

Coal Ash Based Bituminous Mixes with Natural Fiber Reinforcement

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Abstract-In India, coal-fired thermal power plants generate enormous quantities of fly ash and bottom ash, which pose significant environmental and health hazards when disposed of improperly. The effective utilization of these waste materials in pavement construction offers a sustainable solution for waste management while reducing dependence on natural aggregates. This study investigates the performance characteristics of Dense Bituminous Macadam (DBM) mixes incorporating coal ash (fly ash and bottom ash) along with natural sisal fiber as reinforcement.

In this research, fly ash was utilized as a mineral filler and bottom ash as a partial replacement for fine aggregate, while natural aggregates were used as coarse aggregates. Sisal fiber, coated with slow-setting bitumen emulsion (SS-1), was introduced as an additive to enhance the mechanical properties of the mix. The aggregate gradation was selected in accordance with MORTH (2013) specifications for DBM with a nominal maximum aggregate size (NMAS) of 26.5 mm.

The experimental program involved varying fiber content (0%, 0.25%, 0.5%, 0.75%, and 1% by weight of mix) and fiber length (5 mm, 10 mm, 15 mm, and 20 mm). Two grades of bitumen (VG-10 and VG-30) were initially evaluated, and VG-30 was selected based on superior Marshall characteristics. The optimum mix parameters were determined using Marshall Stability analysis, which yielded an optimum binder content of 5.57%, fiber content of 0.5%, and fiber length of 10 mm, corresponding to a maximum stability value of 15 kN.

Further performance evaluation, including Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), moisture susceptibility, and static creep tests, indicated significant improvement in the engineering properties of the modified mixes compared to conventional mixtures. The addition of coal ash and sisal fiber enhanced resistance to moisture damage, improved tensile strength, and reduced permanent deformation.

The study concludes that the combined utilization of coal ash and natural sisal fiber in bituminous mixes is a viable and sustainable approach for pavement construction. This method not only improves the performance and durability of flexible pavements but also provides an economical solution for coal ash disposal while conserving natural aggregate resources and minimizing environmental impact.

Keywords: Bottom ash, Fly ash, Sisal fiber, Emulsion, Indirect tensile strength, Static creep test, Tensile strength ratio, Bituminous Macadam (DBM), Marshall Stability.

Introduction

1.1 Background of the Study

Roads, highways, and pavements are considered the backbone of a nation's infrastructure and play a vital role in its economic and social development. Governments invest heavily in the construction of new roads as well as the maintenance and rehabilitation of existing pavements. Achieving high performance and long-term durability in both flexible and rigid pavements requires substantial financial and material resources.

In India, highways form the primary transportation network, and significant investments have been made by the government to enhance their construction and maintenance. Comprehensive engineering studies are essential to optimize material usage, reduce costs, and improve the reliability and performance of highways.

In the context of flexible pavements, two key aspects are of primary importance: mix design and pavement design. This study focuses on evaluating the engineering properties of bituminous mixes incorporating non-conventional or alternative materials, with the aim of improving performance while promoting sustainability.

1.2 Bituminous Mix Design

1.2.1 Overview on Bituminous Mix Design

Das et al. (2004) review indicates that the bituminous paving technique was first introduced on rural roads in the 1900s. The first formal mix design method was developed using the Hubbard field method, originally created for sand-bituminous mixtures. However, this method struggled to handle large aggregates. Subsequently, Francis Hveem, a project engineer at the California Department of Highways, developed the Hveem stabilometer to assess the stability of bituminous mixtures. Initially, Hveem lacked experience in determining the optimum amount of bitumen for mix designs. He borrowed the surface area calculation concept from cement concrete mix design to estimate the necessary bitumen quantity. Meanwhile, Bruce Marshall invented equipment to test the stability and deflection of bituminous mixtures, a method adopted by the US Army Corps of Engineers in the 1930s and further refined in the 1940s and 50s.

1.2.2 Bituminous Mix Design

Bituminous pavement comprises of a mixture of stone chips, graded from nominal maximum aggregates size (NMAS), through the fine fraction smaller than 0.075 mm mixed with appropriate amount of bitumen that can be compacted adequately with smaller air voids and will have adequate dissipative and elastic properties. The aim of bituminous mix design is to determine the fair proportion of bitumen and aggregates fraction to yield a mixture that is effective, durable, reliable and economical.

1.3 Problem Statement

Bituminous mixtures conventionally utilize aggregates in three fractions, namely coarse, fine, and mineral filler, to achieve the desired gradation and mechanical performance. However, in many regions, the availability of well-graded aggregates is limited, necessitating their procurement from distant sources, which significantly increases construction costs and environmental burden associated with transportation.

Simultaneously, the rapid expansion of coal-fired thermal power plants to meet growing energy demands has led to the generation of substantial quantities of coal ash. In India, approximately 120 million tonnes of ash are produced annually from around forty major thermal power plants. The conventional disposal practices such as land filling in open areas, ash ponds, and dumping yards pose serious challenges related to land utilization, environmental degradation, and potential health hazards.

Therefore, the safe management and beneficial utilization of coal ash have become critical concerns for sustainable development. A systematic and in-depth investigation is essential to explore viable engineering applications of these waste materials, there by addressing environmental issues, reducing dependency on natural aggregates and fulfilling the increasing infrastructural demands in an economical and sustainable manner.

1.4 Objectives of Research

The primary objective of this experimental study is to optimize the utilization of coal ash as a non-conventional aggregate in bituminous mixtures, in combination with natural sisal fibre as a reinforcing additive. The study aims to ensure adequate performance of the modified mixes in terms of fatigue resistance, moisture susceptibility and creep characteristics.

1.5 Scope of the Study

The present study focuses on the utilization of coal ash as a fine aggregate substitute in Hot Mix Asphalt (HMA), with the objective of developing high-performance bituminous mixes capable of providing durable, smooth-surfaced pavements under varying environmental and loading conditions. The incorporation of coal ash not only aims to enhance engineering performance but also promotes sustainable waste management and cost-effective construction practices.

Furthermore, the combined use of unconventional materials such as coal ash and natural fibers (sisal fiber) is explored to develop innovative bituminous mix designs. This approach seeks to partially replace conventional materials such as natural sand and stone dust, thereby addressing issues related to depletion of natural resources, disposal of industrial waste, and environmental degradation.

A comprehensive comparative analysis has been carried out on Dense Graded Bituminous Macadam (DBM) mixes under different material combinations. The scope of the study includes the following key investigations:

1. **Evaluation of Marshall Properties of DBM Mixes** under varying conditions:

- ❖ Mixes containing both fiber and coal ash
- ❖ Mixes containing fiber without coal ash
- ❖ Mixes containing coal ash without fiber
- ❖ Conventional mixes without fiber and coal ash

2. **Assessment of Performance Characteristics of Bituminous Mixes:**

(a) **Moisture Susceptibility Analysis** (with and without fiber and coal ash) using:

- ❖ Tensile Strength Ratio (TSR) Test
- ❖ Retained Stability Test

(b) **Thermal Cracking Resistance** evaluated through Indirect Tensile Strength (ITS) Test on DBM mixes with and without fiber and coal ash.

(c) **Permanent Deformation Characteristics** assessed using Static Creep Test to evaluate rutting resistance of the mixes.

Review of Literatures

Putman, Bradley J., and Serji N. Amir Khanian (2004) studied the use of waste fiber in stone mastic asphalt mixture (SMA). He used waste tire and carpet fibers as an additive to stabilizing the excessive drain-down due to relatively high air void in SMA. He also studied the performance characteristics of SMA mixtures prepared with waste tire and carpet fibers. A comparative study has been done between SMA modified with tire and carpet fibers and with other mixes prepared with cellulose and polyester.

From the observation he found that the sample containing carpet and tire fibers, were effective in stopping unnecessary drain-down of the SMA mix. The toughness of the SMA mixes increases when added with tire and carpet fibers as compared to other cellulose fibers. The mix comprising tire fibers did not lose any toughness when conditioned in water. The resistance to moisture induced damage of the bituminous mixes, which contained tire and carpet fibers 100.9 and 101.8%, respectively.

Kumar, Pawan, Satish Chandra, and Sunil Bose (2007) studied the performances of the SMA mixture modified with crumb rubber modified binder (CRMB) and low viscosity binder coated jute fibers. The performance of SMA mixture were assessed by conducting two different methods of drain-down, durability test, moisture susceptibility test, fatigue life tests and rutting test. He also compared the characteristic of modified SMA prepared with coated jute fiber and with other patented fibers. From the test observation he conclude that fiber content of 0.3% by weight of the mix improve the Drain-down property of the mix. Also in moisture susceptibility test the mixture shows satisfactory result. The observation from Hamburg wheel tracking tests, aging tests and flexural fatigue tests carried out on three mixes of SMA indicate better result than conventional mix.

Kar, Debashish (2007) studied the effect of indigenously available sisal fiber on SMA and BC mixture. He considered sisal fiber as an additive for BC mix and stabilizing agent for SMA Mix. Fiber content varied from 0% to 0.5% by weight of total mix whereas binder content was varied from 4% to 7%. For mineral filler he used fly ash, as it has shown satisfactory result at the initial stage of experiment. For the performance test the BC and SMA mixes were subjected to various tests such as

Drain down test, Static Creep test and Static Indirect Tensile Strength Test. From the Marshall properties test it was observe, addition of fiber helps to improve the Marshall Stability and indirect tensile strength, it also reduces the Drain down. He again observed that the indirect tensile strength of SMA mixture is better than BC mixture. From Marshall test he found that the optimum binder content for BC and SMA were 5% and 5.2% respectively whereas optimum fiber content were 0.3%.

2.2 Summary

Previous studies show that coal ash (bottom ash and fly ash) can effectively be used as a partial replacement of natural aggregates in bituminous mixtures. It improves properties like skid resistance, stability, fatigue, and moisture resistance, but may require higher bitumen content and can reduce density.

Research also indicates that adding natural fibers such as sisal, jute, and coconut enhances Marshall stability, tensile strength, and reduces drain-down, thereby improving overall pavement performance. The optimum fiber content is generally found to be around 0.3%.

Overall, the combined use of coal ash and natural fibers is a sustainable approach that improves engineering properties of bituminous mixes, although proper optimization is necessary to balance strength, durability, and cost.

Materials and Methodology

3.1 Materials

The materials used in the present study include conventional aggregates along with coal ash and natural fiber reinforcement. Each component of the bituminous mix is described below:

3.1.1 Aggregates

Crushed stone aggregates were used as coarse aggregates. The aggregates were procured from a local quarry and sieved into different sizes as per the required gradation. These aggregates provide the primary load-bearing capacity to the bituminous mix.



Figure 3.1 Stone Chips

3.1.2 Bottom Ash

Bottom ash obtained from a nearby thermal power plant was used as a partial replacement for fine aggregates. It was incorporated up to approximately 9% by weight of total mix. Due to its porous nature, bottom ash contributes to improved interlocking but increases binder demand.



Figure 3.2 Bottom Ash

3.1.3 Fly Ash

Fly ash was used as mineral filler in the mix at about 5% by weight of total mix. It helps in filling voids and improves the binding characteristics between aggregates and bitumen.



Figure 3.3 Fly Ash

3.1.4 Bitumen

VG-30 grade bitumen was used as the binder in this study. Initially, VG-10 and VG-30 were compared, and VG-30 was selected due to its superior Marshall Stability performance.

3.1.5 Sisal Fiber

Natural sisal fiber was used as a reinforcing additive. The fibers were:

- ❖ Coated with slow-setting emulsion (SS-1)
- ❖ Oven dried at 110°C for 24 hours
- ❖ Cut into lengths of 5 mm, 10 mm, 15 mm, and 20 mm

Sisal fiber improves tensile strength, reduces cracking, and enhances durability of the mix.

3.1.6 Bitumen Emulsion

SS-1 type slow-setting bitumen emulsion was used for coating the fibers to improve bonding with the bituminous mix.

Table 3.1 Physical Property of Coarse Aggregate and Fine

Property	Code specification	Test Result	
		Natural Aggregate	Bottom Ash
Aggregate Impact Value, %	IS:2386 part-IV	14	-
Aggregate Crushing Value, %	IS:2386 part-IV	13.4	-
Los Angles Abrasion Test, %	IS:2386 part-IV	18	-
Soundness Test (Five Cycle In Sodium Sulphate), %	IS:2386 part-V	3	8.1
Flakiness Index, %	IS:2386 part-I	11.8	-
Elongation Index, %	IS:2386 part-I	12.4	-
Water Absorption, %	IS:2386 part-III	0.13	10.73
Specific Gravity	IS:2386 part-III	2.6	2

Table 3.2 Physical Property of Binder

Physical Properties	IS Code	Test Result
Penetration at 25°C/100gm/5s, 0.01mm	IS:1203-1978	46
Softening Point, °C	IS:1205-1978	46.5
Specific gravity, at 27°C	IS:1203-1978	1.01
Absolute viscosity, Brookfield at 160°C, Centi Poise	ASTM D 4402	200

Table 3.3 Physical and Chemical Property of Sisal Fiber [13]

Chemical Composition	
Composition	Test Result
Cellulose, %	65
Hemicellulose, %	12
Lignin, %	9.8
Waxes, %	2
Physical Property	
Property	Test Result

Density, Gm/Cc	1.50
Tensile Strength, Mpa	510-640
Young's Modulus, Mpa	9.5-2.0
Elongation At Break, %	2.0-2.5

3.2 Mix Design

Dense Bituminous Macadam (DBM) mix was designed as per MORTH (2013) specifications. The Marshall mix design method was adopted to determine the optimum binder content.

The selected aggregate gradation satisfied the specified limits for DBM with a nominal maximum aggregate size of 26.5 mm.

3.3 Experimental Variables

The study involved variation in fiber content and fiber length as follows:

Fiber Content

- 0% (Control mix)
- 0.25%
- 0.5%
- 0.75%
- 1% (by weight of total mix)

Fiber Length

- 5 mm
- 10 mm
- 15 mm
- 20 mm

3.4 Preparation of Specimens

The preparation of bituminous specimens was carried out using the Marshall method as follows:

1. Aggregates and bitumen were heated separately to a temperature of 150–160°C.
2. Coated and cut sisal fibers were added to the hot aggregates.
3. Required quantity of VG-30 bitumen was added and mixed thoroughly to obtain a uniform mix.
4. The mix was poured into pre-heated Marshall moulds.
5. Compaction was done using 75 blows on each face.
6. Specimens were allowed to cool at room temperature for 24 hours before testing.

3.5 Testing Methods

The performance of the prepared DBM mixes was evaluated using the following tests:

3.5.1 Marshall Stability Test

Figure 5.1 illustrates that, in comparison to a conventional mix, the use of coal ash in the DBM mix is not satisfactory in terms of stability value. When 14% of the mix's weight contained coal ash, the highest stability value of 11.83 kN was reached when creating DBM samples.

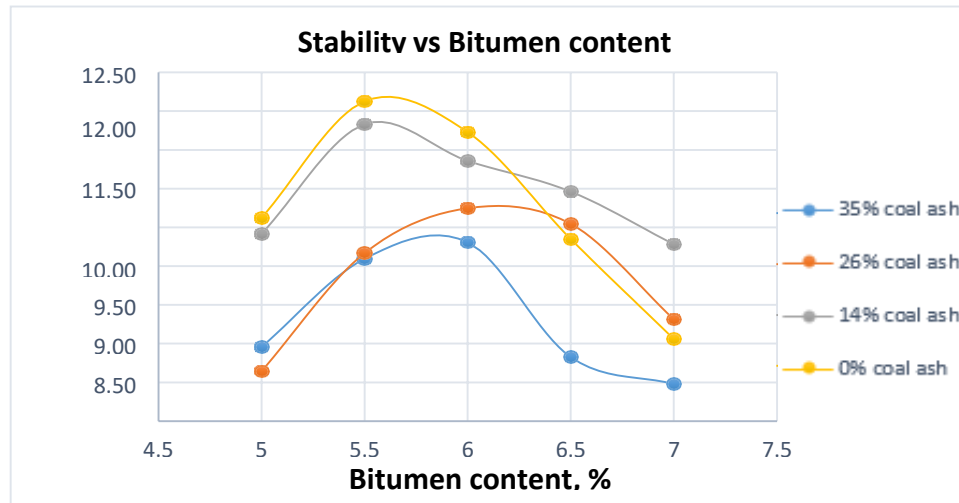


Figure 3.4 Variation of Stability Value with Bitumen Content at Different Coal Ash Content

3.5.2 Indirect Tensile Strength (ITS) Test

This test evaluates the tensile strength of the mix and its resistance to cracking under load.

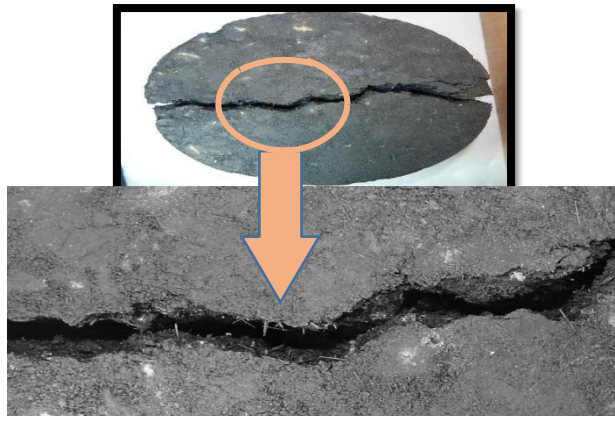


Figure 3.5 Criss-Cross Pattern of Sisal Fiber at Tensile Failure Crack

3.5.3 Tensile Strength Ratio (TSR)

TSR test was conducted to assess moisture susceptibility by comparing wet and dry tensile strengths.

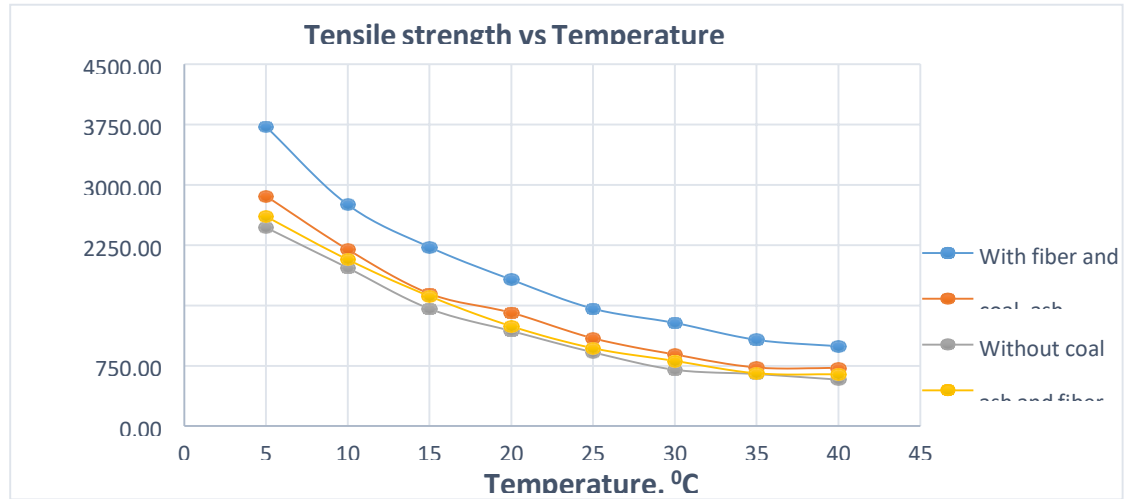


Figure 3.6 Graph between Tensile Strength Vs Temperature

Table 3.4 TSR of DBM Mixes with and Without Fiber and Coal Ash

Tensile Strength Ratio			Design Requirement
Type of Mixes	DBM With Coal Ash	DBM Without Coal Ash	
DBM With fiber	84.77%	82.04%	Minimum 80% (as per MORTH specification)
DBM Without fiber	82.35%	80.26%	

3.5.4 Retained Stability Test

This test measures the ability of the mix to retain strength after exposure to moisture

Table 3.5 Retained Stability of DBM Mixes With and Without Fiber and Coal Ash

Retained Stability				Design Requirement
Type of Mixture	Average Stability After Half an Hour in Water at 60°C (Kn)	Average Stability After 24 Hours in Water at 60°C (Kn)	Average Retained Stability (%)	
DBM with Fiber and Coal Ash	14.78	13.21	89.37	Minimum 75% (As per Morth Specification)
DBM with Coal Ash	13.88	10.17	73.21	
DBM with Fiber	12.63	10.10	79.94	
DBM without Fiber and Coal Ash	13.56	10.45	77.03	

3.5.5 Static Creep Test

Used to evaluate permanent deformation and rutting resistance under sustained load.

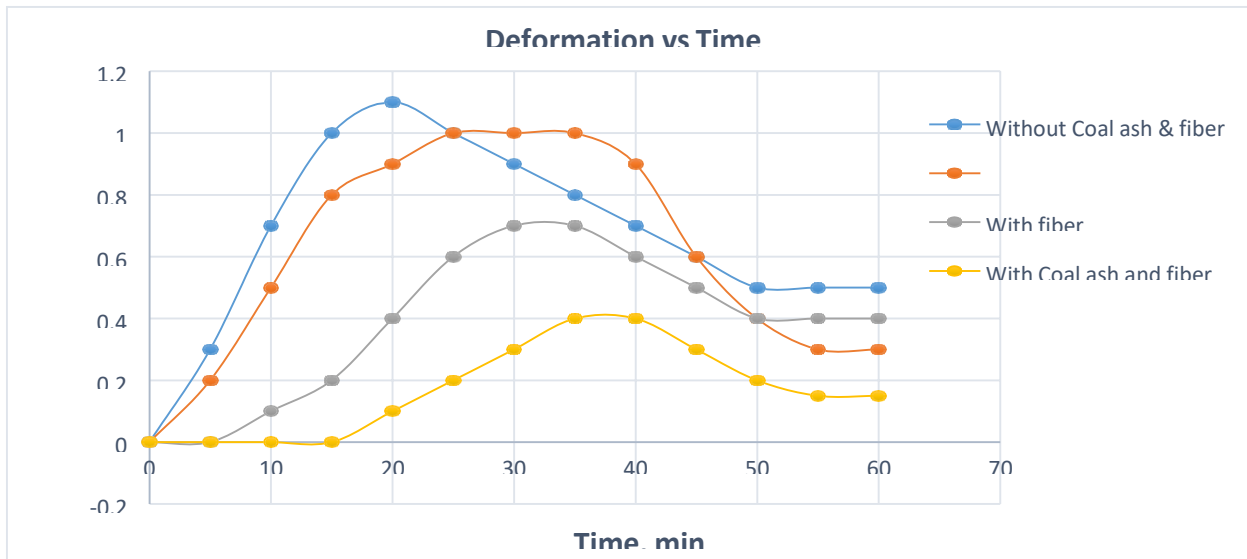


Figure 3.7 Variation of Deformation Value at 40°C for DBM Sample With Respect To Time

3.6 Evaluation Parameters

The performance of mixes was analyzed based on:

- ❖ Marshall Stability
- ❖ Flow Value
- ❖ Air Voids (VA)
- ❖ Voids in Mineral Aggregate (VMA)
- ❖ Voids Filled with Bitumen (VFB)
- ❖ ITS and TSR values
- ❖ Deformation characteristics



Figure 3.8 Loading and Failure Pattern of Indirect Tensile Strength Test

Conclusion and Future Scope

6.1 Conclusion

Based on experimental study the following conclusions were drawn, The results of the study indicate that Dense Bituminous Macadam (DBM) mixes incorporating bottom ash (300–75 micron) and fly ash (passing 75 micron) can be effectively optimized to meet Marshall design criteria. The optimum combination was achieved at 5.6% bitumen content, 0.5% fiber content, and 10 mm fiber length.

Marshall Stability and flow values remained within acceptable limits when coal ash content was maintained up to 15%, demonstrating the suitability of ash as a partial aggregate replacement. It was observed that increasing fiber content and fiber length led to a reduction in air voids and flow values, while the Marshall Quotient increased due to improved stability. However, higher fiber content and length required an increase in optimum bitumen content and emulsion to ensure proper coating and bonding. The indirect tensile strength results revealed that the addition of emulsion-coated fibers and coal ash significantly enhanced the strength and resistance of the mix against thermal cracking.

Furthermore, the inclusion of coal ash and emulsion-coated fibers improved resistance to moisture-induced damage, as indicated by higher tensile strength ratio and retained stability values. Overall, the combined use of coal ash and sisal fiber contributes to improved engineering performance and durability of DBM mixes, making it a sustainable and effective alternative in pavement construction.

6.2 Future Scope

The present study highlights the potential of sisal fiber as a natural reinforcing material in bituminous mixes. However, further research can be extended by exploring other natural fibers such as jute and coconut fiber to evaluate and compare their performance in Dense Bituminous Macadam (DBM) mixes.

This study was limited to the use of SS-1 emulsion as a coating medium for sisal fibers. Future investigations should consider other types of emulsions, such as rapid-setting (RS) and medium-setting (MS) emulsions, to assess their effectiveness and influence on the performance characteristics of the mix.

Moreover, the role of different mineral fillers such as cement and lime should be explored in detail. Lime can act as an anti-stripping agent, while cement may enhance the stability of the mix. Future studies should focus on evaluating these materials to further improve the strength, durability, and moisture resistance of DBM mixes.

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