the mix to create a more elastic layer than the one containing only the cement (or lime). In general, the mixtures blended only with cement (or lime) assume very stiff behaviour, while mixes bound only with bitumen have a more viscoelastic one. The Cement-Bitumen Treated Mixtures (CBTM) have an intermediate position between a stiff behaviour and a ductile one (Bocci et al, 2011; Pasetto and Baldo, 2014). Increasing the bitumen content, the behaviour of the CBTM tends to look like a bituminous mixture (internal cohesion and temperature dependence increased), while increasing the cement content the behaviour become stiff, like the concrete (stiffness and crack predisposition increased).

In this work CBTM with recycled and artificial aggregates, foam bitumen, cement and fibres were analysed. Some researchers dealt with the use of fibres in the hydraulic mixes employed in the bottom layers of the pavement (Grilli et al, 2013; Hoyos et al, 2011), but the literature is not very extensive in this field. Several studies deal with the stabilization of the soil with fibers: polypropylene fibres (Correia et al, 2015; Consoli et al, 2010) and coir ones (Anggraini et al, 2015) are used. In the literature even a limited number of researches on the cold mixtures with fibres are present: polypropylene fibres (Martinez-Arguelles et al, 2015; Kim and Park, 2013) cellulose and polymeric ones (Toraldo et al, 2014). However, successful experiences in including fibers on HMA (Pasetto et al, 2017) suggest large potential benefits about the fibre application into the CBTM. Thus, this paper focuses on CBTM with fibers to evaluate the improvement in terms of stiffness and resistance to fatigue. The authors assessed also the improvement in the cohesion of the mixes through the indirect tensile strength (dry and wet).

EXPERIMENTAL PROGRAM

The experimental program is based on the improvement of the CBTM by adding three different fibres. The authors prepared three mixes: one with virgin aggregates, coming from a quarry, as reference and two with recycled materials (secondary waste process materials). The authors used cement and foam bitumen as binders.

In this paragraph the materials (aggregates, fibres and binders), the procedures and the testing equipment, as well as the mix design phase used during the work will be explained and described.

Materials

The fibres used are shown in the Figure 1: the first is a cellulose/glass fibre (named “C”), the second is a structural fibre (named “S”) and the third is a multifunctional fibre (named “M”).

Figure 1. Fibre types: a) cellulose-glass fibre (C), b) structural fibre (S) and c) multifunctional fibre (M).

The fibre C forms a three-dimensional grid in the mix matrix involving an increase of the capacity to absorb deformation energy. The fibre S is based on high density polymers and is used to obtain greater stiffness and resistance to cyclic loads. The type M is a polypropylene stabilizer fibre which gives an improvement in the tensile strength and greater stiffness to the mixes.

The authors used a cement CEM I 32.5 R Portland type and a 70/100 pen foamed bitumen: penetration (EN 1426) was equal to 91 tenths of a millimetre and softening point (EN 1427) to 47 °C.

For this work materials coming from reuse of secondary products were mainly utilized: Electric Arc Furnace (EAF) steel slags, foundry sand, fly ash and Reclaimed Asphalt Pavement (RAP). The use of marginal materials is largely adopted in the road construction sector (Chomicz-Kowalska and Maciejewski, 2015; Pasetto and Giacomello, 2014; Papavasiliou and Loizos, 2013; Pasetto and Baldo, 2012; Kavussi et al, 2011; Mallick and Hendrix, 2004). Each year the industries and the companies produce high amount of waste, particularly steel slags and RAP, that need to be disposed: the reuse in the road construction field allows to avoid the landfill disposal. These materials need a toxicological characterization because they could contain heavy metals, which leach into the soil mainly in the case of reuse in the foundation (or base) layers (where the aggregates are not completely covered by bitumen).

In this paper the toxicological characterization of aggregates was omitted for conciseness, but the leaching of aggregates used fell within the legal limits.

Moreover, the authors utilized the virgin aggregates (limestone) to produce the reference mix. All the aggregates (EAF steel slags, foundry sand, fly ash, RAP and limestone) were tested to evaluate their physical and mechanical properties (Table 1).

Table 1. Physical and mechanical characterization of the aggregates

Property	Standard	Unit	EAF steel slags	RAP	Fly ash	Foundry sand	Limestone
Particle density	EN 1097-6	Mg/m^3	3.71	2.44	2.07	2.11	2.76
L.A. coeff.	EN 1097-2	%	12.4	-	-	-	16
Shape index	EN 933-4	%	7.0	3.4	-	1.2	10.3
Flakiness index	EN 933-3	%	8.7	3.0	-	1.4	10.5
Sand equivalent	EN 933-8	%	79	89	60	66	78

Table 1 shows that the properties of the aggregates are very different. The steel slag has a high density compared to the other aggregates and exhibits a low L.A. value: it is a heavy material with a high resistance to fragmentation and toughness. The value of sand equivalent is high for RAP, limestone and steel slag, indicating a high cleanliness. In addition, the limestone has a good Los Angeles value. All aggregates show good shape and flakiness indexes. All properties fit the value range required by the Italian technical specification.

Testing equipment and procedures

The tests were mainly carried out to implement a preliminary study to evaluate the CBTM with fibres. In this work the test procedures described into the European standards for the hot mix asphalt were used: EN 12697-26 to test the stiffness (Indirect Tensile Stiffness Modulus – ITSM), EN 12697-23 for the Indirect Tensile Strength (ITS), EN 12697-24 to evaluate the fatigue resistance and EN 12697-12 for the water susceptibility.

In the first step, the samples were produced mixing the aggregates with cement and water. Cement and water contents are calculated in relation with the weight of the aggregates. After the setting of the foam machine, the bitumen was added to the mix.

As stated by the European standard EN 12697-30, the samples were compacted using the Marshall procedure (75 blows per face).

After the compaction, the samples were place in a climatic chamber at constant temperature (40 °C) and relative humidity (55 ± 5 %) for at least 72 hours: this accelerated curing simulates the field curing condition as stated by several researchers (Marquis et al, 2003; Kim et al, 2011; Pasetto and Baldo, 2012).

The Indirect Tensile Stiffness Modulus (ITSM) and the dry Indirect Tensile Strength (ITS_d) were determined conditioning the samples at 25 °C for 24 hours, while the wet Indirect Tensile Strength (ITS_w) was evaluated at 25 °C after a water conditioning of 72 hours at 40 °C. To study the water susceptibility the Indirect Tensile Strength Ratio (ITSR) was calculated. The ITSM test was performed using a rise time of 124 ms.

The fatigue behaviour of the mixes was tested at 25 °C through the Indirect Tensile Fatigue Test (ITFT), imposing fixed stress values equal to: 250 kPa, 300 kPa and 350 kPa.

Mix design

For the mix design the grading envelope (Table 2) proposed by Wirtgen (Wirtgen GmbH, 2012) was used. Three mixes were produced: the first one as reference mixture (called R) and two mixtures (called A and B) with secondary aggregates.

Table 2. Mixture gradations: volumetric design.

Sieve [mm]	Passing [%] (volumetric)				
	R	A	B	min. gradation	max. gradation
20	100.0	100.0	100.0	70.0	100.0
10	79.7	84.8	81.5	58.0	80.0
5	56.0	67.9	66.5	45.0	70.0
2	38.7	49.6	51.6	30.0	55.0
0.4	20.2	22.8	28.5	15.0	35.0
0.18	14.4	14.3	15.8	10.0	28.0
0.075	8.9	6.4	7.1	6.0	20.0

In the Table 3 the mixtures' composition of the is showed. The main difference between the mixes A and B is the introduction of 20% of foundry sand in substitution of RAP (Table 3). The reference one was constituted by virgin materials (limestone) coming from a quarry in Northern Italy.

Furthermore, in the reference mix was used a limestone powder as filler, while for the other two mixes (A and B) the fine fraction of the fly ash was used.

Table 3. Composition of the mixes (in percentage) by weight.

Mixes	EAF slags			Fly Ash	Foundry Sand	RAP	Limestone				
	0/10	10/15	15/20	-	-	-	filler	0/4	4/8	8/12	12/20
R	-	-	-	-	-	-	8	45	22	15	10
A	15	10	5	10	-	60	-	-	-	-	-
B	15	10	5	10	20	40	-	-	-	-	-

The mix design was conducted using different percentages (from 1% to 3%) of cement and bitumen in the mixes. The best composition of the CBTM was verified using indirect tensile strength test (EN 12697-23) in relation to the best dry bulk weight of the samples (Namutebi et al, 2017). The mix design phase was carried out changing the contents of water and binders (cement and bitumen). The aggregates were mixed with the cement and the bitumen, using the foaming machine. The water content (4 %) necessary for the hydration of the cement was set before the study of the binder content. Three CBTM were prepared as result of the mix design phase: one mix with 2% of bitumen and 3 % of cement (mix 2 3), one with 3 % of bitumen and 3 % of cement (mix 3 3) and one with 3 % of bitumen and 1.5 % of cement (mix 3 1.5).

In addition, the three types of fibre (Figure 1) were put into the mixes. These fibres were added to the CBTMs by the weight of the aggregates: 2 % for the fibre C, 0.5 % for the other two (S e M).

RESULTS AND DISCUSSION

The tests (ITSM, ITS_d, ITS_w and ITFT) were done for all the mixes, except for the mix B on which the ITFT was not performed yet.

The ITSM and the ITS_d values are showed in two different graphs, while the ITFT results (numbers of the cycle before the failure of the specimen vs. the fatigue stresses)

are displayed in a graph bilogarithmic. In these graphs, the CBTMs are identified with a fixed acronym, using an alphanumeric code composed by: a letter for the mix type (R, A and B), a number for the bitumen content (2 % or 3%), a number for the cement content (1.5 % or 3%) and a letter for the fibre type (C, S and M).
The mean results for all the mixes are shown in the Table 4, where, from left to right, are indicated: the mix type (R, A and B), the bitumen content (2 % or 3%), the cement content (1.5 % or 3%), the fibre type (C, S and M), the mean value of stiffness [MPa], the mean value of dry Indirect Tensile Strength [MPa], the mean value of the wet Indirect Tensile Strength [MPa] and the mean value of the Indirect Tensile Strength Ratio [%] (as the ratio of the wet Indirect Tensile Strength (ITS_w) and the dry Indirect Tensile Strength (ITS_d) by percent).

Table 4. Mean stiffness, indirect tensile strength (dry and wet) and ITRS results.

Mix	Bitumen [%]	Cement [%]	Fiber	Stiffness [MPa]	ITS_d [MPa]	ITS_w [MPa]	ITSR [%]
R	3	1,5	-	1101	0,30	0,25	84
A	2	3	-	1737	0,39	0,26	66
A	2	3	C	1434	0,27	0,18	68
A	2	3	S	7248	1,10	0,99	91
A	2	3	M	7615	0,87	0,74	86
A	3	3	-	2092	0,37	0,26	70
A	3	3	C	2056	0,32	0,22	70
A	3	3	S	8055	1,11	0,91	82
A	3	3	M	8824	1,17	1,03	88
A	3	1,5	-	7016	0,63	0,50	79
A	3	1,5	C	7137	0,83	0,64	78
A	3	1,5	S	8771	0,81	0,68	84
A	3	1,5	M	7625	0,93	0,76	82
B	2	3	-	5850	0,56	0,39	70
B	2	3	C	3382	0,47	0,34	73
B	2	3	S	8023	0,81	0,66	81
B	2	3	M	10406	1,18	0,99	85
B	3	3	-	5696	0,57	0,40	71
B	3	3	C	4901	0,59	0,46	77
B	3	3	S	9570	1,22	0,99	81
B	3	3	M	10019	1,26	1,06	84
B	3	1,5	-	8949	1,27	1,09	86
B	3	1,5	C	9879	1,29	1,14	88
B	3	1,5	S	11600	1,45	1,30	90
B	3	1,5	M	13435	1,94	1,75	90

The values in the Table 4 demonstrate that the mix B has higher stiffness and ITS values, with respect to the mix A and the reference mix R. Inserting the fibre in the mixes, the stiffness and the strength values increase, except for the fibre C
The stiffness growth is high when fibres S and M are added (from 25 % to 317 % and from 9 % to 338 % respectively). The increase of ITS values shows a trend similar to stiffness: fibres S and M (from 14 % to 199 % and from 48 % to 217 % respectively) provide a high gain, with respect to the mixes with no fibres and fibres C.

Moreover, the CBTMs without fibres show an increase of stiffness and strength compared with the reference one (R) as further reported: the mix A reaches a 537 % of increment in terms of stiffness and a 108 % in terms of strength, while the mix B has best results (713 % in terms of stiffness and 323 % in terms of strength).

The strength of the samples tested in wet condition (ITS_w) decrease with respect to the strength in dry condition (ITS_d), but the level of the strength in wet condition (ITS_w) lasts sufficiently high: the ITSR values demonstrate good performance of the mixes with fibres in relation to the other one. The CBTMs A and B with no fibres, compared to the reference mixtures (R), have a similar behaviour concerning water susceptibility. The fibres create a better interlocking effect in the skeleton of the mixes and the water susceptibility (in terms of ITSw and ITSR) of mixes with fibres is higher than the mixtures without fibres.

In the Figure 2 the graph with the mean values of Indirect Tensile Stiffness Modulus – ITSM in MPa was proposed, while the Figure 3 shows the results of the dry Indirect Tensile Strength – ITS_d in MPa. These Figures contain the bars with the standard deviation values.

The ITSM value of the reference mixtures is very low if compared to the mixes A and B with the same content of bitumen and cement. The Figure 2 confirms the results described before: the mixtures with fibres S and M reach a good level of stiffness, while the fibre C do not show a reasonable increase with respect to the mixtures with no fibres.

As written before, the ITS values in the Figure 3 have a behaviour similar to the ITSM values: the mixes with fibres S and M have a better performance compared to the mixes with fibre C and no fibres. However, all the mixes have a strength higher than the minimum value required by the Italian specification.

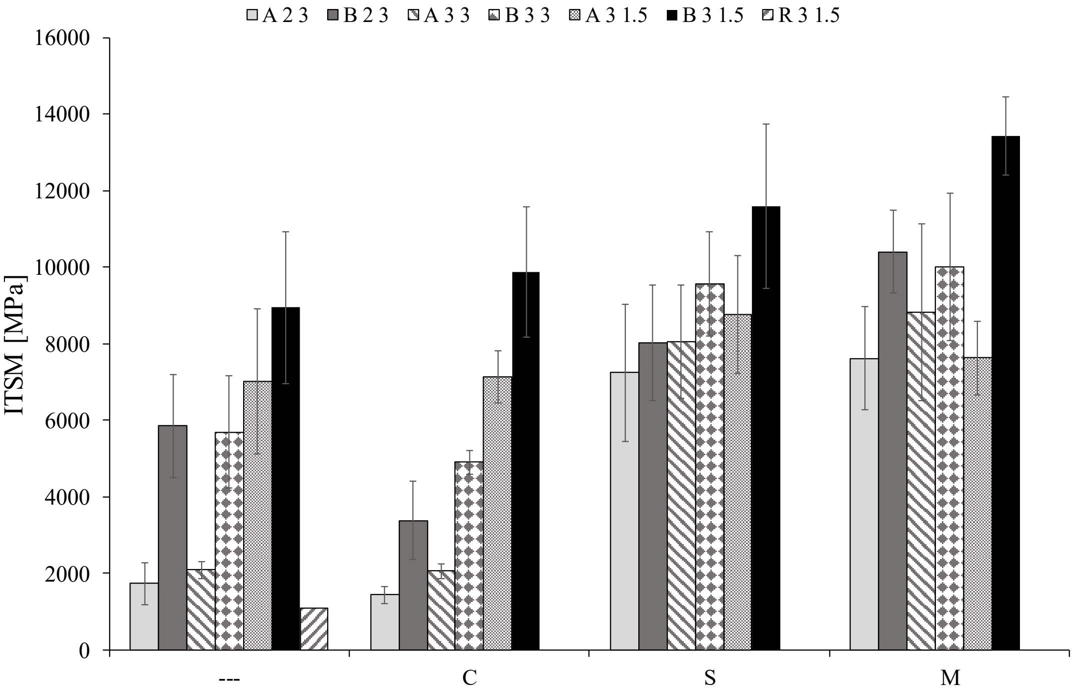

Figure 2. Indirect Tensile Stiffness Modulus - ITSM [MPa] for the mixes.

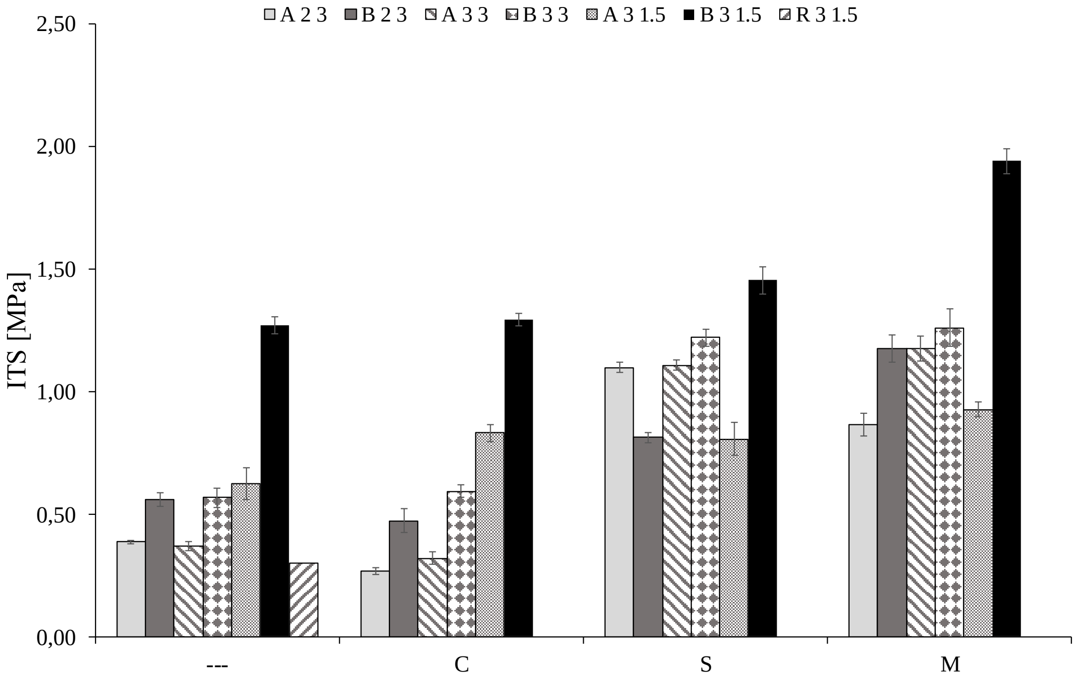

Figure 3. Dry Indirect Tensile Strength - ITS$_d$ [MPa] for the mixes.

By adding the fibres S and M, the mixes A and B with a bitumen content from 2 % and 3 % and a cement content equal to 3 % demonstrate a better performance, in terms of stiffness and strength. Whereas, the mixes A and B with 3 % of bitumen and 1.5 % of cement exhibit a good stiffness and strength even without the fibres (Figures 2 and 3).

The statistical significance of the different measured stiffnesses among the mixes was assessed through a one-way Analysis of Variance (ANOVA) at a 95% confidence level. Comparing the CBTMs A and B with the same cement content, ANOVA output indicates that the change of the bitumen content does not have an high effect on the behaviour of the matrix skeleton (p-value > 0,05). On the contrary, ANOVA output shows that the cement content, comparing the mixes A and B with the same bitumen content, affect the stiffness of the mixes (p-value < 0,05).

Furthermore, the fibre C does not have a statistical significance on the stiffness of the mixes: the ANOVA output does not demonstrate a significative difference between the performance (in terms of ITSM) of the mixes with and without fibre C.

The ANOVA outputs confirm that the fibres S and M have a significative statistically change on the stiffness for the mixes A and B with a bitumen content from 2 % and 3 % and a cement content equal to 3 %. In the case of the mixes A and B with 3 % of bitumen and 1.5 % of cement the ANOVA results do not demonstrate a significative change (p-value > 0,05) in the mix behaviour, except for the mix B with 3 % of bitumen, 1.5 % of cement and the fibre M (p-value < 0,05).

The Figures 4, 5 and 6 show the fatigue behaviour for the mixes A. At the moment, the fatigue tests result for the mix B is still being assessed.

To make comprehensible the fatigue data for the mix A, they were subdivided in three plots: Figure 4 shows the mixture A with 2 % of bitumen and 3 % of cement, Figure 5 exhibits the mixes A with 3 % of bitumen and 3 % of cement, Figure 6 contains mixes with 3 % of bitumen and 1.5 % of cement. Each Figure includes the fatigue result for mix R (as reference).

In general, the fatigue results of mix A with no fibre and with fibre C are placed on the left on the graph with the reference mixture, both for the mix with 2 % of bitumen and 3 % of cement and for the one with 3 % of bitumen and 3 % of cement. The mix A has a better fatigue behaviour when the content of bitumen is equal to 3 %, the content of cement is equal to 1.5 % and no fibres are employed.

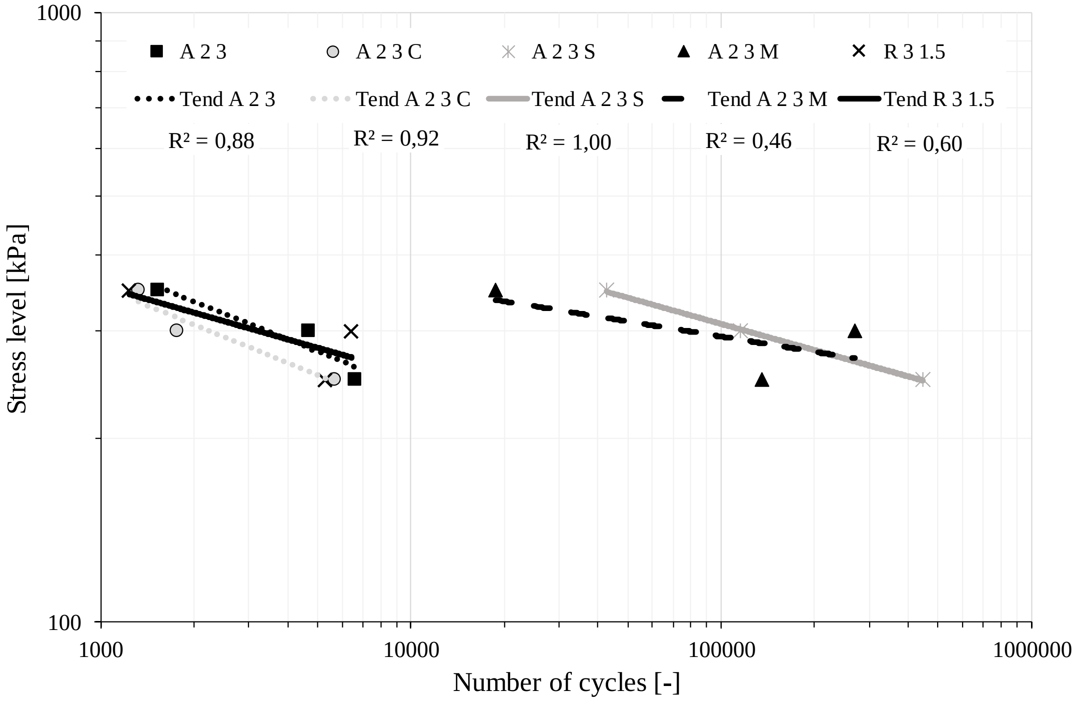

Figure 4. Fatigue behaviour for the mixes A with 2 % of bitumen and 3 % of cement.

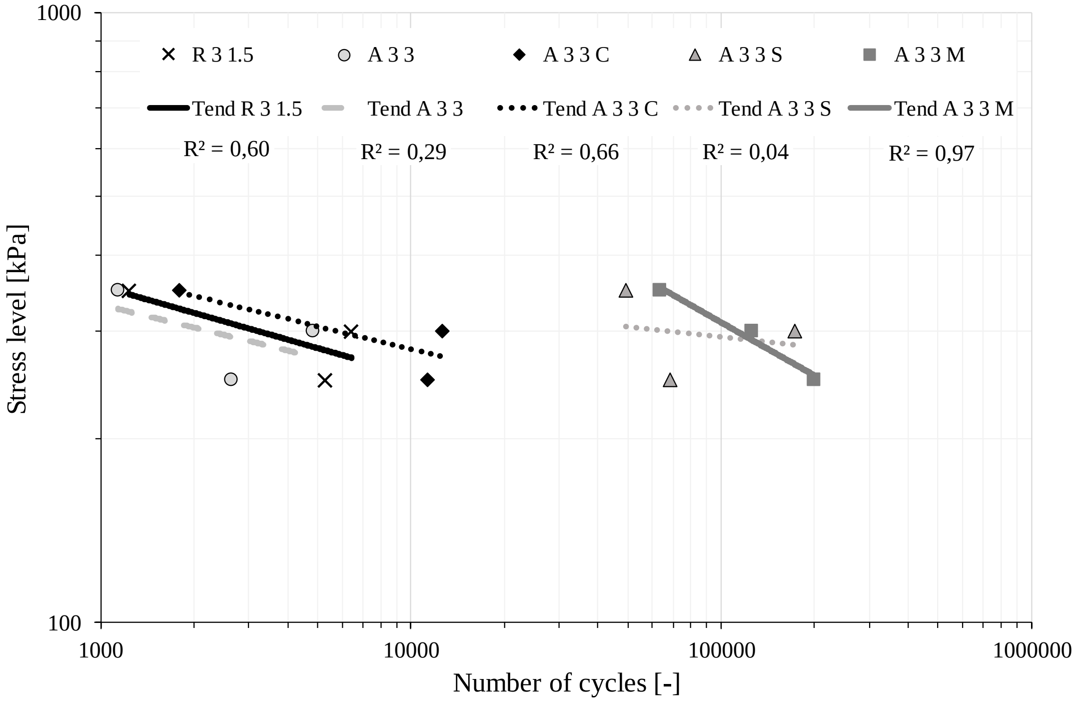

Figure 5. Fatigue behaviour for the mixes A with 3 % of bitumen and 3 % of cement.

Moreover, adding the fibres “S” and “M”, the CBTMs become more durable with respect to those with fibre C and no fibres. By incorporating the fibres in the mix A with 3% of bitumen and 1.5 % of cement, the fatigue results do not change significantly if compared to the mix A with no fibres.

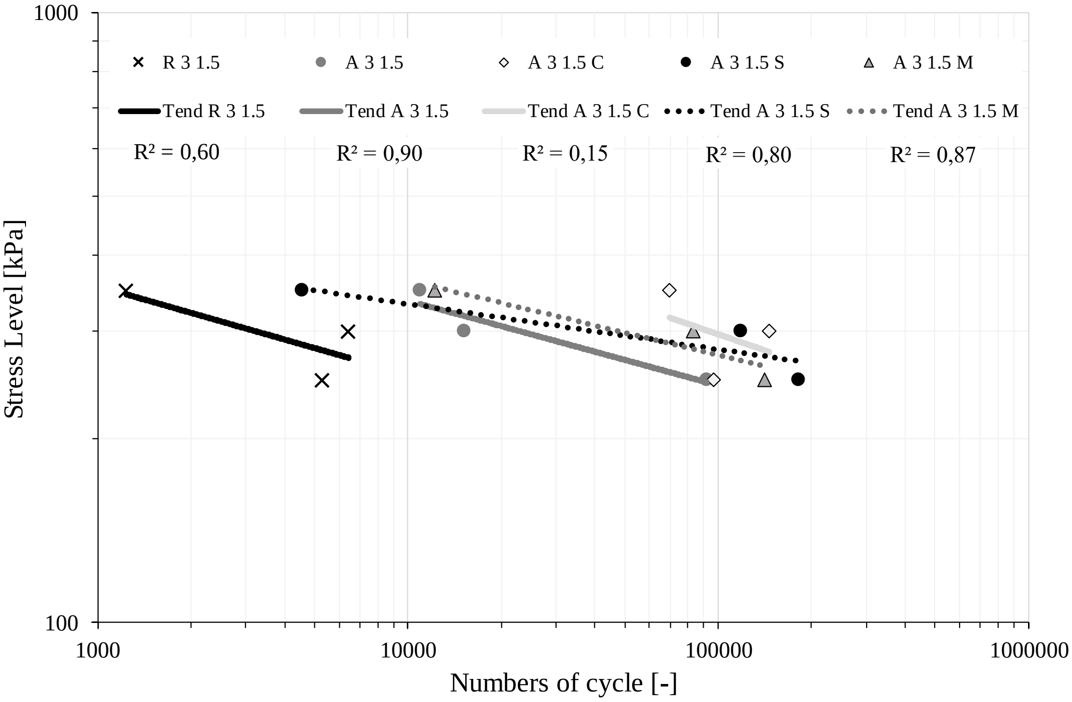

Figure 6. Fatigue behaviour for the mixes A with 3 % of bitumen and 1.5 % of cement.

All CBTMs with fibres “S” and “M” have a reasonable good fatigue resistance, indicating a good interlocking effect on the mixtures given by the addition of the fibre. The Figure 7 shows the broken samples after the fatigue test: the fibres increase the internal resistance and the cohesion/internal adherence of the samples. The inclusion of fibres into the CBTMs changes the behaviour of the material from brittle to more ductile.

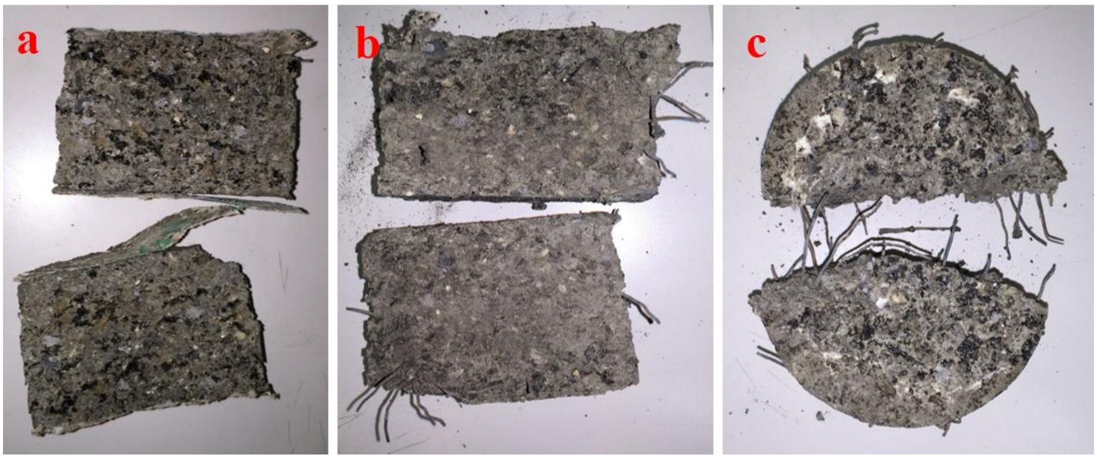

Figure 7. Broken CBTM samples after the tests: a) with no fibres, b) with fibre “S”, c) with fibre “S” from another perspective.

CONCLUSIONS

The present paper concerned the feasibility of utilizing fibres with marginal aggregates in cement-bitumen treated mixtures. The lack of investigations about the use of fibres in foundation or base layers encouraged the authors to study this topic.

The experiments were performed to assess the mechanical properties (stiffness, strength, water susceptibility and fatigue resistance) of CBTMs with fibres at the typical test temperature prescribed for foundation/base layer (25 °C).

The main conclusions of such research can be summarized as follows:

- the marginal materials could substitute the virgin aggregates creating noticeably better performance of the mixes;
- in general, the fibres introduction increased stiffness, strength, water and fatigue resistance of the CBTMs in a different way, depending to the fibres type;
- the fibres C (cellulose/glass) did not improve stiffness and strength of the CBTMs highlighting their poor efficiency (Toraldo et al, 2014);
- the fibres S (polymeric) and M (polypropylene) had better performance, enhancing the properties of the mixtures, because the shape and the conformation of the fibres allowed to create a tough frame with the matrix (Martinez-Arguelles et al, 2015; Kim and Park, 2013).

Overall, this research clearly states that the addition the fibres (mainly polypropylene and polymeric ones) led to the enhancing of CBTMs performance thanks to the interlocking effect on mixes given by the fibres.

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