Effects of Banana Fibers on Mechanical Characteristics of Stone Mastic Asphalt

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Abstract

The pavement industry faces challenges due to global warming and population growth, causing frequent rutting and fatigue cracking in the pavements. To combat these pressing issues, Stone Mastic Asphalt (SMA) can be a viable solution for heavy-traffic-prone road networks. However, polymer-modified asphalt binders and natural or synthetic fibers are typically required to prevent draindown because of their high binder content. Meanwhile, a huge amount of Banana fibers is disposed of in the form of waste generated by Banana cultivation, posing environmental challenges. Therefore, this research article investigates the effects of adding banana fibers to Stone Mastic Asphalt for sustainable and environmentally friendly road construction by utilizing agricultural waste. During the Modification of SMA Banana fibers at a fiber content of: 0.2%, 0.3%, and 0.4% with fiber lengths of 20mm, 25mm, and 30mm were examined based on draindown experiments, in which 0.3% was found to be optimum fiber content. The mechanical properties of banana fiber-modified stone mastic asphalt (BFM-SMA) prepared at optimum fiber content were compared to the conventional SMA using the Marshall Stability and Cantabro loss test. It has been discovered that the increased fiber length improves the mechanical characteristics of the BFM-SMA, as the modified SMA with banana fibers of 30mm length shows the best results, which strongly suggests that this approach could effectively address road problems.

Keywords: Bitumen; Modified SMA; Banana fibers; Sustainability; Mechanical properties.

1. Introduction

Transportation infrastructure is facilitated by road networks, which enable different regions to be interconnected, effective flow of humans, material, and resources [1]. Road networks should not be underestimated, as they possess serious consequences with respect to economic growth, social development, and environmental viability [2]. However, the maintenance and expansion of road networks pose serious challenges, particularly in the context of aging infrastructure and increasing demands on the transportation network system. One of the key issues facing road networks is the problem of rutting, fatigue cracking, and thermal cracking, which can lead to the deterioration of road surfaces and compromise the performance of the transportation network infrastructure. [3] Hot mix Asphalt (HMA) under high traffic arterial settings is exposed to problems of deforming, cracking, and being affected by moisture. To address these challenges, SMA can prove to be an effective solution. It is a high-performance asphalt surface layer that contains exceptional resistance to rutting and fatigue cracking [4]. This type of asphalt has a different aggregate structure with deliberate gaps between the stones, emphasizing stone-to-stone contact and increasing stability and internal friction [5]. To ensure the mixture's impermeability, the asphalt binder and filler are used to fill the

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mineral spaces. To minimize exudation and segregation during compaction and mixing, SMA mixtures typically require 1% to 1.5% more bitumen content than dense-graded mixes [6]. This additional binder content helps to reduce coating oxidation and disintegration. However, the inherent characteristics of SMA, such as its high binder content and dense mineral skeleton, necessitate the use of stabilizing additives, particularly in the form of natural fibers as synthetic ones have harmed the environment, including the aggregation of non-biodegradable products, changes in global temperature. Extensive research on bio-based polymers has been conducted in response to growing environmental concerns caused by the excessive usage of synthetic polymers. [7]. Therefore, the use of natural fibers as a stabilizing agent in SMA has been extensively explored in the research community. These natural fibers, derived from renewable sources, have proven to be impactful in enhancing the overall performance and service life of the asphalt mixture [8]. The addition of natural fibers, such as cellulose and other plant-based materials, plays an important role in enhancing the performance and durability of Stone Matrix Asphalt [9]. These fibers add to the mixture's stability by preventing the drainage or loss of the binder, a common problem in high-binder content mixtures. Additionally, the absorbent nature of natural fibers allows them to effectively mitigate the susceptibility of the asphalt mixture to water damage, improving its resistance to moisture-induced stripping and deterioration, which is an important factor in the long-term performance of SMA pavements [10]. Among all the resources of natural fibers, Banana fibers are derived from Banana cultivation, which generates the highest amount of waste, and it has been estimated that this cultivation generates approximately 220 tons of byproducts or waste per hectare annually [11]. This waste is a serious challenge to the environment if not properly disposed of or reused.

The use of natural and synthetic fibers in SMA has been extensively studied to enhance the performance characteristics of asphalt mixtures, particularly regarding draindown resistance, mechanical properties, and overall durability. Natural fibers, such as Banana (banana) fiber, sisal, coir, and jute, have emerged as promising alternatives to synthetic fibers like polypropylene and glass. However, the use of natural fibers in asphalt mixtures is not a new concept, with evidence suggesting that the practice dates back to ancient Egyptian building specifications. More recently, researchers have explored the use of a variety of natural fibers, including Banana fibers, as stabilizing additives in SMA [12]. The primary motivation for this approach is the potential to enhance the asphalt mixture's performance qualities, while also reducing the environmental impact and cost associated with traditional stabilizers. So, the possibility of employing fibers obtained from the pseudo-stem of the banana plant as a stabilizing factor in SMA mixtures using draindown tests and the effectiveness of different fiber contents and lengths in avoiding binder draindown, enhancing mechanical properties of the stabilized SMA mixture using tests such as Indirect Tensile Strength, Marshall stability, and Cantabro shows that the banana fibers are an effective alternative for SMA, effectively stabilizing binder draindown and enhancing mixture mechanical performance, particularly at fiber lengths of 20 mm [13]. Similarly, incorporating banana fibers significantly improved SMA's stability and flow properties, effectively reducing the draindown of the asphalt binder during high temperatures. This is crucial as SMA mixtures are prone to asphalt separation due to their high binder content. It is revealed that adding 0.3% banana fiber by weight of the aggregate resulted in enhanced mechanical properties, including increased indirect tensile strength and Marshall stability [14]. In addition to that, banana plants were shown to experience an early mass loss of about 7% in natural fibers. Around 200°C was the point at which banana fiber deterioration started, and it quickly accelerated as the temperature rose to 350°C. A mass loss of 83% was seen and confirmed at this location, which is related to the hemicellulose breakdown. The banana fibers can be effectively used as the stabilizing additives in the SMA, making it superior to other available natural fibers, which show a significant mass loss at the asphalt production temperature [15]. Moreover, the comparison of the effects of various natural fibers, including sisal and coir, on SMA mixtures revealed that sisal fibers also improved stability and reduced draindown, similar to Banana fibers [16]. Furthermore, when fibers are mixed with other substances like crumb rubber, polymer modifiers, and nano-size modifiers, it shows that using natural fibers in asphalt pavements works. It also shows how important it is, to find the best way to mix fibers and the right amount of fibers to get the best performance. [17]. In addition to that, rice straw fibers effectively reduced draindown and improved the properties of SMA, suggesting their potential as a cost-effective alternative to synthetic fibers [18]. The incorporation of coconut fibers showed that these fibers improved the mechanical properties and reduced draindown, reinforcing the versatility of natural fibers in SMA applications [19]. Forecasts indicate that the worldwide asphalt market will expand at a CAGR (compound annual growth rate) of 2.9% during 2020–2027, going from a 2019 valuation of USD 222.0 million to a 2027 valuation of USD 321.5 million. This growth is driven by increasing infrastructure development, particularly in road construction, which accounts for about 70% of bitumen usage. Governments worldwide are investing heavily in infrastructure projects, including highways, bridges, and airport runways, further propelling the market. The introduction of innovative asphalt products, such as bio-based asphalt, enhances performance and sustainability, attracting more investments [21]. In addition to that, the banana cultivation industry generates substantial fiber waste, particularly from the pseudostems of banana plants, which are often discarded after harvesting. Globally, approximately 3.87 million tons of banana fiber waste are produced annually. [22]. The global market for natural fibers, including banana fiber, was valued at USD 4.2 billion in 2022 and is estimated to reach 8.3 billion USD by 2032, with a compound annual growth rate of 7.3%. The increasing demand for sustainable materials drives this growth as industries shift from synthetic fibers due to environmental concerns [23]. Overall, the addition of natural fibers in SMA presents a viable solution to address the challenges of draindown and improve the mechanical properties of asphalt mixtures, setting the path for a more robust and environmentally friendly road infrastructure [20]. Lastly, the use of natural fibers can provide a more sustainable and cost-effective solution than traditional stabilizers. The availability and low cost of natural fibers, such as banana fibers, make them an economical option for use in SMA, particularly in regions with low availability of conventional stabilizers. Hence, A detailed analysis of the literature highlights the difficulties associated with evaluating the long-term performance of fiber-reinforced SMA in actual environmental settings and investigating new fiber combinations to optimize advantages.

To address these multidimensional problems, Banana fibers are added to the SMA. Banana fibers have emerged as a promising candidate with several advantages over other natural and synthetic fibers when used as a stabilizing additive in SMA. One of the primary advantages of banana fibers is their high absorbency, which can effectively address the issue of drain-down in asphalt, a common concern in the application of porous and stone matrix asphalt. Furthermore, the innate flexibility and tensile strength of banana fibers can contribute to improved resistance to fatigue and cracking in the asphalt, ultimately extending the service life of the pavement [8]. Additionally, it has been observed that adding Banana fibers to SMA improves the mixture's overall mechanical qualities, such as its ability to withstand cracks at low temperatures and high temperatures. However, choosing the right kind, quantity, and length of fibers is crucial to maximizing SMA's performance [12]. To conduct further analysis on the usage of Banana fibers in SMA this study explains the effect of extended fiber length incorporated in the SMA by evaluating its mechanical properties, to propose a technically feasible and environmentally friendly method of preventing draindown.

2. Materials and Methods

This study uses 60/70-grade bitumen, Banana fibers extracted from the furthest layer of the banana plant pseudo-stem, Coarse aggregates, and stone dust as a filler. Banana fiber is recognized for its biodegradability, renewability, and superior physical properties, making it an attractive alternative to synthetic fibers in textiles, composites, and construction materials. Consequently, adopting BFM-SMA is potentially a sustainable solution for the road construction industry [24], considering the rising problems of rutting, fatigue cracking, and up to some extent, thermal cracking in heavy traffic pavements, aligning with the current environmental aspects of agri-business waste. The flow chart below illustrates the flow of work carried out to investigate the effects of banana fibers on stone mastic asphalt.

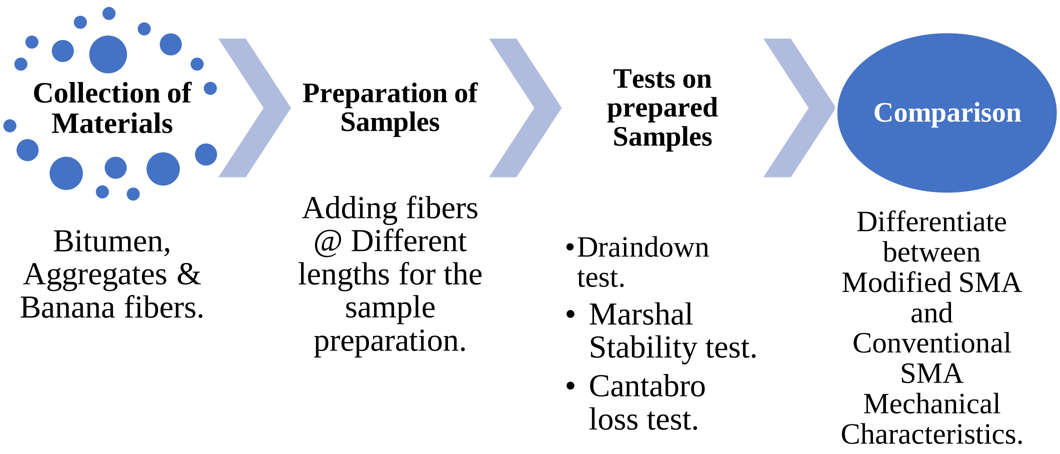

Fig 1. Research Methodology Flow Chart.

In this study, the properties of bitumen and aggregates used were characterized, the characterization tests were carried out, and all assessed properties were within the limits set by the ASTM standards.

TABLE 1. Characterization of bitumen binder.

Properties	Standards	limits	Results
Penetration at 25°C	ASTM D5	60-70	67
Softening Point	ASTM D36	49-56°C	50°C
Ductility at 25°C	ASTM D113	100 min.	>100
Flash point	ASTM D92	225°C min.	260°C
Specific Gravity @ 25°C	ASTM D70	1.01-1.06	1.02

TABLE 2. Characterization of aggregates.

Properties	Standards	Requirements	Results
Los Angeles Abrasion	ASTM C131	Maximum of 30% loss for coarse aggregate	27.83
Bulk Specific Gravity	ASTM C127/C128	2.4-2.9 for coarse aggregate	2.7
Flat or Elongates %	ASTM D4791	Maximum of 5% @5:1 & 20% @ 3:1 for coarse aggregate	3:1 14.8 5:1 2.31
Apparent Specific Gravity	ASTM C127/C128	2.4-2.9 for coarse aggregate	2.62
Impact Value	ASTM D5821	Maximum of 30% for coarse aggregate	21.27

2.1 Banana fibers.

The exterior layer of the banana plant's pseudostem is made up of fibers used in the furniture industry and several other handmade crafts, because of their excellent mechanical qualities, including their elastic nature and high strength [25]. In this study, the fibers used have a medium diameter of 100µm obtained from the Cavendish Dwarf (Barsai) banana plant type which is most commonly cultivated in Sindh, Pakistan. There was less quantity of fibers required to complete this study, So, the manual cutting method was utilized. Mechanical extraction and cutting procedures are advised to ensure the addition of Banana fiber in SMA as a time and cost-effective approach.

2.2 SMA mix design.

The specimens of SMA for this study were designed as per AASHTO Designation: M 325.
After ensuring the suitability of the SMA components, sieve analysis for particle size gradation was done by ASTM C136 from which the blend to be used for the SMA was selected as shown below in Figure 1.

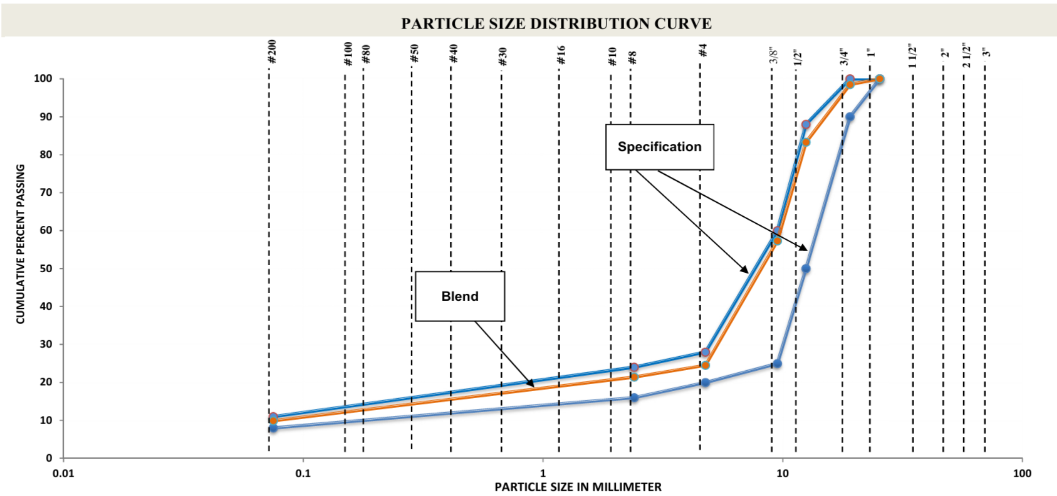

Fig 2. Particle size distribution of the aggregates.

Cylindrical specimens of 102 x 64 mm were compacted using the Marshall method of mix design with 50 blows on each side of the specimen and for optimum binder content, three specimens of asphalt mix for each bitumen content of 6, 6.5 & 7% were prepared and tested and the one with binder content of 6.5% were optimum as its Stability and flow values were more satisfactory than the other respective samples. Banana fibers were not added to the specimens at this stage. Moreover, this binder content also ensures the prerequisites as per the standards of AASHTO M325.

Table 3. Parameters of SMA mix at 6.5% binder content.

Va%	**VMA%**	**VCA ratio**
3.91	17.5	0.81

Banana fibers were manually cut up to the length of 20 25mm, and 30mm. The dry method was used to incorporate the fibers into the asphalt mixtures. The quantity of fibers added to the mixtures decreased the bulk of the mineral aggregates proportionately. Before being mixed with the asphalt binder, the fibers and aggregates were heated in an oven to 165°C for aggregate heating. Since the process temperature of 165°C is lower than the temperature at which fibers begin to deteriorate, there is no risk of fiber deterioration.

2.3 Draindown test.

The objective of this test is to quantify the extent of draindown in an uncompacted asphalt mixture under conditions of high temperatures similar to those experienced during the placement, transportation, and production storage of the mixture. This test specifically pertains to combinations that include open-graded courses and Stone Matrix Asphalt. Following [26], the uncompacted mixture was poured into a basket and placed in an oven set at two distinct temperatures: 150°C (mixed temperature) and 165°C (15°C above mixing temperature) for draindown. The draindown refers to the fraction of the mixture that undergoes separation from the sample and descends beyond the wire basket container. This drained material may be made up of just the binder or a combination of the binder and fine aggregate which minimizes the performance of the SMA. This study assessed the SMA mix stabilized with or without the Banana fibers as an additive having lengths of 20mm, 25mm, and 30mm at a fiber content of 0.2%,0.3% & 0.4%.

2.4 Mechanical tests.

2.4.1 Marshall Stability test.

The Marshall stability test is an essential tool in asphalt mix design, providing valuable data on the stability and flow characteristics of asphalt mixtures. Its simplicity and effectiveness have made it a standard method used by engineers and researchers worldwide to ensure the quality and performance of asphalt pavements. The stability is the maximum load carried by the test specimens. In this assessment, the Marshall stability test of each cylindrical specimen (102 x 64 mm) made with different fiber lengths and the conventional mix samples was conducted according to the Marshall method of mix design as per ASTM D6926 and ASTM D6927.

2.4.2 Cantabro loss test.

In this study, the cantabro loss of each cylindrical specimen (102 x 64 mm) with or without Banana fibers as an additive was examined by using the Los Angeles Abrasion Machine as per AASHTO TP 108 [27]. The cantabro loss test is critical for evaluating the performance of SMA mixtures, particularly in terms of their ability to resist raveling and maintain structural integrity under traffic loads. A lower percentage of mass loss indicates better performance and durability of the asphalt mix.

3. Results

3.1 Draindown sensitivity.

For the Optimum fiber content, an SMA mix was prepared for each fiber length of 20mm,25mm, and 30mm at the dosage of 0.2%, 0.3%, and 0.4% of the Banana fibers, as per previous research, which suggests that these natural fiber contents can potentially prevent draindown [13] Kumar, Sikdar, Bose & Chandra, 2004 [29]. The fiber content of 0.3% and 0.4% gives the draindown% less than the minimum requirement for each addition of Banana fiber at different lengths as per AASHTO M325, which is 0.3%, So the optimum fiber content used in this research is 0.3% of the aggregate's weight to check the mechanical properties of the BFM-SMA.

TABLE 4. Draindown for different fiber content @ 20mm length.

Fiber content	Draindown%	
	150°C	**165°C**
0.2%	0.15	0.72
0.3%	0.07	0.27
0.4%	0.05	0.17

TABLE 5. Draindown for different fiber content @ 25mm length.

Fiber content	Draindown(%)	
	150°C	**165°C**
0.2%	0.12	0.61
0.3%	0.06	0.22
0.4%	0.03	0.15

TABLE 6. Draindown for different fiber content @ 30mm length.

Fiber content	Draindown%	
	150°C	**165°C**
0.2%	0.12	0.58
0.3%	0.05	0.22
0.4%	0.02	0.14

A tendency of decreasing draindown was observed with the increase of fiber length and these results are consistent with Laiana Ferreira, Grangeiro de Barros, Lêda, Christiane & Adriano

Elísio, [13] who identified that an increase in fiber length decreases the draindown of the SMA using Banana fibers as a stabilizer.

3.2 Marshall Stability test.

Figure 2 provides a graphical representation of the Marshall Stability test observations for conventional SMA and BFM-SMA. All three samples tested for each fiber length and the one without any fiber content addition also gives higher values than the minimum prescribed value of Marshall Stability of ≥ 6.2 kN as per the requirement of AASHTO M325 which applies to the samples compacted with a Marshall hammer.

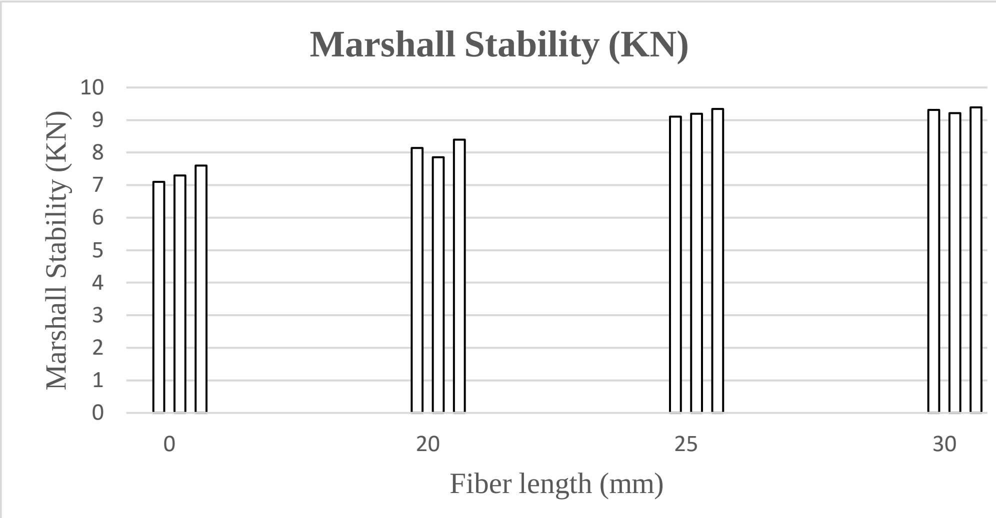

Fig 3. Marshall Stability test results @ Optimum Fiber Content of 0.3%

It has been noted that the change in Banana fiber length affected the results, as the longer the fiber used, the higher the Marshall stability of the BFM-SMA. Thus, in terms of this criteria, the SMA mix stability is enhanced with the increment in the length of the Banana fiber.

3.3 Cantabro loss test.

Figure 3 demonstrates the observations of Cantabro loss (%) values of the BFM-SMA and SMA without the Banana fiber stabilizer. The laboratory results indicate that the inclusion of Banana fibers improves SMA cohesiveness and decreases its disintegration in response to abrasive forces.

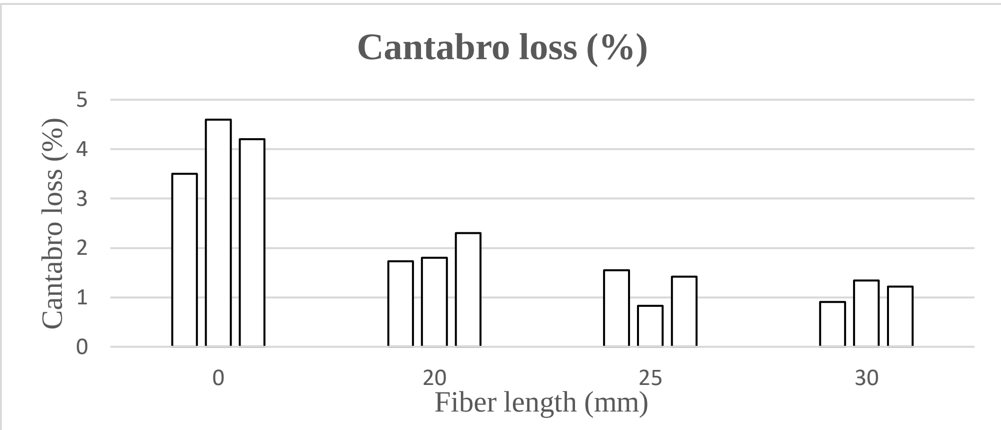

Fig 4. Cantabro loss (%) test results @ Optimum Fiber Content of 0.3%

The SMA specimens without stabilizer performed satisfactorily as well. This indicates that the aggregate's Los Angeles abrasion value has considerably influenced the SMA mix, as the stone-to-stone contact was ensured by ensuring $VCA_{DRC} > VCA_{MIX.}$ which was within the prescribed limit for SMA.

4. Discussion

The BFM-SMA gives elevated results as compared to the conventional SMA. It has been found that the Banana fiber content at 0.3% by the weight of the mix irrespective of the fiber length is the minimum percent of fibers required to obtain the draindown of the asphalt mix lower than the minimum prescribed value, Additionally, the Marshall stability increases with the inclusion of Banana fibers into the SMA, following the decrement in the Cantabro loss which ensures the resistance to the abrasion during traffic loading. Using the Marshall method for mix design, this research work's optimum binder content was 6.5% at which all the specimens were prepared and examined. It has been found that the mechanical properties of the BFM-SMA at 20mm length show better results than the conventional SMA, but the BFM-SMA prepared at the fiber length of 25mm & 30mm gave better results than the BFM-SMA at 20mm fiber length which emphasizes that the increase in the length of Fiber increases the performance of the BFM-SMA.

5. Conclusions

The Banana fibers can be effectively used to produce an eco-conscious, high-performance, and sustainable asphalt mix to mitigate the draindown problem as well as for the improvement of mechanical properties of the SMA, especially at the 25mm & 30mm fiber length, provided that the working temperature does not exceed 200°C. Moreover, the Banana fibers in this study are used along with the bitumen binder grade 60/70, which considerably has no major effect on the workability. However, it can be a significant problem when used at a greater range in the field. So, this query should have been closely evaluated before using this innovative BFM-SMA to a large extent.

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