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(Article begins on next page)

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A Preliminary Laboratory Evaluation on the Use of Shredded Cigarette Filters as Stabilizing Fibers for Stone Mastic Asphalts

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Abstract: Cigarette butts can be considered as one of the most common contemporary sources of waste, considering the large consumption of cigarettes all over the world. Despite the fact that different solutions have been developed and tested in the recent years aiming to recycle them, cigarette butts are currently landfilled and incinerated. Following the circular economy principles, the experimental application proposed in this paper is an exploratory investigation on the use of shredded cigarette filters as sustainable alternative to the addition of fibers into Stone Mastic Asphalts (SMAs). This represents the preliminary step for a wider research project, aiming to find a possible recycling solution for cigarette butts as fibers in bituminous materials. The use of fibers is a common and well-established solution for the production of high bitumen content mixtures. The fibers have a double function: acting, generally, as a stabilizing agent and, where possible, improving the mechanical performance of the bituminous mixtures. In the present research, two different SMAs were produced and tested aiming to analyze the effects given by the addition of the shredded cigarette filters. The first asphalt concrete, produced with traditional cellulose fibers was taken as a reference mixture, while the experimental mixture was produced with the shredded cigarette filters. The data highlight interesting and promising results for future development, making the use of waste cigarette filters a potential eco-friendly alternative to common cellulose fibers for SMAs.

Keywords: cigarette filters; recycled cigarette butts; asphalt concrete; SMA; fibers

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1. Introduction

Sustainable and responsible development is probably the most important task for a modern society finally aware of the damage caused to the environment by the uncontrolled growth of the last 30 years. As stated in the 7th Environment Action Programme (EAP) produced by the EU, the recycling and reuse of waste can be considered as one of the principal tools for addressing this new challenge [1].

Cigarette butts (CBs) can be classified as one on the most common sources of waste, considering their large consumption all over the world [2]. According to the most recent estimates, around 1.2 million tons of cigarette butts are produced every year [3]. From an environmental point of view, the CBs represent a real problem considering the lack of disposal control and their slow degradation rate. Several researches based on interviews to cigarette smokers, highlighted that around the 73% of the users do not have specific practices for the CBs disposal [4,5]. Furthermore, as stated in the report "Tobacco and its Environmental Impact: an overview" from the World Health Organization, around 70% of CBs are released into the environment, generally discarded directly on the ground [6]. The vast majority of cigarette filters are mainly made of cellulose acetate with a very limited degradation rate [7]. Brodof (1996) assessed that the breakdown of a common cellulose acetate generally takes around 18 months under normal conditions [8]. Recent studies verified that the slow process of degradation of CBs discarded on the ground could last up to 13 years [9].

Furthermore, the presence of toxic chemicals within CBs is now a well-known fact [10,11]. A cigarette filter is mainly designed to reduce the inhalation of several substances during tobacco combustion; as a result, it absorbs and retains toxic substances that can be released into the environment when discarded. Several detailed studies and researches highlighted that around 7000 chemicals (USDHHS, 2010) are released by CBs into the environment, with potential effects on humans and ecosystems [12–16].

Still, the lack of standardized protocols or best practices for CB disposal makes the management of this kind of waste a real issue. Thus, the majority or CBs are currently landfilled and incinerated. In the light of the above, it is clear that these disposal solutions will no longer be feasible, and it is evident that finding recycling alternatives to disposing of CBs in landfill is now crucial.

Different recycling methods and applications have been tested and are currently under investigation in order to find possible solutions in line with the principles of circular economy [17]. Several alternative solutions are available in the literature for the recycling and re-use of CBs. Good results have been obtained for the recycling of CBs in the production of new construction materials (i.e., fired bricks, lightweight bricks, precast concrete blocks) or acoustic insulation systems [18–20]. A few studies have also been developed on the use of CBs as bituminous materials for road pavements, and the proposed experimental applications were mostly focused on the use of waste CBs as bitumen modifiers/additives [21,22].

The research proposed in this paper is a preliminary study on the direct application of brand new cigarette filters (CF) for the production of asphalt concretes (AC). The work is the preliminary and exploratory step of a wider research project aiming to study the re-use of waste cigarette butts as a potentially sustainable alternative to fibers (both traditional and innovative ones) for ACs. The use of fibers, in fact, is a common practice for the production of high bitumen content mixtures for pavements such as stone mastic asphalt (SMA) and porous asphalt [23]. The fibers can have the double function of working as a stabilizing agent, avoiding the separation between the aggregates and the bitumen during the storage and transport operations, and are also used to improve the mechanical performance of the final AC [24,25].

Considering the wide use of fibers, a new market to recycle waste in the production process of new cellulose-based fibers has been generated, taking into account the good properties of the waste in terms of binder absorption, when compared to mineral fibers [26–31]. In order to evaluate the effects given by the addition of the grinded brand new CFs in the bituminous mixture, two different SMAs were produced in the laboratory and tested: one (labelled SMA0) with common cellulose stabilizing fibers, and another (labelled SMAF) containing CFs. The aim of the present research is to explore the possible use of this waste as a pavement material, and therefore to develop a new recycling application to limit the landfilling of waste cigarette butts.

2. Materials and Methods

As aforementioned, the experimental application of CFs in substitution of common stabilizing fibers has been carried out, adding common shredded CFs during the mixing operation of a traditional SMA.

2.1. Cigarette Filters and Stabilizing Fibers

In the case being studied, brand new cigarettes were collected and filters were cut off. In order to represent what could happen on a real scale, cigarette from different producers were used in this experimental application. However, it is worth mentioning that all the collected CFs were made of cellulose acetate-based material.

The CFs were grinded using a mechanical shredder, set up in order to have particles up to 10 mm. From a visual analysis of the obtained shredded CFs (Figure 1), the material is mostly composed of cellulose acetate fibers, with traces of plug wrap paper and tipping paper.

Figure 1. Shredded cigarette filters and a EUR 1 coin as size reference.

Some traditional cellulose-based stabilizing fibers were used as reference fibers. The physical and mechanical properties of the reference fibers are reported in Table 1.

Table 1. Properties of cellulose stabilizing fibers.

Fibers Technical Data	
Avg. fibers length	min 200 µm, max 1100 µm
Avg. fibers diameter	min 25 µm, max 45 µm
Melting point	>230 °C
Water solubility (%)	0.450–0.500 kg/m^3

2.2. SMA Mix Design

Stone mastic asphalt was first developed in Germany in the 1960s and it was soon used in the rest of Europe, the United States, Canada and Australia due to its good performance. The combination of selected aggregates according to a gap-graded gradation and the adoption of modified bitumen allows for a high resistance to plastic deformation, making SMA suitable for high- and heavy-traffic roads. Furthermore, the use of high quality aggregates ensures remarkable skid-resistance properties.

In the present research, the adopted mix design for the SMA followed the District of Bologna technical specification [32]. The grading distribution is presented in Figure 2 and Table 2, while the rheological properties of the used bitumen are reported in Table 3.

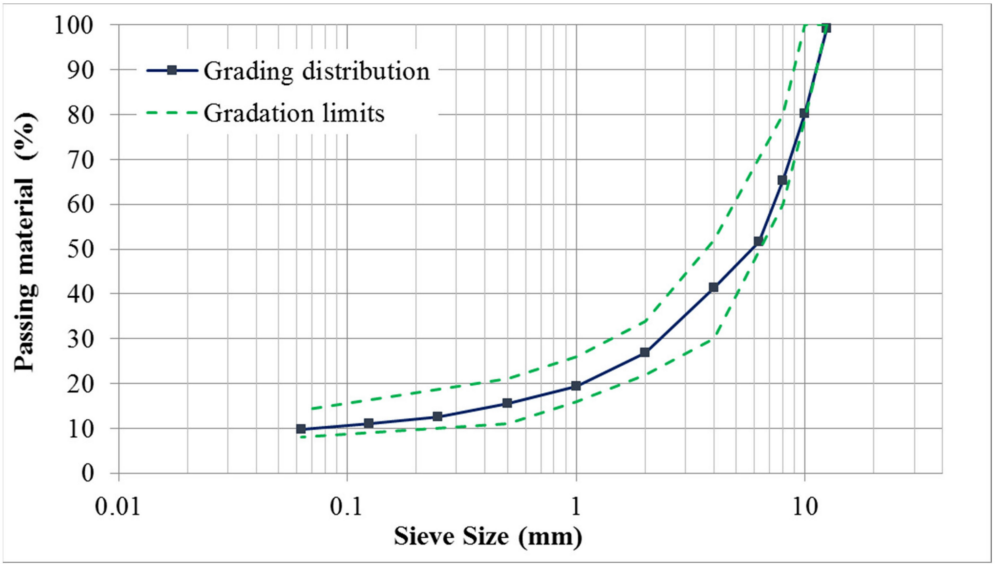

Figure 2. SMA grading distribution.

Table 2. SMA gradation.

Sieve (mm)	Retained Material (%)	Passing Material (%)
14	0.00	100.00
12	0.68	99.32
10	19.10	80.22
8	15.01	65.21
6.3	13.65	51.57
4	10.14	41.42
2	14.62	26.80
1	7.36	19.45
0.5	3.96	15.49
0.25	2.88	12.61
0.125	1.64	10.97
0.063	1.16	9.81
<0.063	9.81	-

Table 3. Conventional properties of the adopted bitumen.

Property	Unit	Characteristic Value	Standard
Penetration @ 25 °C	dmm	50–70	EN 1426 [33]
Softening Point	°C	46–54	EN 1427 [34]
Penetration Index	-	1.05–0.70	EN 12591 [35]
Dynamic Viscosity @ 60 °C	Pa·s	145	EN 12596 [36]
Ductility	%	80	ASTM D 113 [37]

Based on previous studies and laboratory tests on the same SMA mix design, the optimum binder content was fixed at 6% on the weight of aggregates, while the amount of filler was 10% on the weight of aggregates [38].

Following the technical specification of the commercial fibers and the optimum bitumen content, their ratio was 0.3% of the weight of the aggregates for the reference mix (SMA0). As for the SMAF, as shown in the following paragraph, specific drain-down tests (ASTM D6390-11 [39]) were carried out in order to evaluate the absorption properties of the shredded CFs and to define their optimum dosage within the bituminous mixture.

2.3. Experimental Program

The experimental program was based on the physical and mechanical characterization of two different SMAs produced with and without CF as stabilizing fibers. Once the mix design and the absorption properties of the shredded CFs were defined, tests were carried out on SGC (Superpave Gyratory Compactor, EN 12697-31 [40]) specimens. The mixing and compaction operations and temperatures (170 °C) were fixed univocally in order to obtain comparable results.

The volumetric properties of the two different SMAs were assessed with the air voids (AV) content analysis (EN 12697-8 [41]) on three samples for each mixture according to three different compaction levels (10, 100 and 180 gyrations). The evaluation of the workability and compactability properties of the mixtures was corroborated also by the analysis of the gyratory compaction curves.

For each mixture, nine SGS samples (100 gyrations [40]) were prepared for the mechanical characterization. The cohesion properties were assessed in terms of indirect tensile strength (ITS) at 25 °C, according to the EN 12697-23 standard [42]. The mechanical analysis was supported with indirect tensile stiffness modulus (ITSM) tests following the EN 12697-26 standard [43]. The thermal sensitivity of the mixtures was evaluated, repeating the ITSM test at three reference temperatures: 10, 20 and 30 °C. Furthermore, the water susceptibility of the SMAs was investigated in terms of ITS reduction (ITSR, EN 12697-12 [44]), carrying out ITS tests on specimens after saturation in a water bath at 40 °C for 72 h.

The durability of the experimental bituminous mixture was also evaluated in terms of resistance to permanent deformation, in compliance with the EN 12697-25 standard [45], according to a uniaxial test configuration. The repeated load axial test (RLAT) is a laboratory-based, quick method for determining the creep characteristics of bituminous mixtures under cyclic loads at a high temperature (40 °C).

3. Results

3.1. Evaluation of the Absorption Properties of CFs

As mentioned before, drain-down tests were performed in order to assess the bitumen absorption properties of the CFs. The test was carried out in compliance with the [39] standard. This test allows the amount of drain-down in a loose bituminous mixture to be determined, when this is held at high temperature, compared to the amount obtained during the mixture in-plant production, storage and transportation. It is very useful for high bitumen content mixtures, where the addition of fibers is required precisely to prevent the separation of bitumen from aggregates.

Four mixtures were tested, containing shredded CFs at a ratio of 0, 0.2, 0.3 and 0.4% of the weight of the aggregates, and two samples were produced for each mixture. The average results are presented in Table 4.

Table 4. Average drain-down results for the shredded CFs.

Fibers Amount	Drain-Down (%)
0% Fibers	0.6 (±0.2)
0.2% Fibers	0.4 (±0.2)
0.3% Fibers	0.4 (±0.1)
0.4% Fibers	0.3 (±0.1)

Based on these results, the addition of experiment fibers equal to 0.4% of the weight of the aggregates seemed to be suitable, showing average drain-down values below the recommended 0.3% [46]. All in all, the shredded CFs exhibit similar absorption properties to the reference cellulose fibers, even if an increase by 0.1% in their dosage is required to achieve the same drain-down limit effect.

3.2. Physical Characterization

The physical characterization was based on the evaluation of the air voids content (AV, [41]) in SGC samples according three different compaction levels equal to 10, 100 and 180 gyrations. This method represents a rapid control of the compactability and workability properties of bituminous mixtures. The average results are shown in Table 5, while the gyratory compaction curves are plotted in Figure 3.

Table 5. Average AV content for SGC samples.

AV Content	SMA0	SMAF
AV (%) at 10 gyrations	15.3 (±0.6)	15.5 (±0.4)
AV (%) at 100 gyrations	6.0 (±0.2)	6.4 (±0.3)
AV (%) at 180 gyrations	4.5 (±0.2)	4.9 (±0.1)

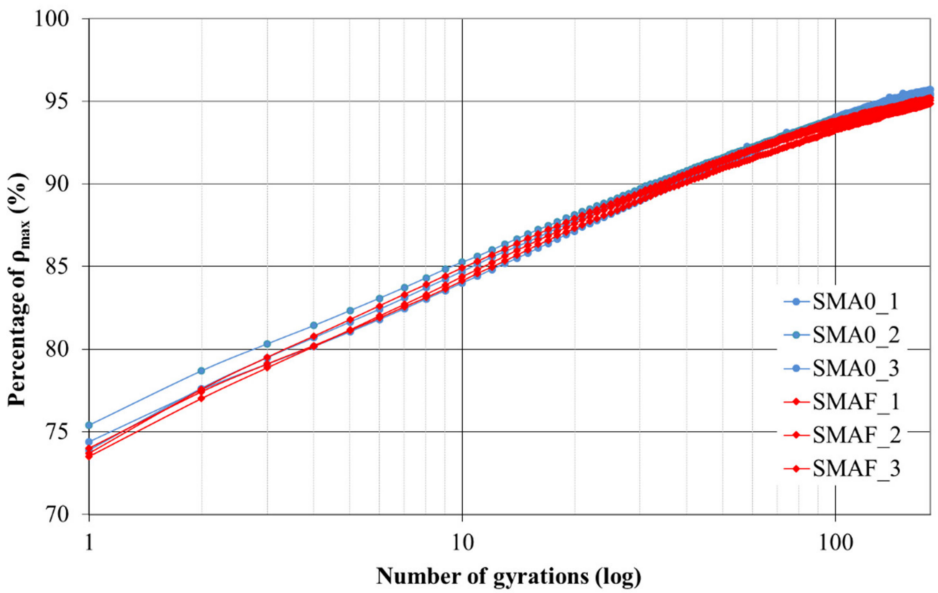

Figure 3. Bituminous mixtures gyratory compaction curves.

All in all, the results are in line with the adopted technical specification requirements (AV < 5% at N_{max}). However, a slight reduction in AV content was recorded for the reference SMA mixture at every compaction level considered.

Overall, there is not a relevant difference between the two mixtures: the presence of CFs does not negatively affect the volumetric properties of the bituminous mixture. Still, the addition of the experimental fibers did not modify or influence the laboratory mixing and compaction operations, confirming the potential application of this material for a real asphalt concrete production. The analysis of the gyratory compaction curves verified the absence of difference in terms of compactability properties due to the presence of CFs. Both SMAs showed comparable densification properties.

3.3. Mechanical Characterization

The mechanical characterization was based on the evaluation of the cohesion properties (ITS, [42]) and the mixtures' stiffness (ITSM, [42]). Furthermore, the stiffness depends on temperature variation in terms of ITSM. Furthermore, the durability of the SMAs was analyzed considering their water susceptibility and the rutting resistance properties.

3.3.1. Indirect Tensile Strength Analysis

The mechanical properties were analyzed in terms of cohesion between aggregates and bituminous mastic with the evaluation of indirect tensile strength (ITS, [42]) at 25 °C. Three SGC samples (100 gyrations [40]) were tested, and the results are presented in Table 6.

Table 6. Indirect tensile strength at 25 °C results.

Mixture	Thickness (mm)	Max Load (N)	Displacement (mm)	ITS (MPa)
SMA0_1	60.6	11400	2.44	1.20
SMA0_1	60.6	12860	1.94	1.35
SMA0_1	61.1	12720	2.28	1.33
avg. SMA0	-	-	-	1.29
SMAF_1	60.8	9250	2.96	0.97
SMAF_1	61.8	9990	2.60	1.03
SMAF_1	61.3	9250	2.60	0.96
avg. SMAF	-	-	-	0.99

Overall, both SMAs show ITS values above the threshold limit suggested by the adopted technical specification (ITS > 0.90 MPa). However, the reference mixture has the best performance. This phenomenon might be attributed to presence of the commercial stabilizing fibers, able to create a stronger cohesion between particles. It is worth noting that, as the SMA mixtures are rich in bitumen, the presence of fibers is fundamental in order to fix the bituminous mastic with the aggregates. The better performance of the reference fibers could be further confirmed by analyzing the displacement data from the ITS tests. Thus, the lower displacement registered for the SMA0 can be attributed to its stiffer structure. Furthermore, the higher ITS results for the reference mixture could also be related to the lower AV content.

3.3.2. Indirect Tensile Stiffness Modulus Analysis

The evaluation of the stiffness modulus was carried out according to the [43] with an indirect tensile test configuration. Three SGC samples (100 gyrations [40]) for each mixture were tested at 10, 20 and 30 °C in order to investigate the thermal sensitivity of the bituminous mixtures. The relation between the stiffness modulus and temperature can be described by the following equation:

$$logS = -\alpha \cdot T + \beta \quad (1)$$

where S is the stiffness modulus at the specific temperature T, while α and β are experimental parameters depending on the material properties. The former parameter is directly related to the temperature sensitivity, as it is generally higher for very temperature-sensitive materials.

The ITSM results are presented in Table 7. In Figure 4, the average results are depicted, but the equations, as well as the coefficients of determination (R^2), are related to the individual values.

Table 7. Indirect tensile stiffness modulus results.

Mixture	ITSM @ 10 °C (MPa)	ITSM @ 20 °C (MPa)	ITSM @ 30 °C (MPa)
SMA0_1	11,114	4518	1493
SMA0_1	12,608	5809	2262
SMA0_1	11,873	5577	2372
avg. SMA0	11,865	5301	2014
SMAF_1	11,041	4486	1683
SMAF_1	11,422	4665	1721
SMAF_1	11,592	4649	1653
avg. SMAF	11,352	4600	1686

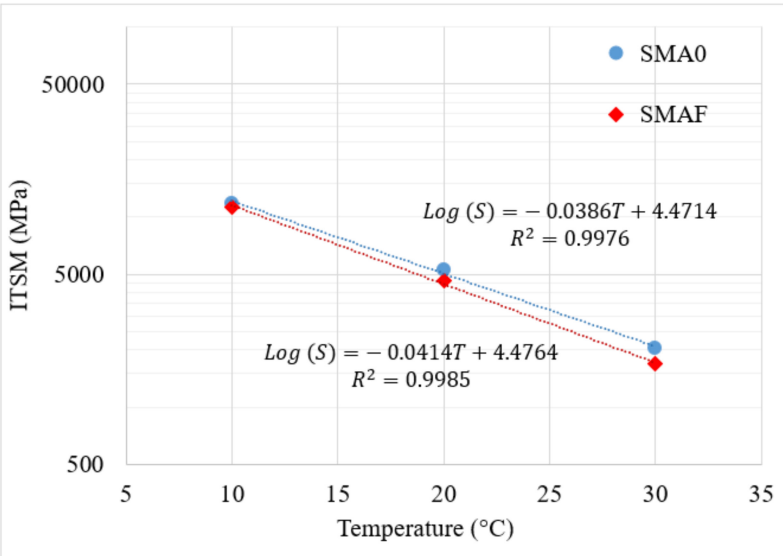

Figure 4. ITSM average results and temperature sensitivity.

In terms of ITSM, the only indication from the technical specification taken as reference is the lower limit for the stiffness modulus at 20 °C (ITSM > 3500 MPa). In this case, both mixtures exceed the threshold limit. The reference SMA shows higher values for each test temperature. Nevertheless, there is not a remarkable difference in terms of stiffness between the two mixtures. The data are in line with the previous physical characterization, with the SMA0 being stiffer than the experimental mixture. In terms of thermal sensitivity, both SMAs show the same trend as confirmed by the comparison of the α parameter in the equations. Thus, the presence of shredded CFs does not modify the mechanical behavior of the SMA mixture in terms of a response to dynamic loads at different test temperatures.

3.3.3. Water Susceptibility

The durability of both mixtures has been assessed in terms of water susceptibility. Following the [44] standard, three SGS samples (100 gyrations, [40]) were submerged in a water bath at 40 °C for 72 h. The water susceptibility is addressed as indirect tensile strength reduction (ITSR).

The ITS results after saturation in water are reported in Table 8, while the ITSR average results are reported in Table 9.

Table 8. Indirect tensile strength results after saturation in water at 40 °C for 72 h.

Mixture	Thickness (mm)	Max Load (N)	Displacement (mm)	ITS_{wet} (MPa)
SMA0_1	60.4	10,540	2.40	1.11
SMA0_1	60.0	10,420	2.32	1.11
SMA0_1	60.2	11,250	2.40	1.19
avg. SMA0	-	-	-	1.13
SMAF_1	61.8	7280	4.06	0.75
SMAF_1	60.9	10,290	2.76	1.08
SMAF_1	61.2	9020	3.50	0.94
avg. SMAF	-	-	-	0.92

Table 9. Average ITSR results.

Mixture	ITS (MPa)	ITS_{wet} (MPa)	ITSR (%)
SMA0	1.29 (±0.04)	1.13 (±0.02)	88
SMAF	0.99 (±0.03)	0.92 (±0.03)	93

All in all, both SMAs are above the ITSR limit imposed by the reference technical specification (ITSR > 75%). The experimental mixture shows a reduced ITS both in normal and wet conditions if compared to the reference SMA. However, it is worth underlining that, in absolute terms, the ITSR is higher for the SMAF. Thus, it can be stated that the presence of CFs does not negatively affect the water susceptibility of the bituminous mixtures.

3.3.4. Repeated Load Axial Test

The durability of the bituminous mixtures was also evaluated in terms of rutting resistance. In fact, this represents a common pavement disease for high bitumen content mixtures for surface layers. According to the [45] standard, method A, a bituminous sample is placed between two parallel plates. The upper plate applies a cyclic compression load and has a dimension smaller than the bituminous sample in order to achieve a certain confinement. The standard specifies a load frequency of 0.5 Hz and a pressure of 100 ± 2 kPa. The specimen's accumulated axial deformation is measured after 3600 loading cycles at 40 °C. Three SGS samples (100 gyrations, [40]) were tested for each mixture and the average results are presented in Table 10 and Figure 5.

Table 10. Average RLAT results.

Mixture	Accumulated Strain (%)	Creep Modulus (MPa)
SMA0	0.36 (±0.1)	29.6
SMAF	0.38 (±0.1)	26.5

Overall, in terms of accumulated strain, there is not a remarkable difference between the two mixtures. The reference SMA, confirming the higher performance highlighted in the previous mechanical characterization, recorded the lowest accumulated strain and, therefore, the highest creep modulus. In this case, the reference technical specifications do not specify any limit for the RLAT but the obtained results were in line with values recorded in previous studies on SMAs with polymer-modified bitumen and modified fibers [38].

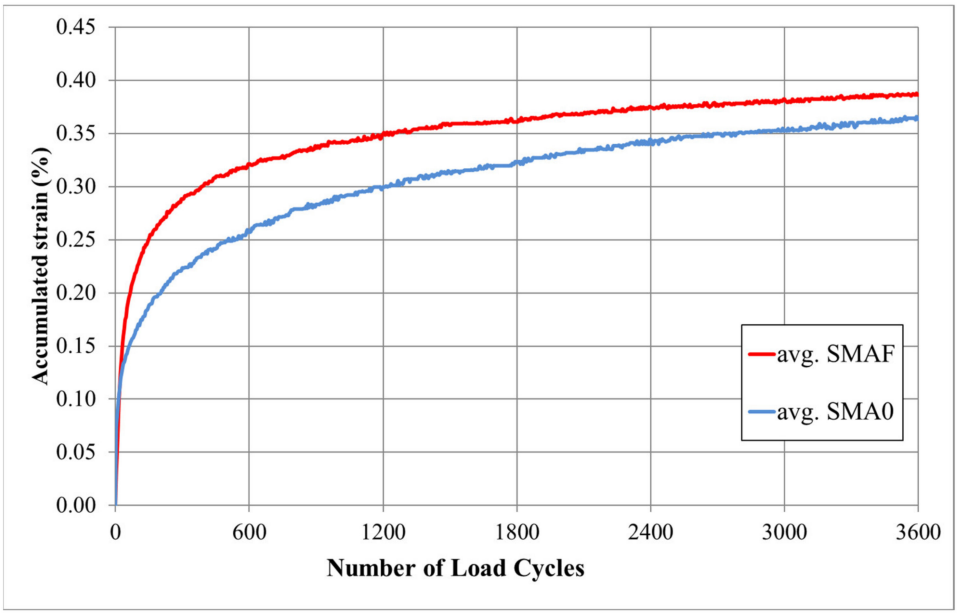

Figure 5. RLAT average results at 40 °C.

The lower performance of the experimental SMA might be related to the higher porosity of the mixture and therefore to the lower stiffness recorded for the SMAF mixture during the ITSM characterization at high temperatures.

4. Discussion

In the present work, an exploratory experimental application of CFs as stabilizing fibers for the production of a bituminous mixture has been proposed. The final aim of this research project is to develop a new recycling solution in order to promote the recycling of waste cigarette butts. Of course, a life cycle analysis (LCA) will assess the sustainability of the proposed recycling process and final application. However, it should be highlighted that the lack of disposal control for this waste is a significant problem, and only with a specific collecting and disposal protocol would the recycling of cigarette butts be feasible.

As for this first experimental application, based on the results:

- The production of the experimental fibers was based on the simple shredding of brand new CFs. The entire outcome of this process was added to the bituminous mixture as a common commercial stabilizing fiber. From the drain-down test results, the shredded CFs show properties similar to the reference fibers. Thus, from an absorption point-of-view, the behavior of the experimental fibers can be compared to the normal cellulose-based stabilizing fibers.
- The addition of shredded CFs into the experimental SMA does not affect the workability and compactability properties of the mixture. The air voids content is in line with the reference mixture and with the technical specifications for this type of asphalt concrete.
- In terms of mechanical properties, the presence of the experimental fibers leads to a slight reduction in the ITS, despite the fact that the obtained values are above the requirements imposed by the reference technical specifications. This reduction could be an indication of a lower cohesion, probably due to the limited effect of the experimental fibers in stabilizing the high bitumen content, and in generating a strong mastic with the finer particles of the mixture. However, the stiffness of the experimental SMA, as well as its thermal sensitivity, was not negatively affected by the addition of CFs.

- As for the water susceptibility, a minimum ITS reduction was registered for the experimental mixture. Furthermore, this reduction was lower even if compared to the reference SMA.
- The presence of shredded CFs does not alter the rutting resistance properties of the bituminous mixture, which were in line with common values for stone mastic asphalt mixtures.

5. Conclusions

All in all, these preliminary results confirm that the addition of shredded CFs as stabilizing fibers for bituminous mixture could be a feasible application.

However, it is worth noting that in this exploratory study, the CFs were simply shredded and directly added to the mixture in a total substitution of commercial fibers. This could represent a simple way to re-use this waste, which can be easily reproduced on an industrial scale.

Nevertheless, the obtained promising results highlighted some downsides that might be exceeded with a proper CFs treatment that could make this material much more similar to the common stabilizing fibers or could mean that it gives an even better performance. In fact, the presence of limited quantities of plug wrap paper and tipping paper after the CF shredding are probably responsible for the lower cohesion properties of the experimental SMA, if compared to the reference one.

Following the positive outcomes of this preliminary experimental application, in the development of this research project, the use of waste cigarette butts will be investigated.

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References

1. DECISION No 1386/2013/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living Well, within the Limits of Our Planet'. Available online: http://data.europa.eu/eli/dec/2013/1386/oj (accessed on 20 November 2013).
2. Torkashvand, J.; Farzadkia, M.; Sobhi, H.R.; Esrafili, A. Littered cigarette butt as a well-known hazardous waste: A comprehensive systematic review. *J. Hazard. Mater.* **2020**, *383*, 121242. [CrossRef]
3. Mohajerani, A.; Kadir, A.A.; Larobina, L. A practical proposal for solving the world's cigarette butt problem: Recycling in fired clay bricks. *Waste Manag.* **2016**, *52*, 228–244. [CrossRef]
4. Novotny, T.E.; Zhao, F. Consumption and production waste: Another externality of tobacco use. *Tob. Control* **1999**, *8*, 75–80. [CrossRef]
5. Patel, V.; Thomson, G.W.; Wilson, N. Cigarette butt littering in city streets: A new methodology for studying and results. *Tob. Control* **2013**, *22*, 59–62. [CrossRef] [PubMed]
6. World Health Organization. *Tobacco and Its Environmental Impact: An Overview*; WHO: Geneva, Switzerland, 2017.
7. Haske-Cornelius, O.; Pellis, A.; Tegl, G.; Wurz, S.; Saake, B.; Ludwing, R.; Sebastian, A.; Nyanhogo, G.S.; Guebitz, G.M. Enzymatic Systems for Cellulose Acetate Degradation. *Catalysts* **2017**, *7*, 287. [CrossRef]
8. Brodof, T.A. The mechanisms of cellulose acetate degradation and their relationships to environmental weathering. In Proceedings of the 50th Tobacco Chemists' Research Conference, Richmond, VA, USA, October 1996. Paper 19.
9. Joly, F.X.; Coulis, M. Comparison of cellulose vs. plastic cigarette filter decomposition under distinct disposal environments. *Waste Manag.* **2018**, *72*, 349–353. [CrossRef] [PubMed]
10. Micevska, T.; Warne, M.S.; Pablo, F.; Patra, R. Variation in, and causes of, toxicity of cigarette butts to a cladoceran and microtox. *Arch. Environ. Contam. Toxicol.* **2006**, *50*, 205–212. [CrossRef]
11. Dobaradaran, S.; Schmidt, T.C.; Lorenzo-Parodi, N.; Jochmann, M.A.; Nabipour, I.; Raeisi, A.; Stojanovic, N.; Mahmoodi, M. Cigarette butts: An overlooked source of PAHs in the environment? *Environ. Pollut.* **2019**, *249*, 932–939. [CrossRef]
12. U.S. Department of Health and Human Services (USDHHS). *A Report of the Surgeon General: How Tobacco Smoke Causes Disease: What It Means to You*; U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Chronic Disease Prevention and Health Promotion, Office on Smoking and Health: Atlanta, GA, USA, 2010.

13. Huerta-Fontela, M.; Galceran, M.T.; Ventura, F. Stimulatory drugs of abuse in surface waters and their removal in a conventional drinking water treatment plant. *Environ. Sci. Technol.* **2008**, *42*, 6809–6816. [CrossRef]
14. Ariza, E.; Jiménez, J.A.; Sardá, R. Seasonal evolution of beach waste and litter during the bathing season on the Catalan coast. *Waste Manag.* **2008**, *28*, 2604–2613. [CrossRef] [PubMed]
15. Slaughter, E.; Gersberg, R.M.; Watanabe, K.; Rudolph, J.; Stransky, C.; Novotny, T.E. Toxicity of cigarette butts, and their chemical components, to marine and freshwater fish. *Tob. Control* **2011**, *20*, 25–29. [CrossRef]
16. Roder Green, A.L.; Putschew, A.; Nehls, T. Littered cigarette butts as a source of nicotine in urban waters. *J. Hydrol.* **2014**, *519*, 3466–3474. [CrossRef]
17. Marinello, S.; Lolli, F.; Gamberini, R.; Rimini, B. A second life for cigarette butts? A review of recycling solutions. *J. Hazard. Mater.* **2020**, *384*, 121245. [CrossRef]
18. Kadir, A.A.; Mohajerani, A. Recycling cigarette butts in lightweight fired clay bricks. *Proc. Inst. Civ. Eng. Constr. Mater.* **2011**, *164*, 219–229. [CrossRef]
19. Wadalkar, S.; Kulkarni, R.; Sawant, N.; Kashyap, A.; Pathan, Z.; Kale, A. Design of precast concrete blocks for paving with the use of cigarette butts (Cellulose acetate). *Int. J. Res. Appl. Sci. Eng. Technol.* **2018**, *6*, 2958–2965. [CrossRef]
20. Gomez Escobar, V.; Maderuelo-Sanz, R. Acoustical performance of samples prepared with cigarette butts. *Appl. Acoust.* **2017**, *125*, 166–172. [CrossRef]
21. Mohajerani, A.; Tanriverdi, Y.; Nguyen, B.T.; Wong, K.K.; Dissanayake, H.N.; Johnson, L.; Whitfield, D.; Thomson, G.; Alqattan, E.; Rezaei, A. Physico-mechanical properties of asphalt concrete incorporated with encapsulated cigarette butts. *Constr. Build. Mater.* **2017**, *153*, 69–80. [CrossRef]
22. Rahman, M.T.; Mohajerani, A.; Giustozzi, F. Possible Recycling of Cigarette Butts as Fiber Modifier in Bitumen for Asphalt Concrete. *Materials* **2020**, *13*, 734. [CrossRef]
23. Wu, B.; Wu, X.; Xiao, P.; Chen, C.; Xia, J.; Lou, K. Evaluation of the Long-Term Performances of SMA-13 Containing Different Fibers. *Appl. Sci.* **2021**, *11*, 5145. [CrossRef]
24. Chen, H.; Xu, Q. Experimental study of fibers in stabilizing and reinforcing asphalt binder. *Fuel* **2010**, *89*, 1616–1622. [CrossRef]
25. Slebi-Acevedo, C.J.; Lastra-Gonzalez, P.; Pascual-Muñoz, P.; Castro-Fresno, D. Mechanical performance of fibers in hot mix asphalt: A review. *Constr. Build. Mater.* **2019**, *200*, 756–769. [CrossRef]
26. Chen, J.; Lin, K. Mechanism and behavior of bitumen strength reinforcement using fibers. *J. Mater. Sci.* **2005**, *40*, 87–95. [CrossRef]
27. Eskandarsefat, S.; Hofko, B.; Oliviero Rossi, C.; Sangiorgi, C. Fundamental properties of bitumen binders containing novel cellulose-based poly-functional fibres. *Compos. Part B* **2019**, *163*, 339–350. [CrossRef]
28. Salas, M.A.; Pérez-Acebo, H. Introduction of recycled polyurethane foam in mastic asphalt. *Građevinar* **2018**, *70*, 5.
29. Wu, S.; Montalvo, L. Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. *J. Clean. Prod.* **2021**, *280*(Pt. 2), 124355. [CrossRef]
30. Moghaddam, T.B.; Karim, M.R.; Syammaun, T. Dynamic properties of stone mastic asphalt mixtures containing waste plastic bottles. *Constr. Build. Mater.* **2012**, *34*, 236–242. [CrossRef]
31. Polaczyk, P.; Ma, Y.; Xiao, R.; Hu, W.; Jiang, X.; Huang, B. Characterization of aggregate interlocking in hot mix asphalt by mechanistic performance tests. *Road Mater. Pavement Des.* **2021**, *22* (Suppl. 1), S498–S513. [CrossRef]
32. Capitolato Speciale d'Appalto. Comune di Bologna. Capo III—Opere Stradali. 2018.
33. EN 1426: 2015. Bitumen and bituminous binders. Determination of needle penetration.
34. EN 1427: 2015. Bitumen and bituminous binders. Determination of the softening point. Ring and Ball method.
35. EN 12591: 2009. Bitumen and bituminous binders. Specifications for paving grade bitumens.
36. EN 12596: 2014. Bitumen and bituminous binders. Determination of dynamic viscosity by vacuum capillary.
37. ASTM D113—17. Standard Test Method for Ductility of Asphalt Materials.
38. Eskandarsefat, S.; Dondi, G.; Sangiorgi, C. Recycled and rubberized SMA modified mixtures: A comparison between polymer modified bitumen and modified fibres. *Constr. Build. Mater.* **2019**, *202*, 681–691. [CrossRef]
39. ASTM D6390—11. Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures.
40. EN 12697-31:2019. Bituminous mixtures. Test methods. Specimen preparation by gyratory compactor.
41. EN 12697-8: 2018. Bituminous mixtures. Test methods. Determination of void characteristics of bituminous specimens.
42. EN 12697-23: 2017. Bituminous mixtures. Test methods. Determination of the indirect tensile strength of bituminous specimens.
43. EN 12697-26: 2018. Bituminous mixtures. Test methods. Stiffness.
44. EN 12697-12: 2018. Bituminous mixtures. Test methods. Determination of the water sensitivity of bituminous specimens.
45. EN 12697-25: 2020. Bituminous mixtures. Test methods. Cyclic compression test.
46. Blazejowski, K. *Stone Matrix Asphalt: Theory and Practice*; CRC Press: Boca Raton, FL, USA, 2016.