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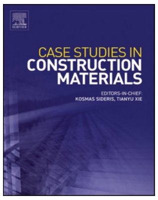

Performance evaluation of stone mastic asphalt reinforced with shredded waste E-cigarette butts

Yunfei Guo [*], Piergiorgio Tataranni, Giulia Tarsi, Cesare Sangiorgi

Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Via Terracini 28, Bologna 40131, Italy

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ABSTRACT

The recycling of waste materials in asphalt pavements is pivotal for advancing the road industry, offering numerous environmental, economic, and societal benefits. This study explores the recycling potential of waste electronic cigarette butts (E-CBs) within stone mastic asphalt (SMA) mixtures, serving as a substitute for cellulose fibres and enhancing mechanical performance. Considering the critical role of fibre size in asphalt mixtures, two different E-CB shredding sizes (10 and 15 mm) were selected for examination. Additionally, the influence of the plastic component within E-CBs was investigated. The stabilizing effects of using the shredded E-CBs were evaluated via drain-down tests, followed by a series of standard laboratory tests aimed at assessing physical and mechanical properties. Results demonstrate acceptable drain-down properties, volumetric properties, and moisture susceptibility for the use of all four shredded E-CBs. Among the four mixtures incorporating the waste fibres, the utilization of 15 mm shredded E-CBs without plastic constituents yielded the highest values for indirect tensile strength (ITS) and indirect tensile stiffness modulus (ITSM), coupled with excellent water susceptibility and rutting performance. It can be considered a promising alternative to the traditional cellulose fibre. Larger shredded E-CBs exhibited potential for improving mechanical properties, encompassing cohesion, stiffness modulus, and rutting resistance. Although plastic inclusion can enhance rutting resistance, the higher thermal susceptibility associated with plastic warrants careful consideration. Future research may focus on investigating the fatigue and low-temperature cracking properties, as well as the reinforcing mechanisms of shredded E-CBs in asphalt mixtures using micro-characterization techniques.

1. Introduction

Anthropogenic waste disposal and management bring pressing challenges in the current world. Since the arrival of filtered cigarettes approximately seven decades ago, cigarette butts (CBs) have emerged as a prominent waste item [1,2]. It is reported that global cigarette consumption reached 5.5 trillion annually in 2016 [3], with projections indicating a surge to 9 trillion by 2025 [4]. The escalating consumption inevitably exacerbates the burden of CBs disposal. The inappropriate littering of CBs has led to the widespread presence of CBs in beaches, urban roads, and marine environments [2,5,6]. The "International Coastal Clean-up" initiative by the Ocean Conservancy identified CBs as the most frequently encountered litter on beaches [7]. Constituent components of CBs typically comprise cellulose acetate filters, papers, ashes, burned and unburned tobacco. These filters have exceedingly slow degradation rates,

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* Corresponding author.
E-mail address: yunfei.guo2@unibo.it (Y. Guo).

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requiring approximately 14 years for complete decomposition [8]. The detrimental effects of the cellulose acetate filters, exacerbated by plasticizers such as diethyl phthalate, emphasize the urgency of addressing CBs litter [8]. Additionally, the release of toxic chemicals poses significant concerns when CBs enter aquatic environments via surface runoff, which is harmful to marine and freshwater organisms [8] Effective management strategies are imperative to mitigate and prevent the contaminating effects of CBs. However, conventional disposal methods, including incineration and landfilling, fail to prevent the dissemination of harmful chemicals into surrounding air, soil, and water [9]. In contrast, recycling techniques offer a more environmentally sustainable approach to CB management.

Utilizing the cellulose acetate fibres is one method of recycling CBs. Within the engineering application in asphalt pavements, various fibre types have been employed, demonstrating significant efficiency in enhancing functional attributes. These fibres act as stabilizers, mitigating bitumen bleeding, and as reinforcing agents, improving the mechanical properties of asphalt concretes [10,11]. The addition of fibres to asphalt mixtures enhances various performance aspects, such as dynamic modulus, rutting, water stability, freeze–thaw resistance, and cracking resistance [12]. For instance, polyester fibres exhibit promising potential in enhancing fatigue resistance by mitigating stress concentration within the mixture, thereby impeding crack formation [13,14]. The introduction of basalt fibres into asphalt mastics forms a three-dimensional network, facilitating stress dispersion and reducing crack propagation, thereby improving cracking resistance [15]. Cellulose fibres are commonly utilized in asphalt mixtures, particularly in high-bitumen content mixes such as porous asphalt and stone mastic asphalt (SMA). The inclusion of cellulose fibres enhances the bonding between bitumen and aggregates and reduces the tendency of binder separation [16]. Mechanical evaluation verified that the cellulose fibres addition contributed to higher resistance to permanent deformation compared to the traditional porous asphalt [17]. Clumping is a significant technical issue during the mixing of fibres and asphalt mixtures. To ensure optimal fibre distribution, increasing mixing temperature and duration is crucial [14]. The introduction of plant-based fibres such as bamboo, coconut, jute, and sisal fibres into asphalt pavements is gaining traction due to their cost-effectiveness and sustainability benefits [12]. Additionally, to mitigate environmental pollution resulting from improper waste disposal, various fibre-based waste materials including waste tires, carpet fibres, nylon wire, plastic fibres, and CBs have been applied to enhance the engineering performance of asphalt mixtures.

Some attempts were made by researchers to recycle CBs in asphalt mixtures. Mohajerani et al. [18,19] studied the utilization of CBs encapsulated with asphalt and paraffin wax in asphalt mixtures. However, the waste CBs did not act as fibres in asphalt mixtures when using this encapsulation method. To enable CBs to function as fibres in asphalt materials, two studies employed a different processing technique involving shredding CBs into smaller particles [20,21]. In the research by Rahman et al. [20], used tobacco-free CBs were shredded into ground fibre and utilized as bitumen modification. Results showed that CBs improved the rheological properties of bitumen. Another type of CB, the cigarette filter (CF) used in new electronic cigarettes (E-cigarettes) without tobacco or ash, was examined in a study by Tataranni and Sangiorgi [21]. Prior to incorporation into SMA, CFs were shredded into particles below 10 mm. Drain-down and mechanical tests demonstrated the feasibility of using the recycled CFs as stabilizing fibres in SMAs. In another research by Guo et al. [22], waste E-cigarette butts underwent shredding before being added to SMA. Results from physical and mechanical tests indicated that the mixture with this shredded E-cigarette butts can meet technical requirements, but it had decreased stiffness modulus and cohesion properties compared to the SMA with traditional cellulose fibres.

One of the challenging issues of producing asphalt mixtures incorporating fibres is to achieve the uniform dispersion and distribution of fibres. Determining an appropriate fibre content is crucial prior to mixture production, as it can significantly impact compactibility properties. Higher percentage of fibre may result in increased air void contents and adverse compaction effects. Additionally, the size of fibres is a critical factor influencing the ultimate performance of asphalt mixtures with fibre addition [23,24]. In investigations exploring various fibres in bituminous mixtures, considerable attention has been devoted to the impact of fibre length [25,26]. Excessively long fibres may cause clumping or balling during mixing, thereby adversely affecting stability and reinforcing properties. When using shorter fibres, the issue of resultant agglomerations must be considered.

Motivated by the demand for environmentally sustainable waste management solutions, this research explored the recycling of electronic cigarette butts (E-CBs) through cellulose acetate fibre utilization, specifically in SMA. Previous studies have shown that shredded CBs can function as fibres in asphalt materials with different processing methods. However, the optimal size of shredded CBs and the influence of plastic component present in E-CBs, remain underexplored. Therefore, the aim of this study is to optimize the recycled use of waste E-CBs as stabilizing and reinforcing fibres in asphalt mixtures. By shredding E-CBs into different sizes and evaluating their drain-down characteristics, physical and mechanical properties, the obtained results are expected to find an effective method of incorporating E-CBs into asphalt mixtures. Additionally, being the plastic included in the structure of this type of CB, the effect of this component was also investigated, considering the well-known influence of plastic in modifying the rheological and mechanical properties of bituminous mixtures. A SMA with conventional cellulose fibre was used as a reference in the laboratory study. The ultimate goal of this research is to improve the engineering properties of fibre-added asphalt mixtures and offer insights into the sustainable handling of CB waste.

2. Materials and methods

2.1. Fibres

2.1.1. Waste electronic cigarette butts

In this study, waste electronic cigarette butts (E-CBs) were recycled and used as fibres in asphalt mixtures. Each E-CB can be divided into four parts according to their different components. As delineated in Fig. 1, the components of E-CB include cellulose fibres, plastic, organic ashes, and traces of plug wrap paper and tipping paper. Notably, plastic residues constitute approximately 34% of the total weight of a single waste E-CB. One E-CB unit encompasses two portions of cellulose acetate fibres, denoted as parts a and c in Fig. 1. The basic properties of E-CBs are listed in Table 1. Given the potential blending challenges associated with integrating collected E-CBs with their original length directly into aggregates, the adoption of a suitable processing method becomes important.

A mechanical shredder was utilized to obtain the shredded waste E-CBs particles for use as fibres in asphalt mixtures. Following the shredding process, two different sizes of shredded E-CBs were obtained, one below 10 mm and the other below 15 mm. Furthermore, shredded E-CBs were produced both with and without plastic residues to investigate the potential influence of plastic constituents on the mechanical performance of SMA. Fig. 2 shows the four shredded E-CBs that were used as fibres in this research, with detailed description provided in Table 2.

The microstructure of cellulose acetate fibres derived from E-CBs were characterized using the Scanning Electron Microscopy (SEM, MIRA3 TESCAN, Czech Republic). As illustrated in Fig. 3, the testing samples were finer powders obtained from the shredded E-CBs post-sieving with a mesh size of 0.063 mm. Notably, Fig. 3 reveals the presence of cellulose fibres, exhibiting a morphology resembling elongated whiskers with a white colour. Further examination, as depicted in Fig. 4(a) and (b), obtained SEM images of shredded E-CBs below 0.063 mm and cellulose fibers separated from the finer E-CBs. Remarkably, Fig. 4(b) highlights the elongated form of cellulose fibres, which tend to bundle together. The surface protruding structure allows the fibre to have a larger surface area for interaction with bitumen, thereby enhancing the cohesion properties of asphalt mixtures. It is noteworthy that similar SEM micrographs depicting cellulose acetate fibres from cigarette filters have been reported in prior studies [27,28].

2.1.2. *Cellulose fibre*

The traditional cellulose fibres were used as the reference and compared with the fibres obtained from waste E-CBs in this research. Table 3 shows the basic properties of the employed cellulose fibres.

2.2. *Bitumen*

A polymer-modified bitumen (PmB) containing Styrene-Butadiene-Styrene (SBS) was selected as the binder for producing asphalt mixtures incorporating fibres. The technical properties of the utilized PmB are provided in Table 4, in accordance with European standard protocols.

2.3. *Mix design*

In this study, a gap-graded mix design was used to produce the SMA mixtures. SMA, characterized by a high proportion of coarse aggregates and modified bitumen, exhibits exceptional performance such as rutting resistance, cracking resistance, and durability [21, 29]. Considering the pivotal role of the mastic in contributing to the cohesion properties of gap-graded mixes, a high-quality mineral filler, specifically the limestone filler, was selected to achieve better mastic properties [29]. Conforming to the technical specifications established in the District of Bologna, Italy [30], the grading distribution and the gradation band are shown in Fig. 5.

Following earlier research on the same mix design [21], the optimum bitumen content was ascertained to be 6% on the aggregates weight, with the filler content set at 10%. Consistent with prior investigations [21,22], the content of cellulose fibres in this research was selected as 0.3% on the weight of aggregates, while the ratio of each shredded E-CBs was set as 0.4%. Subsequent to determining the fibre content, five SMA mixtures incorporating the four waste fibers (with and without plastic constituents) and cellulose fibres were produced and compacted using the Gyratory Compactor.

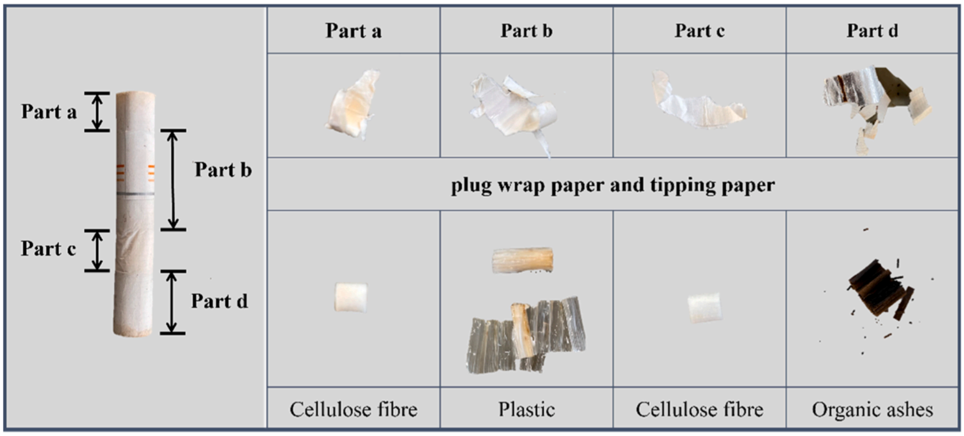

Fig. 1. Components of one E-CBs [22].

Table 1
Basic properties of the E-CBs.

Properties		Value
Colour of cellulose fibre in E-CBs		White or slightly yellowish
Dimension (mm)	Diameter of one E-CB	7.20
	Length of one E-CB	44.96
	Length of part a	7.15
	Length of part b	17.67
	Length of part c	7.97
	Length of part d	12.17
Fixed residue at 500 °C (%)		8.25
Moisture (%)		5.05

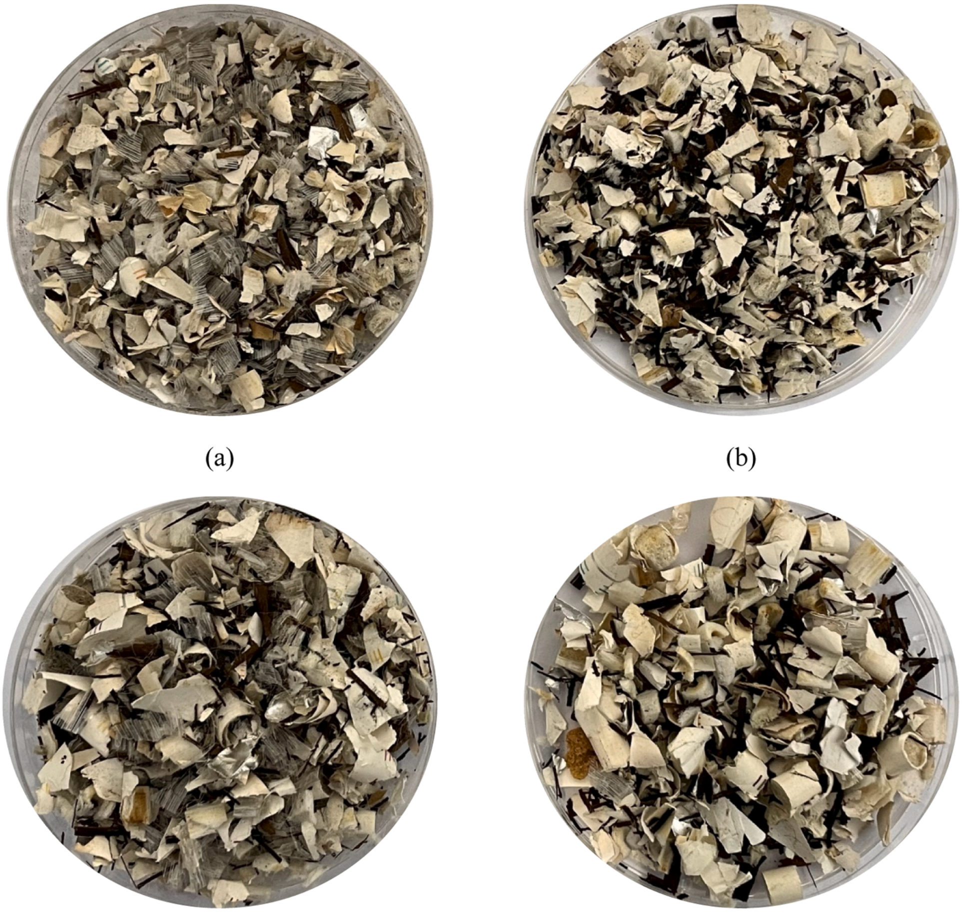
(a) (b) (c) (d)

Fig. 2. Four shredded E-CBs: (a) CBP-10; (b) CB-10; (c) CBP-15; (d) CB-15.

Table 2
Four shredded E-CBs working as fibre in this study.

Number	**Sample ID**	**Description**
1	CBP-10	shredded E-CBs below 10 mm, with plastic
2	CB-10	shredded E-CBs below 10 mm, without plastic
3	CBP-15	shredded E-CBs below 15 mm, with plastic
4	CB-15	shredded E-CBs below 15 mm, without plastic

Fig. 3. Shredded E-CBs after the 0.063 mm sieve.

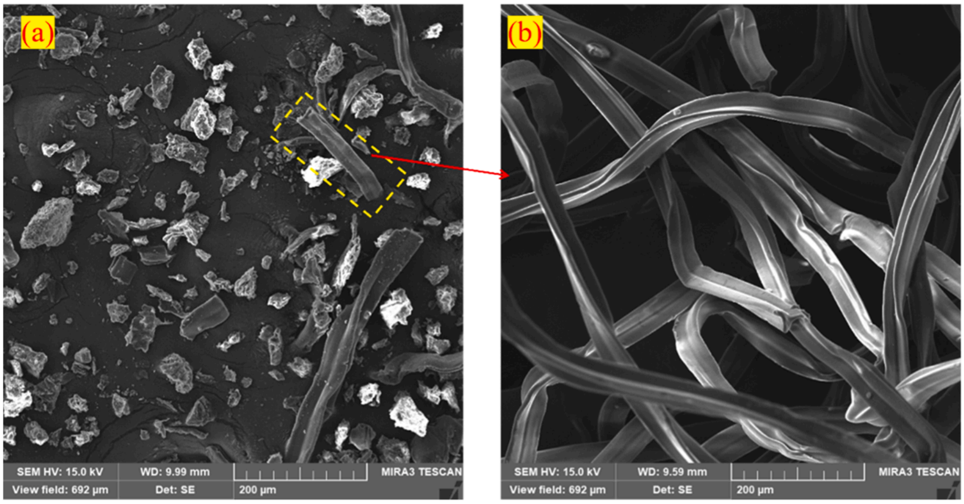

Fig. 4. SEM images of (a) shredded E-CBs below 0.063 mm and (b) cellulose fibres.

Table 3
Basic properties of the adopted cellulose fibres.

Properties	Value
Length of average fibres (μm)	200–1100
Diameter of average fibres (μm)	25–45
Melting point (°C)	>230
Water solubility (%)	0.450–0.500 kg/m^3

Table 4
Technical properties of the adopted cellulose fibres.

Property	Value	Standard
Penetration (dmm, @ 25 °C)	45–80	EN 1426
Softening Point (°C)	≥ 70	EN 1427
Dynamic viscosity (Pa·s, @ 160 °C)	< 0.8	EN 13702–1
Elastic recovery (%, @ 25 °C)	≥ 80	EN 13398
Storage stability-softening point (°C)	≤ 5	EN 13399

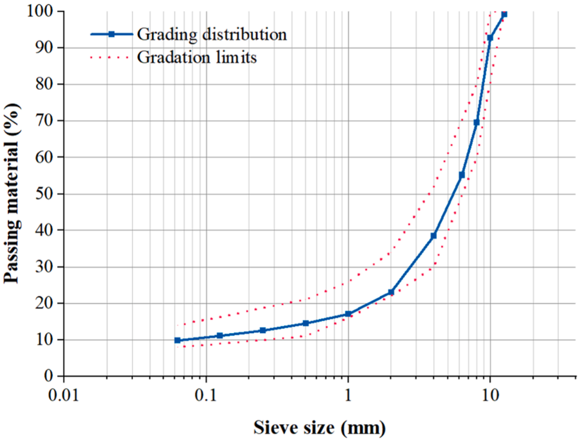

Fig. 5. SMA grading distribution and gradation band.

2.4. *Experimental methods*

2.4.1. *Drain-down property analysis*

Following the standard ASTM 6390–11, bitumen drain-down tests were carried out on the uncompacted mixtures with the use of four shredded E-CBs. These testing specimens maintained identical aggregate gradation and bitumen content as the samples prepared using the gyratory compactor. The mass of each uncompacted specimen in the wire basket was required to be 1200 ± 200 g. Through calculating the weight percentage of drained materials from the loose mixtures, the absorption properties of these waste fibres can be analyzed.

2.4.2. *Volumetric analysis*

The volumetric properties of the compacted SMA mixtures after 180 gyrations were analyzed. In accordance with standard EN 12697–8, data collected from the gyratory compactor comprising measurements of height and density at each gyration cycle, facilitated the computation of air voids (AV) content at the targeted gyration cycle (i.e., 10, 100, and 180 gyrations). The determination of the gyration cycle employed for compacting mixtures for subsequent mechanical testing was predicated on ensuring that the air void content fell within the prescribed limits required for SMA mixtures. By comparing their AV contents, the effect of using different fibres on the compactability of asphalt mixtures was investigated.

2.4.3. *Indirect tensile strength*

Indirect Tensile Strength (ITS) tests were conducted to assess the cohesion properties of cylindrical samples in accordance with the EN 12697–23 standard. Prior to testing, compacted specimens with a diameter of 100 mm were conditioned at 25 °C for four hours. Following the condition procedure, the specimen was placed in the compression testing device between the loading strips and subjected to the compressive loading diametrically with a constant rate of displacement of 50 ± 2 mm/min until it broke. Using the recorded peak load during the test, the ITS (MPa) results can be obtained according to the formula below:

$$ITS = \frac{2P}{\pi DH} \cdot 1000 \tag{1}$$

where P is the peak load (N), D is the specimen’s diameter (mm), and H is the height (mm). The ITS result of each SMA mixture was the average value of three replicates.

2.4.4. *Indirect tensile stiffness modulus*

In contrast to the static ITS test, Indirect Tensile Stiffness Modulus (ITSM) test serves as a method for dynamic characterization, offering a non-destructive assessment operating within the elastic domain of the material. Following the standard EN 12697–26 (Annex C), ITSM tests were carried out to determine the stiffness and thermal susceptibility of cylindrical specimens with a diameter of 100 mm at three different temperatures (10, 20, and 30 °C). The conditioning time for each temperature was four hours. Three specimens were tested for each SMA mixture.

2.4.5. *Indirect tensile strength ratio*

The Indirect Tensile Strength Ratio (ITSR) tests were performed to analyze the moisture susceptibility of asphalt mixtures. The ITSR result is determined as the ratio of the ITS on wet subsets (ITS_{wet}) to that of dry subsets (ITS_{dry}). The ITS_{dry} can be obtained from the ITS tests which were introduced in the previous section. To obtain the value of ITS_{wet}, the test was performed on specimens conditioned in a water bath at 40 °C for 72 hours and then in an air chamber at 25 °C for 4 hours.

2.4.6. *Rutting resistance*

The Hamburg Wheel Track (HWT) test was performed in this study to assess the rutting resistance and stripping susceptibility of asphalt mixtures. As described in AASHTO T 324–11, a pair of two gyratory compacted specimens, each measuring 150 mm in diameter and 60 ± 1 mm in thickness, were prepared for every mixture. Subsequently, these specimens were immersed in a water bath maintained at a temperature of 50 °C throughout the duration of the test. A load of 705 ± 4.5 N was applied to each specimen using a steel wheel with a diameter of 203.2 mm. During the loading process, the wheel should perform 52 ± 2 passes across the specimen per minute. The test was terminated after a 20 mm rut depth was reached or 20,000 passes were completed. The deformation on the sample surface is monitored and recorded continuously during the test.

The flowchart displayed in Fig. 6 shows the experimental program of this study.

3. Results and discussion

3.1. *Drain-down results*

Drain-down, an unignorable concern in SMA mixtures, manifests as the separation of bitumen or mastic from the mixture, particularly in asphalt mixtures with high bitumen content and operating under high temperatures. This concern results in the loss of bitumen content and significantly compromises the compactability properties and long-term durability of the resulting mixtures. In this study, the drain-down properties of the SMA mixtures with four different shredded E-CBs as stabilizing fibres were evaluated. Table 5 lists the drain-down results of the four SMA mixtures. The AASHTO T305 standard delineates an acceptable threshold for drain-down property, stipulating a value below 0.30%. As demonstrated in Table 5, and also verified by earlier studies conducted by the authors [21,22], the use of 0.4% shredded E-CBs met this criterion. Additionally, using shredded E-CBs with a smaller size led to a lower drain-down value. This result is different from prior studies [31,32], which demonstrated that increased drain-down was recorded for using fibres with a shorter length. The reason can be explained by other components in the shredded waste E-CBs, such as organic ashes or traces of paper that may have increased absorbing capacity. When using shredded E-CBs at the same size, the E-CBs without plastic exhibited a slight reduction in drain-down values compared to the original shredded E-CBs containing plastic. Moreover, upon introducing two shredded E-CBs (e.g., CBP-10 and CB-10) into SMA in equal proportions, the one lacking plastic had a slightly higher cellulose fibre content than the other. Consequently, this marginal reduction suggests that cellulose fibre may exert a more pronounced stabilizing effect compared to plastic constituents.

3.2. *Air void contents*

The AV contents of the five different SMA mixes at 10, 100, and 180 gyrations are listed in Table 6. Notably, comparable AV contents were observed for the first three SMA mixtures, suggesting equivalent compactability properties between the SMA mixtures incorporating CBP-10 or CB-10 and the reference SMA using cellulose fibres. When using 10 mm shredded E-CBs, the inclusion of plastic did not bring any significant change to the AV content. This observation can be related to the bitumen absorption properties assessed from drain-down tests; specifically, asphalt mixtures with CBP-10 and CB-10 exhibited similar drain-down values. When 15 mm shredded E-CBs were utilized to produce SMA specimens, lower AV contents were observed. It appears that the longer recycled fibres (i.e. CB-15 or CBP-15) functioned as lubricants within the final asphalt concrete, thereby contributing to the reduced AV content.

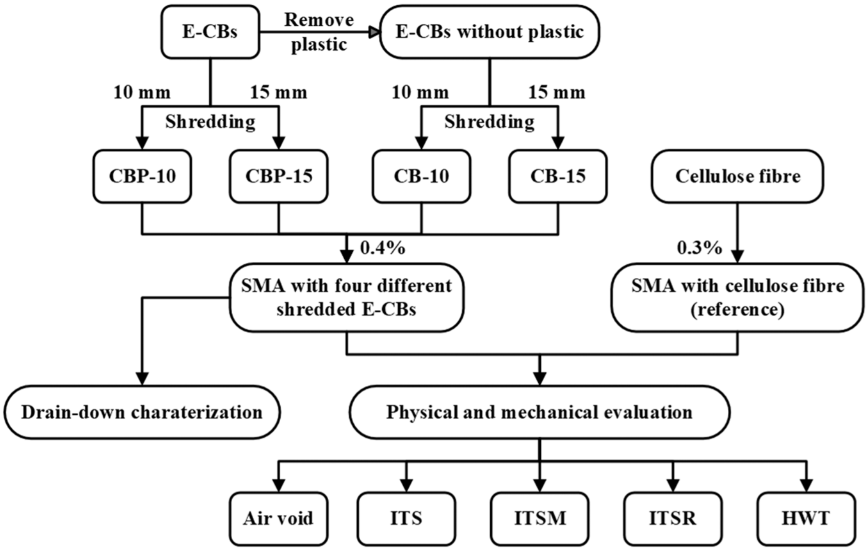

Fig. 6. Flowchart to illustrate the experimental design.

Table 5
Drain-down results of uncompacted specimens with different shredded E-CBs.

Type of shredded E-CBs	Drain-down (%)
CBP-10	0.14 (±0.01)
CB-10	0.12 (±0.01)
CBP-15	0.20 (±0.01)
CB-15	0.15 (±0.01)

Table 6
AV contents of SGC specimens at three different gyrations.

Specimens with different fibres	AV (%) at three different gyrations		
	10 gyrations	100 gyrations	180 gyrations
Cellulose fibre	13.4 (±0.6)	4.4 (±0.2)	3.2 (±0.3)
CBP-10	12.8 (±0.2)	4.4 (±0.2)	3.2 (±0.4)
CB-10	13.2 (±0.5)	4.0 (±0.4)	2.7 (±0.4)
CBP-15	11.8 (±0.5)	2.1 (±0.4)	0.7 (±0.6)
CB-15	12.5 (±0.4)	3.3 (±0.3)	1.9 (±0.3)

Additionally, SMA with CBP-15 exhibited a lower AV content than that using CB-15, suggesting that the inclusion of plastic may increase the lubrication. It is noteworthy that all results at 100 gyrations remained below the 5% threshold, aligning with the Italian specification requirements. Accordingly, a gyration of 100 cycles was selected for compacting mixtures intended for subsequent mechanical testing.

3.3. *ITS results*

The ITS results of the five SMA mixes are shown in Fig. 7. Notably, the SMA with cellulose fibres showed the highest ITS value (1.40 MPa), with no substantial difference observed when compared to the SMA incorporating 15 mm E-CBs. However, a reduction in ITS values was observed upon the incorporation of 10 mm E-CBs, particularly evident in the case of SMA with CBP-10, where the lowest ITS value (1.25 MPa) was recorded. It should be noted that the plastic constituents present in the shredded E-CBs possess a melting point of approximately 170 °C. While the melting of certain small plastic particles during mixing may enhance the bonding and cohesion between bitumen and aggregates [33], this improvement brought by plastic may not be as significant as that brought by the cellulose fibre component. The utilization of CB-10 in asphalt mixtures led to a higher inclusion of cellulose fibre compared to the use of CBP-10, consequently contributing to the higher tensile strength. Overall, each SMA mix exhibited an ITS value exceeding 0.90 MPa, in line with the prescribed threshold limit specified in the adopted technical specification.

3.4. *ITSM results*

The stiffness results of the five SMA mixes tested at three temperatures are presented in Fig. 8. It can be clearly seen that the SMA containing CB-15 showed the highest ITSM values. Conversely, the utilization of the other three shredded E-CBs resulted in lower stiffness modulus values compared to cellulose fibres. Among the three shredded E-CBs, the ITSM values of SMA containing CBP-15 had comparable results to the reference mixture. Furthermore, the comparison of two different sizes of shredded E-CBs revealed that using larger shredded E-CBs resulted in higher ITSM values at each test temperature, consistent with the ITS data indicating superior performance when 15 mm shredded E-CBs were employed. Moreover, the impact of plastic constituents was evident in the SMA utilizing 15 mm shredded E-CBs, resulting in a decrease in stiffness modulus at all test temperatures. However, the influence of plastic inclusion was less pronounced in the SMA incorporating 10 mm shredded E-CBs, with its effect varying depending on the test temperatures without exhibiting a discernible trend.

According to the ITSM data at different temperatures, the following equation can be used to describe the thermal susceptibility:

$$\log S = -\alpha \cdot T + \beta \tag{2}$$

where S represents the indirect tensile stiffness modulus (ITSM) at the testing temperature T, then α and β are experimental parameters referring to materials properties. β represents the intercept of the linear relationship between the logarithm of ITSM and temperature, i.e. the value of $\log S$ at 0 °C. The parameter α refers to the slope of the line, which can be used to assess the thermal sensitivity. The higher α value indicates that the tested material is more sensitive to temperature variations. The ITSM results vs temperature curve, along with their corresponding equations, are illustrated in Fig. 9. Notably, the CBP-10 SMA mixture exhibited the highest α value, indicating the highest thermal susceptibility. When utilizing the same size of shredded E-CBs, the incorporation of plastic led to increased thermal sensitivity in the final asphalt concrete, particularly evident with a shredding size reduction to 10 mm. Specifically, the parameter α exhibited a 30% increase when comparing the use of CBP-10 and CB-10, meaning that the addition of the smaller plastic particles made asphalt mixtures more thermo-sensitive. The influence of plastic presence and size at different temperatures on

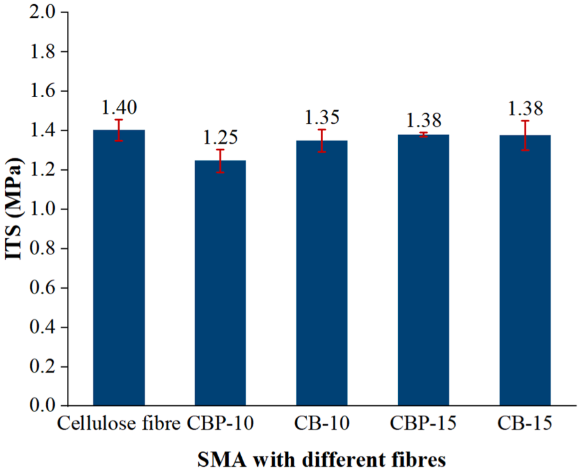

Fig. 7. ITS results of the five SMAs with different fibres.

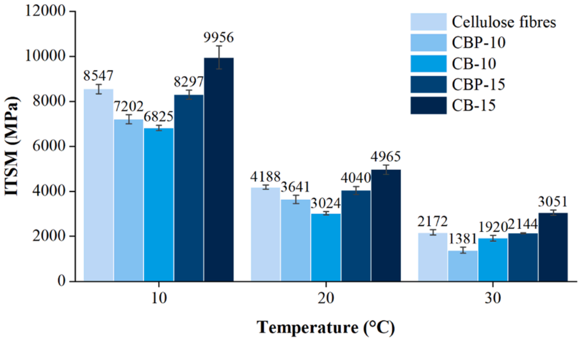

Fig. 8. ITSM results of the five SMAs with different fibres.

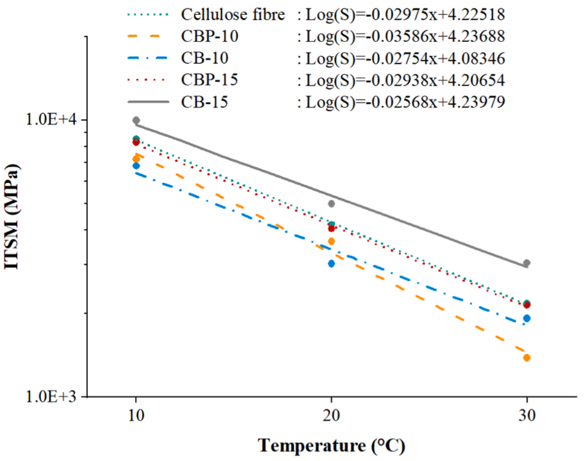

Fig. 9. ITSM results versus temperatures.

stiffness modulus requires further exploration. Overall, apart from the SMA specimen containing CB-10, all specimens met the Italian technical specification, requiring an ITSM value exceeding 3500 MPa at 20 °C.

3.5. ITSR results

One of the common issues in asphalt pavements is moisture damage, referring to the reduced adhesion and bonding properties between bitumen and aggregates caused by the presence of water. In this study, the moisture susceptibility of five SMA mixes was evaluated using ITSR tests. With the higher bitumen and filler content used in the SMA mix design, a thicker film was expected to be formed on the surface of aggregates, resulting in less moisture damage. The ITSR results of all tested specimens are reported in Fig. 10. Notably, all SMA mixes exhibited high ITSR values, surpassing the stipulated minimum threshold of 75% outlined in the technical standards. Compared to the reference mixture, a marginal decline in ITSR was observed solely in the specimen incorporating CB-10. The effect of incorporating plastic into the mixtures was less noticeable when using 15 mm shredded E-CBs, while the SMA with CBP-10 displayed a higher ITSR value than that with CB-10. This might be related to the lowest ITS_{dry} of SMA with CBP-10.

3.6. HWT results

Fig. 11 presents the rut depth results from the HWT tests. Notably, all mixtures were subjected to 20,000 passes during the tests, presenting rut depths below the failure threshold of 20 mm. Among the five SMA mixes, the reference incorporating cellulose fibres exhibited the highest rut depth (3.16 mm), indicating relatively lower rutting resistance compared to the mixtures using the shredded E-CBs. Remarkably, the SMA containing CBP-15 registered the lowest rut depth (1.88 mm), surpassing the reference by 1.28 mm. Additionally, it can be found that the use of larger size E-CBs or the inclusion of plastic contributes to the higher rutting resistance. Earlier studies have also reported the excellent high-temperature performance of asphalt mixtures modified with waste plastic materials [34–36]. Moreover, the asphalt mixes containing larger E-CBs exhibited higher stiffness modulus and rutting resistance compared to those with CB-10 and CBP-10, which may be ascribed to their lower thermal susceptibility. However, the plastic had different effects on the stiffness modulus under different test temperatures. Specifically, when using the 15 mm shredded E-CBs, the presence of plastic led to lower ITSM values but higher rutting performance. This may be related to the lubricant effect ascribed to the addition of plastic. In addition, no stripping inflection point was observed for all mixtures after the 20,000 passes, which implied that no SMA mixtures used in this study had significant moisture damage. This is in line with the high ITSR values stated in the previous section.

4. Conclusions

The present study evaluated the effect of incorporating four waste fibres obtained from shredded E-CBs into SMA mixtures. Through comprehensive physical and mechanical testing, the impact of different shredding sizes and the presence of plastic residues were investigated, thereby advancing strategies for recycling waste E-CBs in asphalt mixtures.

The following conclusions can be drawn from the testing outcomes:

- Drain-down tests conducted on the four shredded E-CBs revealed satisfactory results, with drain-down values below 0.2%. The smaller shredding size contributed to improved drain-down properties. Besides, the cellulose fibre component demonstrates superior stabilizing effects compared to the plastic residues.

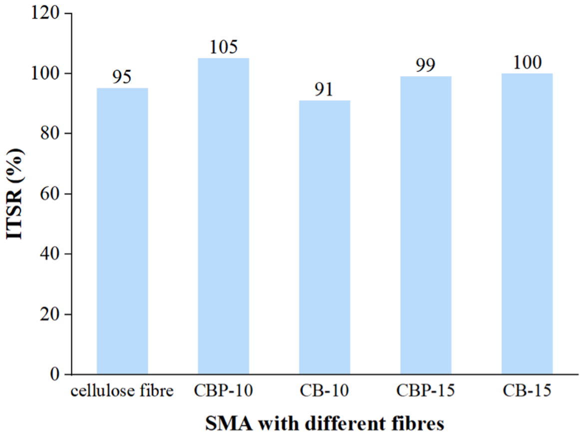

Fig. 10. ITSR results of the five SMAs with different fibres.

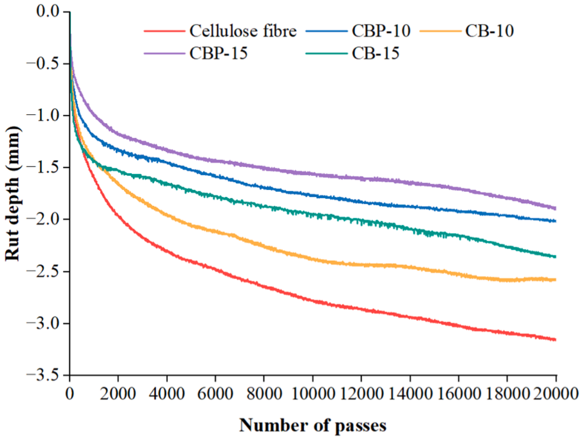

Fig. 11. Rut depth versus number of passes from HWT tests.

- All SMA mixtures exhibited favorable volumetric properties, as indicated by their air void contents. Employing larger shredded E-CBs resulted in decreased AV content. The inclusion of plastic resulted in decreased AV content when using 15 mm shredded E-CBs, while the volumetric change was not substantial when using 10 mm shredded E-CBs.
- In terms of mechanical properties, using the larger size of shredded E-CBs in SMA yields favorable outcomes, i.e., resulting in higher ITS and ITSM values, and lower rut depths. Especially, the utilization of CB-15 contributed to the highest ITS and ITSM values.
- The inclusion of plastic in SMA resulted in varied effects on the mechanical properties at different testing temperatures. Analysis of ITSM results revealed that asphalt mixtures with E-CBs containing plastic particles showed higher thermal susceptibility. This phenomenon is likely attributable to the melting of plastic particles during the incorporation of CBP-10 or CBP-15 into SMA mixtures. However, the presence of plastic contributed to enhanced rutting resistance in the final SMA mixture and this effect is more pronounced than their thermal susceptibility.

Overall, the use of recycled cigarette butts in SMA not only offers a sustainable waste management solution but also introduces innovative materials that can enhance the properties of asphalt pavement. When using recycled cigarette butts to replace typical cellulose fibres in Hot Mix Asphalt (HMA), especially in SMA mixtures, the use of 15 mm shredded waste E-CBs without plastic is the optimal choice for delivering mechanical reinforcement. The impact of plastic residue, taking into account their sizes and temperatures, should be further investigated. It is also worthwhile to explore the reinforcing mechanism of shredded E-CBs in asphalt mixtures through micro characterization techniques. Furthermore, the resistance to fatigue and low-temperature cracking will be tested in the next step, as a comprehensive assessment of the effects of employing waste E-CBs in SMA mixtures is pivotal for their prospective field application.

CRediT authorship contribution statement

Giulia Tarsi: Writing – review & editing, Validation, Conceptualization. **Piergiorgio Tataranni:** Writing – review & editing, Validation, Supervision, Conceptualization. **Cesare Sangiorgi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Conceptualization. **Yunfei Guo:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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