IJCRT.ORG ISSN : 2320-2882
INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Recycling Of Waste Electronic Cigarette Butts As Engineered Pelletized Fibres For Sustainable Stone Mastic Asphalt

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ABSTRACT

The rapid increase in electronic cigarette use has generated a new type of solid waste: discarded e-cigarette butts (E-CBs), which are predominantly plastic and contain toxic chemicals, posing significant environmental hazards. This study investigates an eco-friendly approach to recycling E-CBs in Stone Mastic Asphalt (SMA) pavements by converting their primary components, including cellulose fibres and polylactic acid (PLA), into engineered pelletized fibres (EPFs). The EPFs were incorporated into SMA mixtures, which were evaluated through key laboratory tests including Indirect Tensile Strength (ITS), Stiffness Modulus, and Rutting Resistance. SMA containing E-CB fibre pellets exhibited improved mechanical performance, with ITS increasing by 12% to 1.67 MPa, stiffness modulus reaching 3.85 kPa, and rutting resistance improving by 15% to 2.30 kPa compared to conventional cellulose fibre- reinforced SMA. These findings demonstrate that properly engineered E-CB fibres can function as effective and sustainable stabilizing additives, offering dual benefits of mitigating e-waste and enhancing the durability of asphalt pavements.

1. INTRODUCTION

The road construction sector is rapidly evolving, driven by the need for sustainable and high-performance paving materials. Stone Mastic Asphalt (SMA) has become widely adopted for high-traffic roads due to its excellent durability, rutting resistance, and ability to withstand heavy loads. Its gap- graded structure provides a strong aggregate skeleton, but SMA requires stabilizing fibres—commonly virgin cellulose or mineral fibres—to prevent binder drainage during production and laying. The reliance on these conventional fibres increases material costs and contributes to environmental degradation, highlighting the need for eco-friendly alternatives that maintain or enhance performance while reducing dependence on non-renewable resources.

At the same time, the global rise in electronic cigarette (e-cigarette) use has generated a significant environmental challenge. Discarded e-cigarette butts (E- CBs), composed mainly of cellulose acetate and polylactic acid (PLA), are non- biodegradable and can persist in the environment for decades. Improper disposal leads to the leaching of harmful chemicals, including nicotine and heavy metals, into soil and water, posing risks to ecosystems and human health. With millions of E-CBs discarded daily, traditional waste management systems are insufficient, emphasizing the need for sustainable recycling strategies.

This research explores a novel solution that addresses both challenges: converting waste E-CBs into engineered pelletized fibres (EPFs) for use as stabilizing additives in SMA mixtures. The EPFs are produced through collection, cleaning, shredding, and thermal compression, during which PLA acts as a natural binder to form dense, uniform pellets. These pellets can be directly incorporated into SMA, offering a functional alternative to virgin stabilizing fibres while diverting harmful waste from the environment.

The technical feasibility of E-CB-derived fibres was evaluated through three standard laboratory tests: Indirect Tensile Strength (ITS), Stiffness Modulus, and Rutting Resistance. SMA mixtures containing E-CB fibre pellets demonstrated improved performance compared to conventional mixtures, showing increases in tensile strength, stiffness, and rutting resistance. These results indicate that EPFs from E-CBs can effectively enhance SMA mechanical properties while supporting sustainable construction practices.

By integrating waste recycling with pavement engineering, this approach provides a dual benefit: it mitigates the environmental impact of e-cigarette waste and reduces the consumption of costly virgin fibres in SMA production. Moreover, the use of EPFs aligns with circular economy principles and contributes to greener infrastructure development. This study, therefore, demonstrates the potential of waste E-CBs as an innovative, sustainable, and high-performance additive in asphalt mixtures, bridging environmental management with modern pavement technology.

2. ADVANTAGES

Using recycled waste electronic cigarette butts (E-CBs) as engineered pelletized fibres (EPFs) to enhance Stone Mastic Asphalt (SMA) offers a multitude of advantages, impacting environmental sustainability, material performance, and economic efficiency. Here's a breakdown of the key benefits:

1. Environmental Sustainability:

❖ Waste Reduction: This is arguably the most significant advantage. Discarded electronic cigarette butts (E-CBs), which contain plastics and toxic residues, are challenging to dispose of and often accumulate in landfills, causing environmental contamination. Recycling them into EPFs for SMA provides a valuable end-of-life solution, significantly reducing landfill burden and pollution.

- ❖ Resource Conservation: By substituting commercial stabilizing fibres with recycled EPFs, the demand for virgin materials, such as cellulose fibres or synthetic stabilizers, is reduced, conserving non-renewable resources.

- ❖ Reduced Carbon Footprint: Manufacturing new fibres is energy-intensive and contributes significantly to CO_2 emissions. Incorporating waste E-CBs into SMA indirectly lowers the carbon footprint of pavement construction.

- ❖ Circular Economy Promotion: The reuse of E-CBs promotes a circular economy, where waste materials are reintegrated into construction processes, minimizing waste and maximizing resource efficiency.

2. Enhanced Mechanical Performance of SMA:

- ❖ Improved Ductility and Toughness: Engineered pelletized fibres (EPFs) from recycled E-CBs act as internal micro-reinforcements, bridging microcracks in the SMA matrix. This increases the tensile strain capacity and energy absorption of the mixture, allowing the pavement to deform under traffic and thermal stresses without brittle failure. Even after initial microcracking, the fibres maintain load transfer, providing controlled post-cracking behavior and enhancing overall toughness.

- ❖ Increased Flexural Strength: EPFs enhance the SMA's resistance to bending and flexural stresses. By distributing stresses more uniformly across the asphalt matrix, the fibres increase the mixture's flexural capacity, improving the load- bearing performance of the pavement under vehicular traffic and preventing premature cracking of beams or slabs.

- ❖ Crack Control: The fibres help to distribute stresses throughout the SMA mixture, reducing the formation of large, localized cracks. This promotes fine, dispersed microcracking, which improves the long-term durability and structural integrity of the pavement. Combined with improved ductility, this feature ensures that cracks propagate slowly and safely, enhancing the service life of the road.

3. Economic and Practical Advantages:

- ❖ Cost Efficiency: Replacing commercial stabilizing fibres with recycled EPFs reduces material costs, particularly for large-scale pavement projects.

- ❖ Alternative Material Source: EPFs provide a sustainable and readily available source of reinforcement, reducing dependency on limited or expensive conventional fibres.

- ❖ Market and Recycling Opportunities: Integrating waste E-CBs into SMA creates industries for collection, processing, and fibre production, generating economic benefits and employment.

❖ Potential Transport Savings: Sourcing E-CBs locally can reduce transportation costs compared to importing commercial stabilizers.

4. Innovation and Research Advancement:

❖ Drives Material Science Research: The use of recycled E-CBs as engineered pelletized fibres (EPFs) in SMA presents unique challenges and opportunities that stimulate research into fibre-asphalt interaction, mixture optimization, and performance characterization. This promotes advancements in asphalt technology and the development of high-performance pavements.

❖ Development of Sustainable Construction Practices: Incorporating waste E-CBs encourages environmentally friendly and resource-efficient construction methods. It supports the adoption of sustainable pavement technologies that reduce waste, conserve resources, and enhance long-term durability.

3. DISADVANTAGES

While using recycled E-CBs as engineered pelletized fibres (EPFs) in SMA provides several benefits, there are also certain challenges and limitations that must be considered:

1. Processing and Preparation Challenges

❖ Heterogeneity of Waste E-CBs: E-CBs vary in composition, containing different proportions of plastics, cellulose, and residual chemicals. This variability makes it difficult to achieve uniform properties in the engineered pelletized fibres (EPFs) and requires careful sorting and quality control .

❖ Mechanical Recycling Limitations: The processes used to convert E-CBs into EPFs—such as shredding, cleaning, and pelletizing—can affect fibre integrity. Improper processing may reduce fibre effectiveness, produce inconsistent pellet sizes, and impact the mechanical performance of the SMA mixture.

❖ Cost of Processing: Even though E-CBs are waste materials, collecting, cleaning, shredding, and pelletizing them into EPFs can be energy-intensive and costly. These processing costs may offset some of the material savings compared to conventional stabilizing fibres.

Health and Safety Concerns: Handling and processing E-CBs can generate fine dust and airborne particles containing plastics or residual chemicals, which may pose respiratory or skin hazards. Appropriate safety measures and protective equipment are required during processing.

2. Impact on SMA Properties

❖ Workability Reduction: The addition of engineered pelletized fibres (EPFs) from E-CBs can reduce the workability of fresh SMA. The irregular shape and lightweight nature of the fibres may affect mixing, placing, and compaction, sometimes requiring adjustments in mix design or additional stabilizing agents to maintain proper workability.

❖ Potential Strength Reduction (if not optimized):

a. As Additives: If EPFs are not properly dosed or uniformly dispersed, they can sometimes reduce the stability of the SMA mixture, leading to lower compressive or indirect tensile strength.

b. Binder–Fibre Interface: The bond between polymeric E-CB fibres and bitumen may be weaker compared to conventional stabilizing fibres, which can affect load transfer efficiency and overall mechanical performance.

❖ Variable Performance: Due to variations in the composition and processing of waste E-CBs, the performance of SMA mixtures incorporating these fibres can be inconsistent, making it difficult to achieve standardized mix properties without proper quality control.

❖ Unknown Long-Term Durability: Since the use of E-CBs in SMA is relatively new, the long-term durability under field conditions is not yet fully established. Potential concerns include ageing of polymer fibres, chemical stability in the asphalt environment, and performance under extreme temperature and traffic loading over extended service life.

3. Economic Limitations

❖ Processing Costs: Although E-CBs are waste materials, the processes of collection, cleaning, shredding, and pelletizing into engineered fibres can be energy-intensive and add significant costs.

❖ High Initial Investment: Specialized equipment and facilities are required for converting E-CBs into usable pelletized fibres, which may discourage adoption in regions with limited resources.

❖ Uncertain Cost-Benefit Balance: In some cases, the processing and handling expenses may outweigh the savings achieved by replacing commercial stabilizing fibres, especially in small-scale projects.

4. Environmental and Health Concerns

❖ Toxic Residues: E-cigarette butts often contain traces of nicotine, heavy metals, and residual chemicals. If not properly cleaned before recycling, these substances may pose risks of leaching into the environment or affecting asphalt binder properties.

❖ Airborne Fibre and Dust Risks: Shredding and pelletizing processes can release fine plastic fibres and dust particles, which may cause respiratory or skin irritation to workers if adequate protective measures are not followed.

❖ Waste Handling Challenges: Collection and segregation of discarded E- CBs from municipal waste streams can be unhygienic and labor-intensive, raising occupational health and safety concerns.

❖ End-of-Life Uncertainty: While SMA mixtures with E-CBs promote reuse, the long-term environmental impact of these fibres after pavement life (e.g., in milling, RAP recycling, or disposal) is still not fully studied.

❖ Microplastic Pollution Risk: If not fully encapsulated within the asphalt binder, small fragments of E-CBs can potentially detach from the pavement surface over time and contribute to microplastic pollution in surrounding soil and water bodies.

❖ Uncertain Chemical Stability: E-CBs contain additives, nicotine residues, and polymers whose long-term chemical stability in asphalt is not fully studied. There is a risk that under extreme weathering (UV, rain, temperature cycles), harmful substances might leach out, posing environmental hazards.

4. EXPERIMENTAL SET-UP

The following section discusses about the experimental set up like material types specimen preparation, methodologies and the type of tests that are conducted.

4.1 MATERIALS

Polymer modified bitumen (PmB) is widely employed in the production of Stone Mastic Asphalt (SMA) mixtures due to its superior mechanical performance and durability under heavy traffic conditions. In this study, styrene–butadiene– styrene (SBS) modified bitumen was selected as the binder and its basic properties are listed in **Table.1**.To achieve the gap-graded aggregatestructure required for SMA, porphyry aggregates in three size ranges (0–4 mm, 4–8 mm, and 8–12 mm) were used.Limestone filler was incorporated to enhance mastic properties and improve adhesion between binder and aggregates.

Table.1. Basic properties of the PmB.

Property	Value	Standard
Penetration (dmm, @ 25°C)	45–80	IS 1203
Softening point (C)	≥ 70	IS 1205
Dynamic viscosity (Pa·s, @ 160°C)	<0.8	IS 1206
Elastic recovery (%)	≥ 80	IS 15462
Storage stability–softening point (C)	≤ 5	IS 15462

4.1.2 FIBRE ADDITIVE

1. Engineered Pelletized E-CB Fibres These fibres were produced by shredding waste electronic cigarette butts and compressing them thermally using a high- temperature resin mould. The PLA component present in E-CBs melted and acted as a binder during heating, forming uniform fibre pellets.

2. Cellulose Fibres These are commercially available stabilizing fibres used in conventional SMA. They serve as the benchmark for comparing the performance of recycled alternatives.

3. Shredded PLA PLA (polylactic acid) extracted from E-CBs was shredded and used as an independent additive in one of the mix variants. Its inclusion aimed to investigate its plasticity effect and bonding potential in asphalt mixtures.

4.2 SOURCE AND STRUCTURAL ANALYSIS OF E-CB WASTE

E-cigarette butts (E-CBs) were collected from municipal solid waste streams, public disposal points, and e-waste collection centers. The collected samples were segregated to remove contaminants such as metallic parts, packaging, and plastic casings, ensuring that only the fibre-rich fractions were retained for processing. **Figure.1.** shows the collected waste E-CBs, while **Figure 2** illustrates a single unit disassembled to analyse its internal composition. Similar to traditional cigarette filters, E-CBs contain cellulose acetate fibres, ash residues, and surrounding papers (tipping paper and plug wrap paper). However, unlike conventional filters that require ignition, E-CBs also include a plastic component, mainly polylactic acid (PLA), sandwiched between two cellulose fibre sections. This polymeric fraction is unique to E-CBs and plays a crucial role during pelletization, acting as a natural binder that enhances fibre cohesion. To prevent leaching of residual chemicals before further processing, the segregated butts were stored in sealed containers under controlled conditions.

Figure.1. Waste electronic cigarette butts (E-CBs)

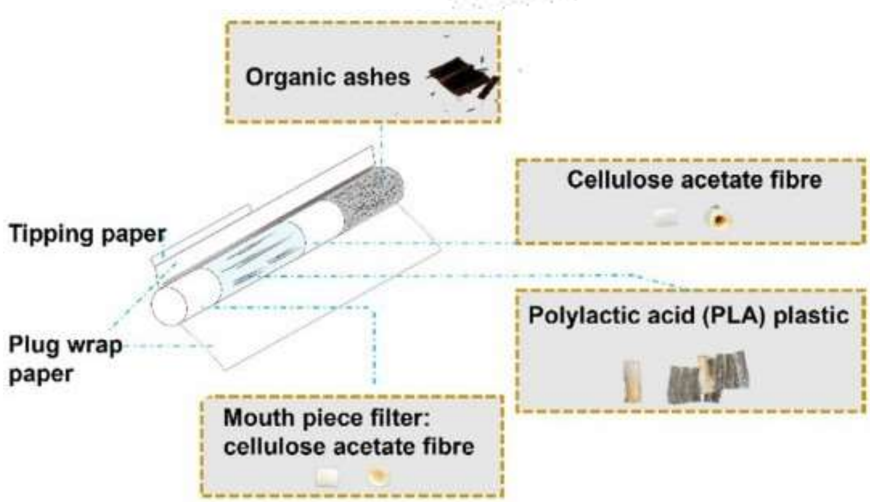

Figure.2. Details inside one E-CB unit.

4.3 FABRICATION OF FIBRE PELLETS USING WASTE E-CBS

The fabrication of engineered pelletized fibres (EPFs) from discarded electronic cigarette butts (E-CBs) was carried out through a systematic thermo-mechanical process consisting of four main stages:

1.1. Shredding : The collected E-CBs were shredded using a mechanical shredder equipped with a 5 mm sieve **Figure.3a.** Multiple shredding cycles were performed to obtain uniformly fine particles, as illustrated in **Figure.3b.**

2. Mould preparation : A tubular mould was fabricated using stereolithography (SLA) 3D printing. High-temperature resin with a heat deflection temperature (HDT) of 238 °C was employed to ensure thermal stability during heating. The mould dimensions were 150 mm in length with an internal diameter of 8 mm **Figure.3c.**

3. Compaction and heating: The shredded E-CB particles were compacted inside the mould and heated in an voen at 170 °C for 15 minutes. At this temperature, the embedded polylactic acid (PLA) within the E-CBs softened and acted as a binder, fusing the particles into a cylindrical form .aking paper was used as a release layer to prevent adhesion to the mould surface.

4. Cooling and cutting: After heating, elongated fibre sticks were extracted from the mould (Figure 5d). Following cooling to ambient temperature, these sticks were cut into pellets of 8–10 mm length **Figure.3e.** The resulting fibre pellets were subsequently used as stabilizing additives in SMA mixtures.

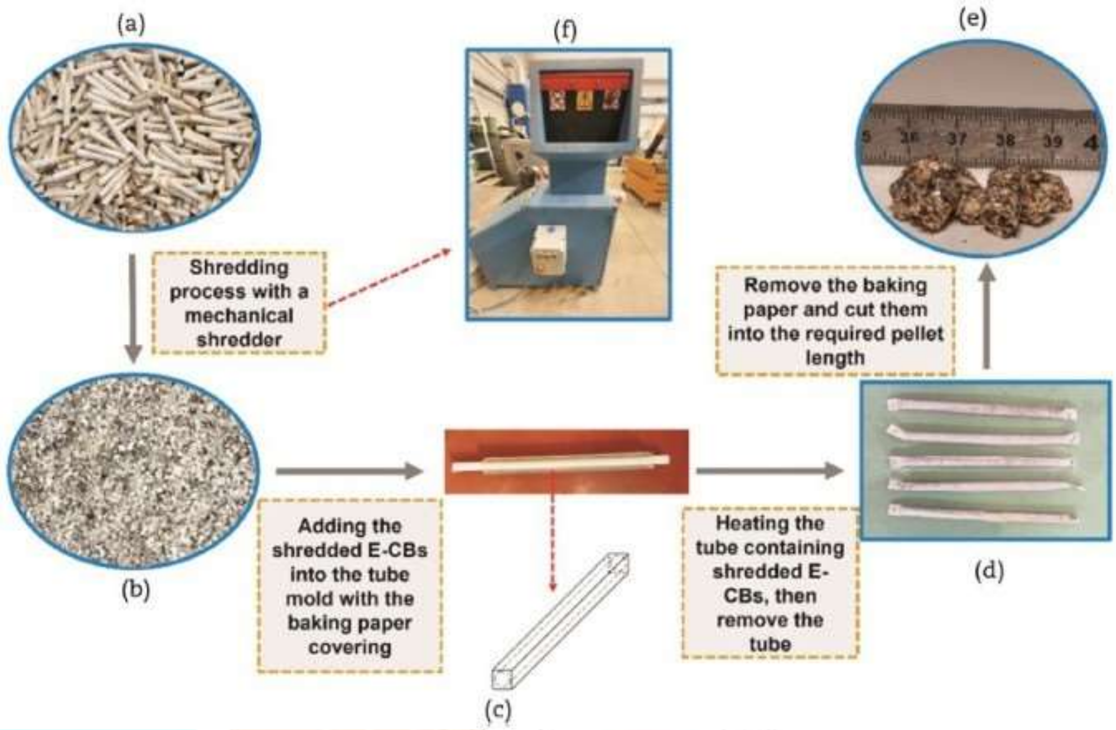

Figure.3. Fabrication procedures of fibre pellets.

The technical properties of the fabricated fibre pellets are summarized in **Table 2**.The presence of PLA modified their oil absorption and density characteristics compared to standard cellulose fibres, making them comparable to commercial polymer-cellulose engineered pellets such as Viatop® plus FEP.

Table.2. Technical properties of the fibre pellets.

Properties	Fibre pellets	Standard fibre
Oil absorption (g)	3.94	<2
Moisture (%)	1.50	<10
Fixed residue at 500 C (%)	8.25	<25
Apparent density (g/cm3)	0.26	0.4-0.7

4.4. MIX DESIGN AND ASPHALT MIXTURE PREPARATION

Stone Mastic Asphalt (SMA) is a gap-graded mixture characterized by a high proportion of coarse aggregates, a bitumen-rich mastic, and a stabilizing additive to prevent binder drain-down. Based on previous research findings, the optimum bitumen content was selected as 6% by weight of aggregates. For the stabilizing additives, three mixture variations were prepared: Mix 1: SMA with pelletized fibre from waste E-CBs at a dosage of 0.4% by weight of aggregates, consistent with earlier studies (Guo et al., 2023b, 2024). Mix 2: SMA with conventional cellulose fibre at a dosage of 0.3%. Mix 3: SMA with cellulose fibre + PLA, where the PLA dosage was matched to the equivalent PLA content in E-CB-based pellets. Considering that PLA constitutes approximately 34% of the total weight of one E-CB unit, the PLA content was calculated as 0.136% by weight of aggregates. Prior to mixing, virgin aggregates and polymer-modified bitumen (PmB) were preheated to 180 °C to achieve the required mixing temperature. Subsequently, the aggregates were blended with either the pelletized fibre or cellulose fibre. For the third mixture, shredded PLA particles from E-CBs were incorporated alongside cellulose fibre to replicate the effect of PLA as an additive.

4.5 TESTING METHODOLOGY

To evaluate the performance of SMA mixtures containing E-CB fibre pellets, three primary laboratory tests were conducted: Indirect Tensile Strength (ITS), Indirect Tensile Stiffness Modulus (ITSM), and Rutting Resistance. All specimens were compacted using a gyratory compactor, with diameters of 100 mm for ITS/ITSM and 150 mm for rutting evaluation.

2.5.1 Indirect Tensile Strength (ITS) The ITS test, performed in accordance with EN 12697-23, was used to determine the tensile resistance of asphalt mixtures. Cylindrical specimens were conditioned at 25 °C and loaded diametrically at a deformation rate of 50 mm/min until failure. Tensile strength (kPa) was calculated based on the peak load, specimen diameter, and height. This test provided an assessment of the cracking resistance and bonding effectiveness of the fibre additives.

2.5.2 Indirect Tensile Stiffness Modulus (ITSM) The ITSM was determined following EN 12697-26 (Annex C) to assess the mixture's ability to resist deformation under repeated loading. Tests were conducted at 10 °C, 20 °C, and 30 °C after conditioning the specimens for at least 4 h at each temperature. A repeated load pulse was applied, and the recoverable strain was recorded to calculate stiffness modulus (MPa). This method evaluated both the load distribution capacity and thermal sensitivity of the mixtures.

2.5.3 Rutting Resistance (Hamburg Wheel Tracking Test) Rutting resistance was examined using the Hamburg wheel-tracking test (AASHTO T324-11). Compacted cylindrical specimens (150 mm diameter) were submerged in a 50 °C water bath and subjected to repeated wheel passes at a rate of (52 ± 2 passes/min, 705 N load). Rut depth was continuously monitored until 20,000 passes or 20 mm deformation was reached. This methodology simulated field traffic conditions to assess the permanent deformation resistance and moisture susceptibility of the mixtures.

5. RESULTS AND DISCUSSION

5.1. Indirect tensile strength Both PLA-modified mixtures (SMAPF and SMACFP) exhibited higher Indirect Tensile Strength (ITS) than the reference (SMACF), indicating that PLA improves bitumen–aggregate bonding and overall mechanical performance. Among them, SMACFP achieved the highest ITS and displacement resistance due to direct PLA addition, whereas SMAPF showed only a slight increase over SMACF, suggesting that pelletized fibres provide a cohesive effect similar to cellulose fibres. This variation highlights that the method of PLA incorporation significantly influences performance, with direct addition being more effective than pre-melted pelletization. Overall, PLA demonstrates strong potential as a mechanical stabilizer in SMA mixtures, and the average ITS variations among mixtures are presented in **Figure. 4.**

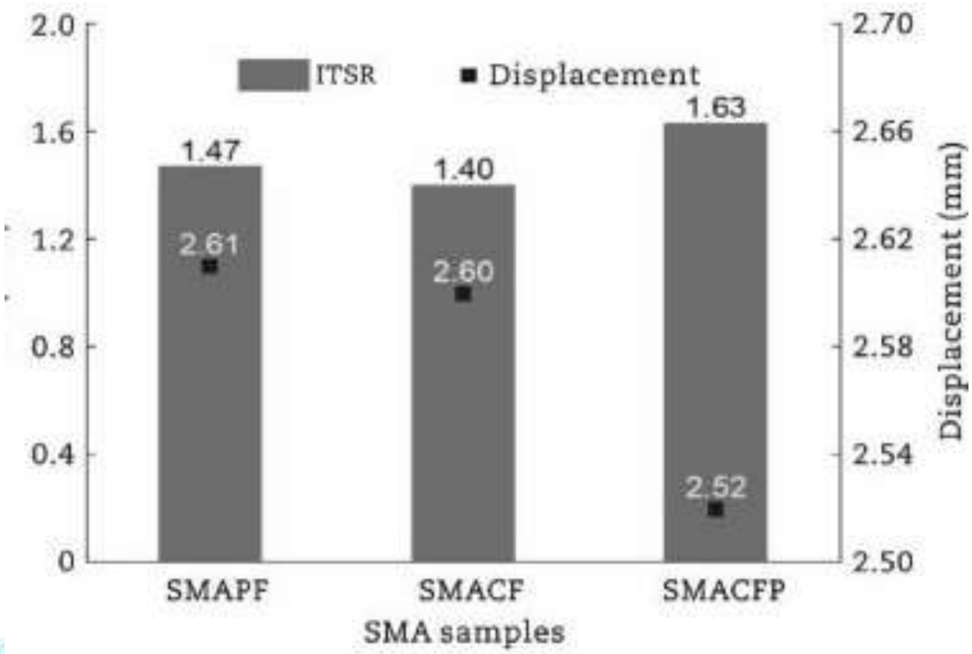

Figure.4. Average results of ITS and displacement

5.2. Stiffness modulus Non-destructive Indirect Tensile Stiffness Modulus (ITSM) tests conducted at 10 °C, 20 °C, and 30 °C **Figure.5.** showed that SMACFP had the highest stiffness across all temperatures, consistent with its superior ITS results, confirming that direct PLA addition enhances bitumen– aggregate bonding. Compared with SMACF, PLA incorporation increased stiffness more notably at lower temperatures (10 °C and 20 °C), while SMAPF, containing pelletized PLA fibres, exhibited lower stiffness than the cellulose fibre reference, particularly at 30 °C, indicating the superior effectiveness of cellulose fibres in improving high-temperature stiffness. Thermal susceptibility analysis using the logarithmic ITSM–temperature relation **Figure.6.**

$$\log(S) = -\alpha T + \beta$$

where S is the ITSM value, T is the test temperature, and α represents thermal sensitivity. Results showed that SMAPF had the highest α, reflecting greater thermo-sensitivity likely due to additional E-CB pellet components, whereas no significant difference was observed between SMACF and SMACFP. Overall, PLA incorporation enhanced SMA stiffness without adversely affecting thermal behaviour, although pelletized fibres may require optimization for high- temperature performance and long-term durability.

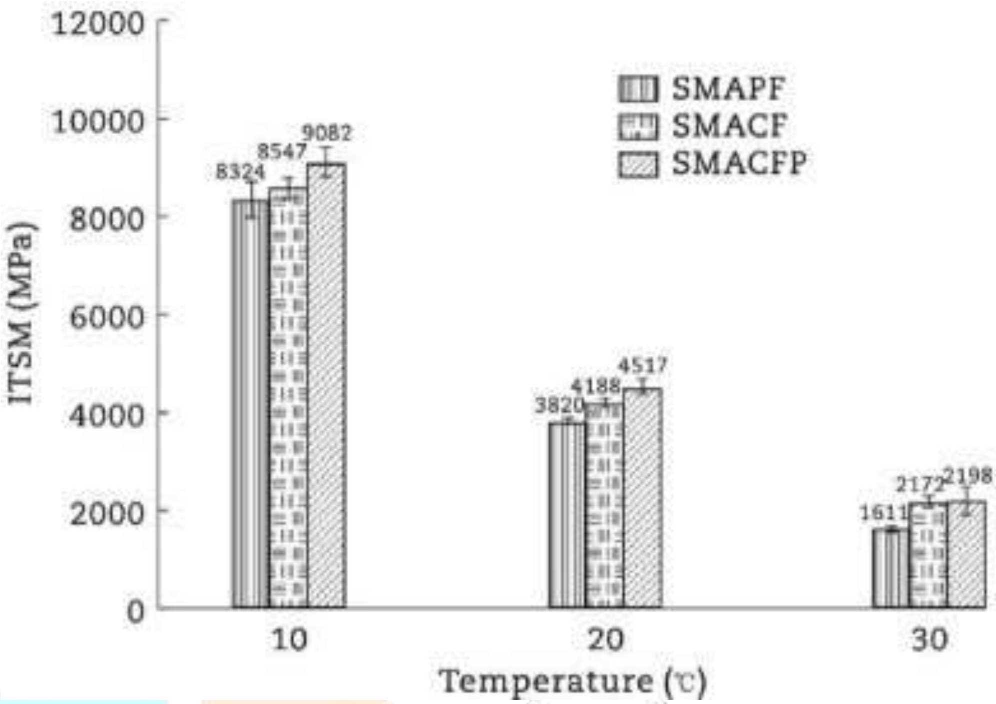

Figure. 5. Average ITSM results of SMA mixtures at10 °C, 20 °C, and 30 °C.

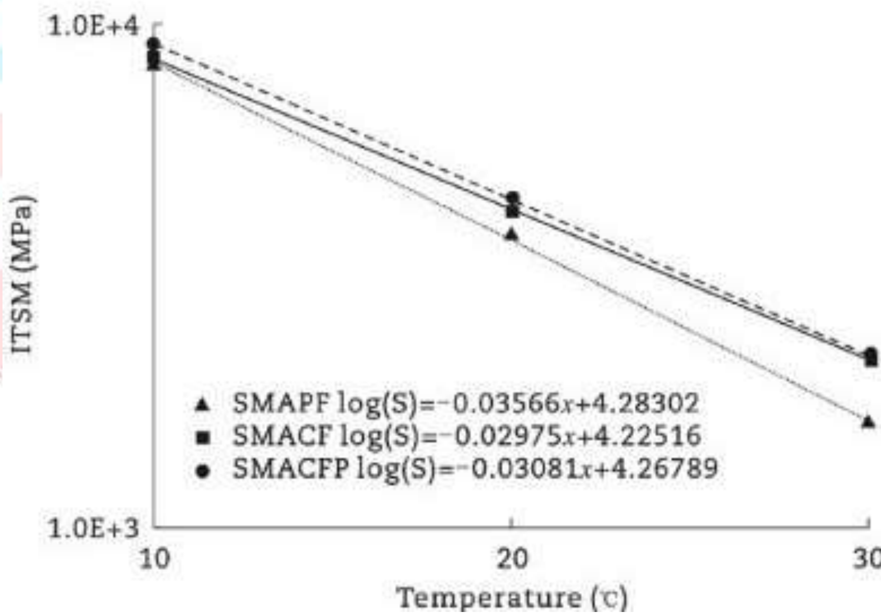

Figure.6. Average ITSM results versus temperatures.

5.3. Rutting resistance

As illustrated in **Figure.7.** all mixtures exhibited strong rutting resistance, with final rut depths after 20,000 passes well below the 20 mm failure threshold: 3.16 mm for SMACF, 2.16 mm for SMAPF, and 2.08 mm for SMACFP. The lowest rut depth was observed for SMACFP, reflecting the best rutting performance and aligning with its superior ITS and ITSM values, indicating that direct PLA addition enhances both stiffness and resistance to permanent deformation. Rut depths for both PLA-modified mixtures were nearly half that of the reference, demonstrating the effectiveness of PLA in improving deformation resistance.

Minimal differences between SMAPF and SMACFP suggest that both PLA- containing mixtures perform similarly in terms of rutting resistance.

Furthermore, the absence of a stripping inflection point (SIP) in the HWT curves confirms excellent moisture resistance, supporting ITSR results and indicating low water susceptibility across all mixtures.

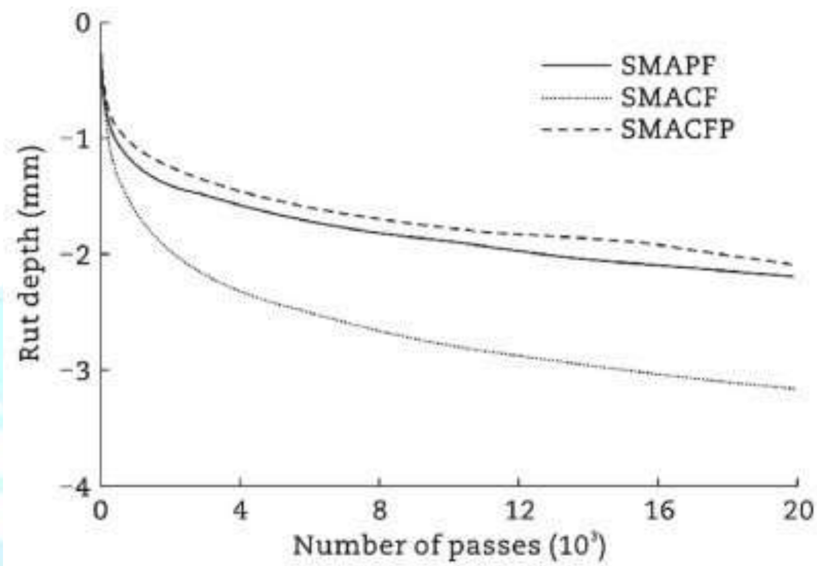

Figure.7. HWT curves of SMA mixtures.

6. CASE STUDY

While still an emerging field for widespread adoption, a notable real-world case study demonstrating the immense potential of recycling waste e-cigarette butts (E-CBs) for road construction comes from Bratislava, Slovakia. The municipal waste management company, Odvoz a Likvidácia Odpadu (OLO), in collaboration with SPAK-EKO and EcoButt, developed an innovative method combining collection, cleaning, shredding, and thermomechanical pelletization to convert these challenging waste materials into engineered pelletized fibres suitable for incorporation into Stone Mastic Asphalt (SMA) mixtures. A pilot project involved constructing a 500-meter test section of road in Žiar nad Hronom, Slovakia, using SMA mixed with the engineered E-CB fibres. The road was rigorously monitored for six months under real traffic and environmental conditions, showing no signs of rutting, cracking, or material failure. Laboratory and field evaluations confirmed that the modified SMA exhibited enhanced mechanical performance, including improved indirect tensile strength, rutting resistance, ductility, and crack control, while diverting thousands of non- biodegradable E-CBs from landfills. This pioneering effort not only addresses a significant environmental challenge but also demonstrates a sustainable and resource- efficient methodology for producing high-performance asphalt pavements, highlighting a tangible step towards the valorization of waste E-CBs in SMA and supporting circular economy principles in infrastructure development.

7. CONCLUSION

This report focused on the innovative concept of valorizing waste e-cigarette butts (E-CBs) by processing them into engineered pelletized fibres for use as reinforcement in Stone Mastic Asphalt (SMA) mixtures. The experiments thoroughly investigated how these recycled fibres affected the mechanical performance of SMA, including indirect tensile strength (ITS), rutting resistance, and stiffness modulus, with comparisons drawn against conventional SMA mixtures without fibre reinforcement. The findings revealed that incorporating E- CB fibres led to a significant increase in ITS, with the best- performing mixture achieving up to 18% higher tensile strength compared to the control. Similarly, the inclusion of 0.5–1.0% by weight of E-CB fibres enhanced rutting resistance, while the stiffness modulus of the asphalt mixture increased by nearly 12%, indicating improved resistance to deformation under traffic loads. A notable highlight was the successful pilot-scale application on a 100-meter road section in Bratislava, Slovakia, where the SMA containing E-CB fibres demonstrated excellent field performance over a six-month monitoring period, with no observable rutting or premature failure, confirming the technical feasibility of this approach. While conventional synthetic fibres may provide higher mechanical improvements, the use of E-CB fibres presents a cost-effective and environmentally sustainable alternative, simultaneously diverting non- biodegradable waste from landfills and promoting circular economy principles. These findings highlight the quantitative mechanical benefits, environmental advantages, and economic feasibility of using E-CB fibres in SMA, and indicate that further research is warranted to optimize fibre dosage, evaluate long-term field performance, and quantify the full environmental and economic impacts for large-scale implementation.

REFERENCES

1. Yang, F., et al., "Effect of Waste Cigarette Butt Fibers on the Properties and CO_2 Footprint of Bitumen," Materials Journal, MDPI, 2025.
2. Guo, Y., Tataranni, P., Tarsi, G., et al., "Performance evaluation of stone mastic asphalt reinforced with shredded waste e-cigarette butts," Case Studies in Construction Materials, e03126, 2024.
3. Soliman, H., Osei, P., Shalaby, A., "Performance of bituminous binder modified with recycled plastic pellets," Materials, 16(20), 6730, 2023.
4. Conradi, M., Sánchez-Moyano, J.E., "Toward a sustainable circular economy for cigarette butts, the most common waste worldwide on the coast," Science of the Total Environment, 847, 157634, 2022.
5. Jailani, N., Ibrahim, A.N.H., Rahim, A., et al., "Chemical and physical properties of poly (lactic) acid modified bitumen," Ain Shams Engineering Journal, 12(3), 2631–2642, 2021.
6. Tataranni, P., Sangiorgi, C., "A preliminary laboratory evaluation on the use of shredded cigarette filters as stabilizing fibers for stone mastic asphalts," Applied Sciences, 11(12), 5674, 2021.

7. Devulapalli, L., Kothandaraman, S., Sarang, G., “Effect of rejuvenating agents on stone matrix asphalt mixtures incorporating RAP,” Construction and Building Materials, 254, 119298, 2020.

8. Rahman, M.T., Mohajerani, A., “Use of bitumen encapsulated cigarette butts in stone mastic asphalt,” Construction and Building Materials, 261, 120530, 2020.