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Experimental Study of Dense Grade Bituminous Mixes with Natural Fiber Modified Coal Ash Incorporation

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Abstract- Coal-fired thermal power plants in India generate significant fly ash and bottom ash, posing environmental hazards. This review explores repurposing these byproducts in bituminous paving materials, with bottom ash as fine aggregate, fly ash as mineral filler, and sisal fibers to enhance engineering properties. The methodologies adhere to Ministry of Road Transport and Highways (MORTH, 2013) specifications, focusing on dense graded bituminous macadam (DBM) with a nominal maximum aggregate size of 26.5 mm. Sisal fibers coated with slow-setting emulsion (SS1) improve the mix, showing optimal performance with VG30 bitumen. Key findings include a Marshall stability of 15 kN, optimal bitumen content of 5.57%, and optimal fiber content and length of 0.5% and 10 mm, respectively. Performance tests reveal enhanced moisture susceptibility, indirect tensile strength, and creep behavior. This sustainable approach offers a viable alternative to traditional materials, promoting resource-efficient and resilient infrastructure development.

Keywords- Bottom ash, Fly ash, Sisal fiber, Emulsion, Indirect tensile strength, Static creep test, Tensile strength ratio.

I. INTRODUCTION

Roads, highways, and pavements stand as the backbone of a country, serving as the critical infrastructure upon which progress and development hinge. Most nations actively pursue programs aimed at either constructing new road networks or enhancing existing ones. The construction of both flexible and rigid pavements involves substantial investments to ensure optimal performance and the creation of durable, smooth surfaces that withstand the test of time.

In the context of India, where highways play a pivotal role in the transportation network, the Government has consistently allocated significant financial resources for the development and maintenance of pavement infrastructure.

Undertaking a meticulous engineering study becomes paramount in optimizing investments and ensuring the longevity and reliable performance of the highways in service.

In the realm of flexible pavements, the focus shifts to two crucial aspects: pavement design and mix design. Pavement design involves the strategic planning and layout of the road surface to accommodate the expected traffic loads and environmental conditions. Mix design, on the other hand, pertains to the composition of materials, particularly bituminous mixes, to achieve the desired engineering properties and performance characteristics.

The current research study is specifically oriented towards exploring the engineering properties of bituminous mixes that are crafted from alternative or nonconventional materials. By delving into the use of such materials, the research aims to assess their viability and effectiveness in pavement construction. This approach aligns with the broader goal of sustainable and cost-effective infrastructure development, promoting innovation and resource efficiency in the construction and maintenance of vital transportation networks.

As nations strive for efficient and resilient highway systems, the incorporation of alternate materials in bituminous mixes emerges as a promising avenue. This research not only contributes to the scientific understanding of these unconventional materials but also holds the potential to revolutionize the way pavements are designed and constructed. Ultimately, the pursuit of innovative engineering solutions is key to ensuring the robustness and longevity of the highways that form the lifelines of a nation's connectivity and economic prosperity.

II. BITUMINOUS MIX DESIGN

Bituminous pavement is a composite material consisting of a blend of stone chips, carefully graded according to the nominal maximum aggregate size (NMAS). This graded mixture includes the fine fraction, particles smaller than 0.075 mm, which is combined with a suitable amount of bitumen. The objective is to create a mix that can be compacted effectively, resulting in smaller air voids within the pavement. The desired outcome is a mixture with optimal dissipative and elastic properties.

Objectives of Research

- Determine optimal use of coal ash as nonconventional aggregate in bituminous mixes.
- Investigate the impact of adding Sisal fiber to enhance bituminous mix performance.
- Assess fatigue resistance, moisture susceptibility, and creep value of the modified mixes in field conditions.
- Analyze the influence of Sisal fiber on stability, flexibility, and deformation resistance of bituminous mixes.
- Assess sustainability and environmental implications of modified bituminous mixes.

III. PARAMETER USED IN THIS STUDY

Following parameters are used in this study related to marshal stability test.

1. Bulk Specific Gravity of Aggregate (Gsb)
Gsb indicates the density of the aggregate in the mix, considering the volume occupied by the aggregate, air voids, and absorbed bitumen.

$$G_{sb} = \frac{\text{Mass of aggregate}}{\text{Volume of (mass of aggregate + air void in mix + absorbed bitumen)}}$$

2. Effective Specific Gravity of Aggregate (Gse)
Gse represents the effective density of the aggregate in the mix, accounting for the volume of aggregate and air voids.

$$G_{se} = \frac{\text{Mass of aggregate}}{\text{Volume of (mass of aggregate + air void in mix)}}$$

3. Apparent Specific Gravity (Ga)
Ga reflects the apparent density of the aggregate, considering only the volume occupied by the aggregate itself.

$$G_{a} = \frac{\text{Mass of aggregate}}{\text{Volume of aggregate in saturated surface dry condition}}$$

4. Theoretical Maximum Specific Gravity of Mix (Gmm)
Gmm calculates the maximum possible density of the entire mix, factoring in the volume of the mix and air voids.

$$G_{mm} = \frac{\text{Mass of mix}}{\text{Volume of (mix - air void)}}$$

5. Bulk Specific Gravity of Mix (Gmb)
Gmb provides the density of the entire mix, considering the bulk volume of the mix.

$$G_{mb} = \frac{\text{Mass of mix}}{\text{Bulk volume of mix}}$$

6. Air Voids (VA)

Air Voids measure the percentage of voids in the mix, indicating the space not occupied by the aggregate, bitumen, or other components.

$$VA = 1 - \frac{G_{mb} \times 100}{G_{mm}}$$

7. Voids in Mineral Aggregates (VMA)

VMA assesses the percentage of voids specifically within the mineral aggregates, accounting for the total aggregate mass and its percentage in the mix.

$$VMA = \left(1 - \frac{G_{mb} \times Ps}{G_{mm}}\right) \times 100$$

8. Voids Filled with Bitumen (VFB)

VFB represents the percentage of voids filled with bitumen, providing insights into the effectiveness of bitumen in occupying the available void spaces.

$$VFB = \frac{VMA - VA \times 100}{VMA}$$

IV. RESULT ANALYSIS

This comprehensive chapter is segmented into three sections. The first section elucidates the parameters and equations used for analyzing Marshall properties, establishing a foundational understanding of the mechanical characteristics of DBM mixes. The second section focuses on calculating and comparing critical parameters such as optimum binder content, optimum fiber content, and optimum fiber length, specifically exploring the influence of incorporating coal ash. Lastly, the third section delves into a nuanced analysis of performance indicators derived from various tests, including static indirect tensile strength, static creep tests at 40°C, moisture susceptibility tests (Tensile Strength Ratio), and retained stability tests.

1. Influence of Coal Ash (Bottom Ash and Fly Ash) on Dense Graded Bituminous Mix

In the preliminary phase of the experiment, bottom ash and fly ash were incorporated as fine replacements in the Dense Graded Bituminous Mix (DBM). The total coal ash content was set at 35% by weight of the entire mix. Within this composition, the percentage of fly ash, serving as the mineral filler, was fixed at 5% of the total mix weight. The variation

Marshall Stability

Figure 1 illustrates that the utilization of coal ash in the DBM mix falls short in terms of stability value when compared to the conventional mix. The highest stability value, reaching 11.83 kN, was attained when incorporating 14% of coal ash by the weight of the mix in the preparation of DBM samples.

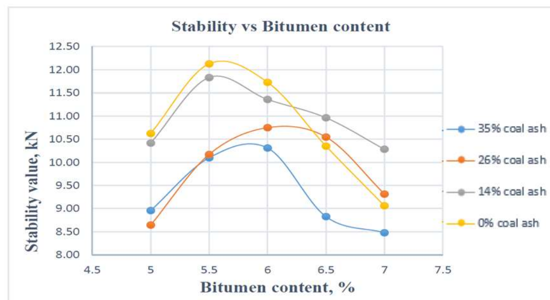

Figure 1 The fluctuation of stability values concerning different levels of bitumen content at varying coal ash concentrations

Marshall Flow Value

The graphical representation in Figure 2 illustrates the relationship between flow value and bitumen content. The observed trend indicates a general increase in flow value with higher bitumen and coal ash content. However, a notable deviation occurs when the coal ash content reaches 14% by weight of the mix, leading to a decrease in flow value compared to the conventional mix.

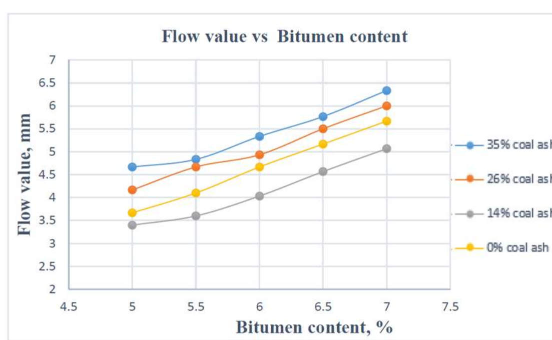

Figure 2 The fluctuation of Flow values concerning different levels of bitumen content at varying coal ash concentrations

Air Void

The graph depicted in Figure 3 reveals a direct correlation between coal ash content and air voids. As coal ash content increases, there is a corresponding rise in air voids. Notably, when 14% coal ash by weight of the mix is incorporated, the air void is relatively close to that of the conventional mix. This observation suggests that coal ash utilization, with certain adjustments, can lead to properties approaching or surpassing those of the conventional mix.

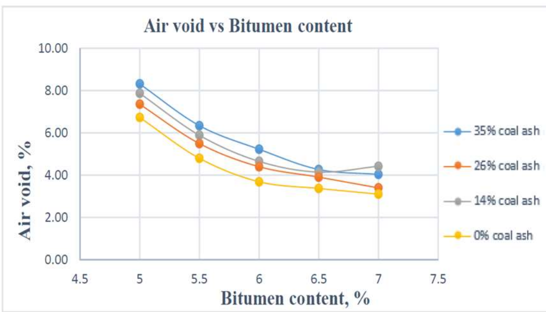

Figure 3 The fluctuation of Air Void concerning different levels of bitumen content at varying coal ash concentrations

Unit Weight

Figure 4 illustrates a noticeable trend regarding the relationship between coal ash content and the unit weight of Dense Graded Bituminous Mix (DBM) samples. The graph clearly demonstrates that as the percentage of coal ash in the DBM mixture increases, there is a corresponding decrease in the unit weight of the samples. This trend is primarily due to the lightweight properties of coal ash, which contributes to reducing the overall density of the asphalt mix.

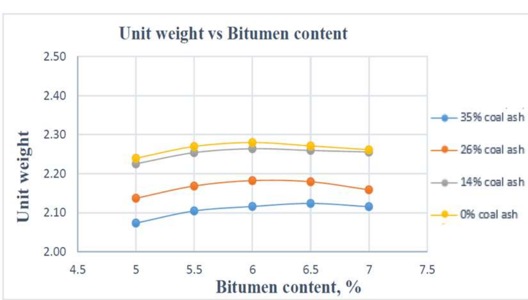

Figure .4 The fluctuation of Unit weight concerning different levels of bitumen content at varying coal ash concentrations

Voids in Mineral Aggregate (VMA)

The graph in Figure.5 provides insightful observations on the relationship between VMA (Voids in Mineral Aggregates) and bitumen content. It is evident that an initial increase in bitumen content leads to a rapid decrease in voids in mineral aggregate. However, beyond a certain point, the trend reverses, and there is a steady increase in voids in mineral aggregate with further increments in bitumen content.

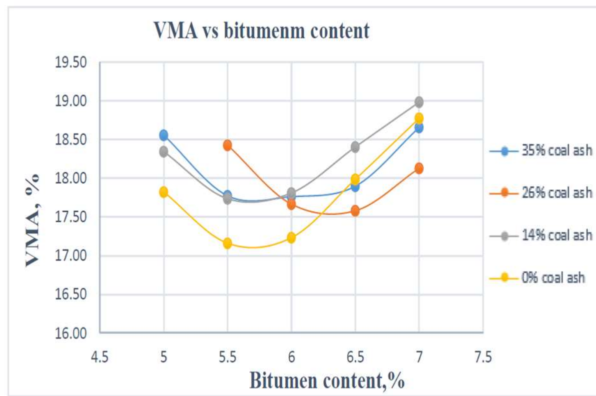

Figure 5. The fluctuation of VMA concerning different levels of bitumen content at varying coal ash concentrations

Voids Filled with Bitumen (VFB)

The graph depicted in Figure.6 reveals a notable observation regarding the relationship between VFB (Voids Filled with Bitumen) and bitumen content. The trend illustrates a rapid increase in VFB with higher levels of both bitumen and coal ash content.

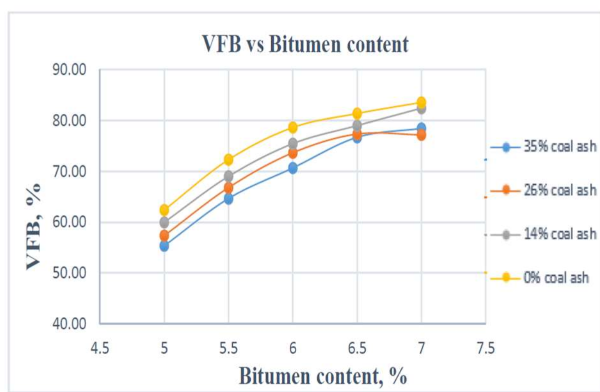

Figure 6 The fluctuation of VFB concerning different levels of bitumen content at varying coal ash concentrations

2. Influence of Coal Ash Sisal fiber and Coal ash (Bottom ash and Fly ash) on Dense Graded Bituminous Mix.

Upon careful examination of the Marshall properties of the DBM mix incorporating coal ash, it becomes evident that using coal ash alone does not yield satisfactory results. The stability and flow values fall outside the specified range for DBM mix. Additionally, key volumetric analyses, such as air void, unit weight, VMA, and VFB, do not meet the standards set by the conventional mix. To address these limitations, the study introduces sisal fiber as an additive to the DBM mix containing coal ash. The selected coal ash content is 14%, as it exhibited better results than other content levels. The study further explores varying fiber content from 0% to 1% with 0.5% increments, coupled with different fiber lengths ranging from 5mm to 20mm. This comprehensive approach aims to enhance the engineering properties of the mix and overcome the shortcomings associated with the use of coal ash alone.

Marshall Stability Value

Marshall Stability Value refers to the maximum load in kilograms sustained by a cylindrical specimen of asphalt mix before failure during a standardized test procedure. It is a key parameter used to assess the strength and resistance of asphalt concrete to deformation under traffic loading conditions. This value is crucial in determining the suitability and durability of asphalt mixes for pavement construction and maintenance, ensuring they meet specified performance standards and requirements.

The analysis of the stability and bitumen content graph, depicted in figures 7 to 10, reveals a notable trend. With an increase in bitumen content, fiber content, and fiber length, the stability value shows an initial increase up to a certain limit, followed by a subsequent decrease. Through an examination of the optimum binder content, it was determined that the maximum stability of 15 kN was achieved at an optimum binder content of 5.57%. This optimal performance was observed with a fiber content of 0.5% by weight of the mixture and a fiber length of 10 mm. Importantly, the fibers were coated with SS-1 emulsion and subjected to a 24-hour curing process at 110±10°C.

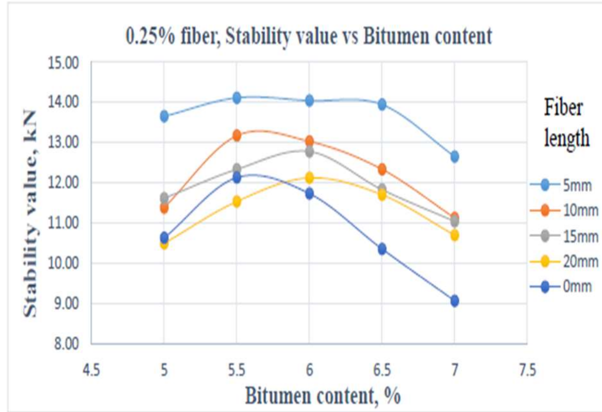

Figure.7 The fluctuation of stability values concerning different bitumen content in 0.25% fiber content at different fiber length

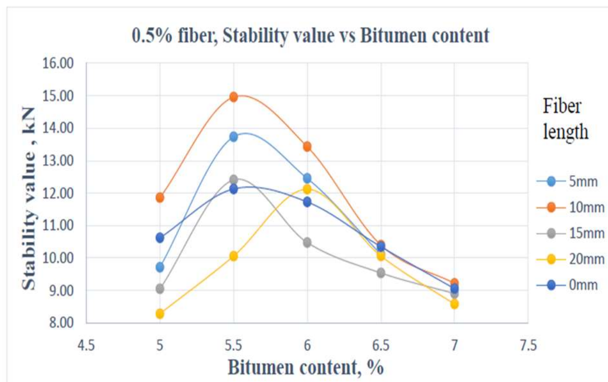

Figure.8 The fluctuation of stability values concerning different bitumen content in 0.5% fiber content at different fiber length

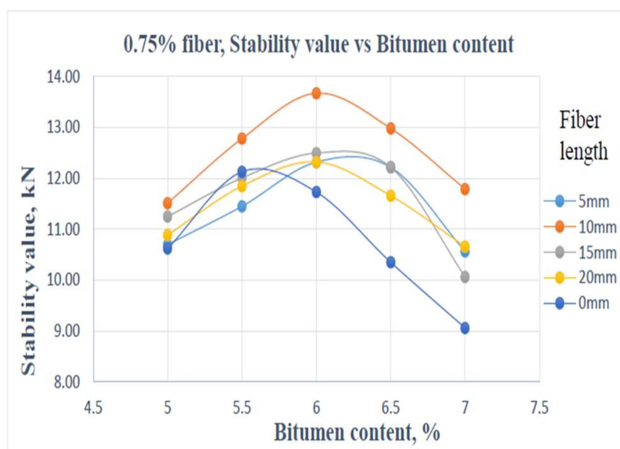

Figure.9 The fluctuation of stability values concerning different bitumen content in 0.75% fiber content at different fiber length

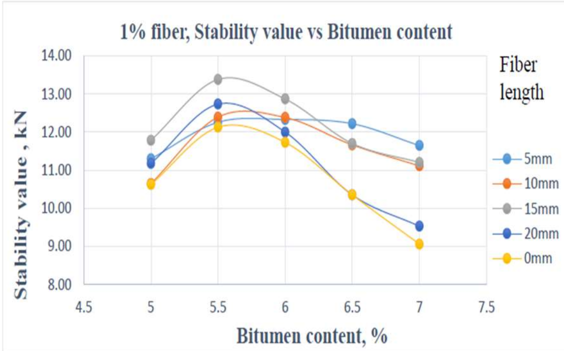

Figure.10 The fluctuation of stability values concerning different bitumen content in 1% fiber content at different fiber length

Marshall flow value

The measurement of deformation in millimeters (mm) that occurs when an asphalt concrete specimen undergoes a standardized load during a Marshall Stability Test. It indicates the asphalt mix's ability to deform under stress, aiding in assessing potential rutting and overall pavement performance.

In the preliminary stages, samples incorporating coal ash exhibited higher flow values compared to the conventional DBM mix. However, upon the introduction of sisal fiber, a noticeable reduction in the flow value was observed, as illustrated in figures 11 to 14. The length of sisal fiber emerged as a significant factor influencing the flow value. A clear trend indicates that an increase in fiber length corresponds to a decrease in the flow value. This phenomenon is attributed to the enhanced stiffness of the mixture induced by the addition of sisal fiber.

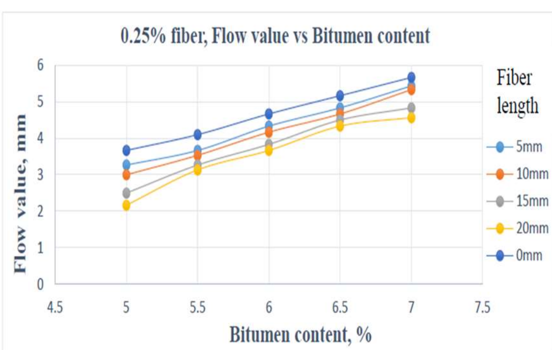

Figure.11 The fluctuation of flow values concerning different bitumen content in 0.25% fiber content at different fiber length

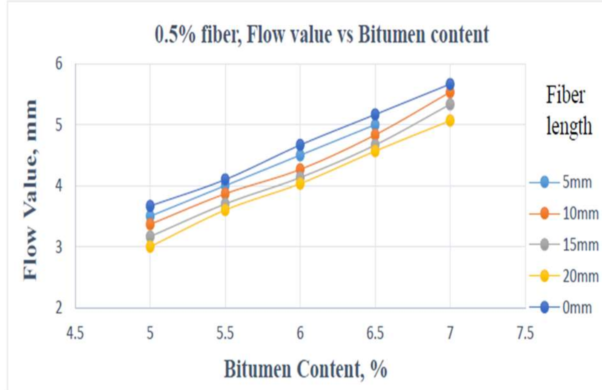

Figure.12 The fluctuation of flow values concerning different bitumen content in 0.50% fiber content at different fiber length

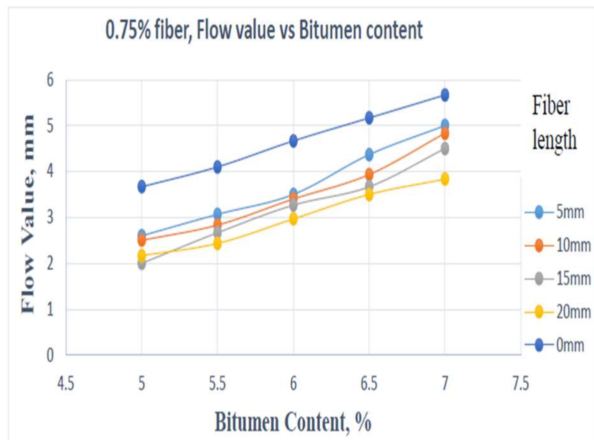

Figure.13 The fluctuation of flow values concerning different bitumen content in 0.75% fiber content at different fiber length

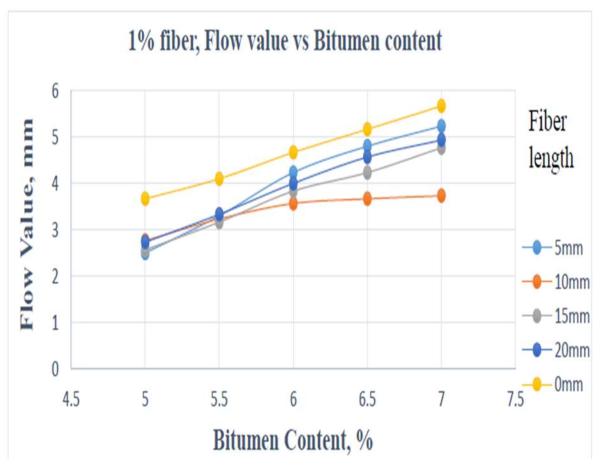

Figure.14 The fluctuation of flow values concerning different bitumen content in 1% fiber content at different fiber length

Unit Weight

The graphs presented in figures 5.15 to 5.18 distinctly demonstrate that the introduction of fiber results in a decrease in unit weight compared to the conventional mix. Notably, both the addition of fiber and coal ash contribute to the reduction in unit weight, as both materials are lighter than bitumen. Furthermore, it was observed that the content and length of the fiber exert a substantial influence on minimizing the unit weight of the mixture.

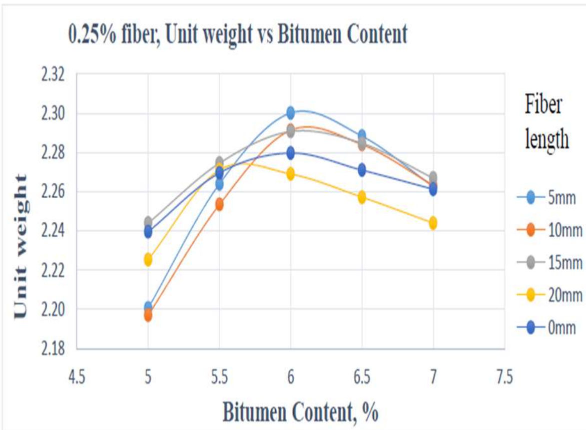

Figure.15 The fluctuation of Unit weight concerning different bitumen content in 0.25% fiber content at different fiber length

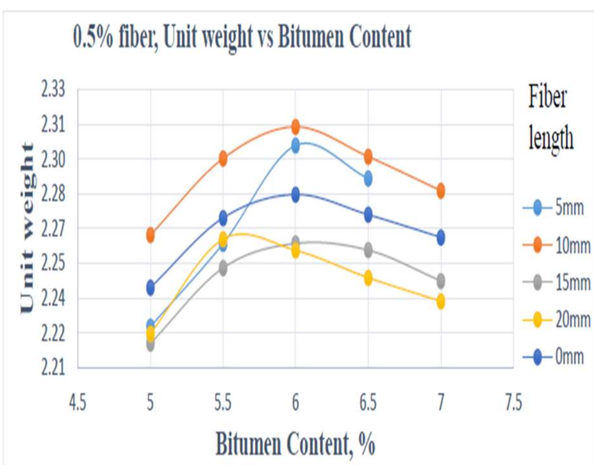

Figure.16 The fluctuation of Unit weight concerning different bitumen content in 0.5% fiber content at different fiber length

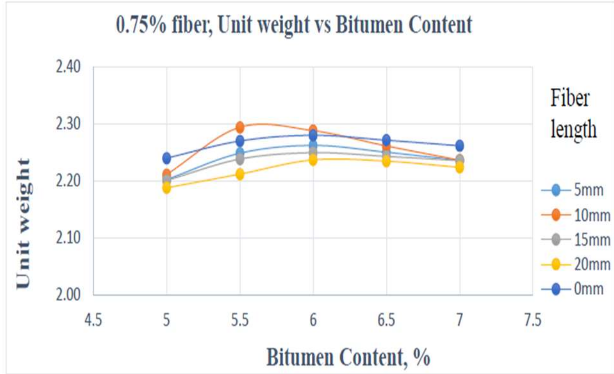

Figure.17 The fluctuation of Unit weight concerning different bitumen content in 0.75% fiber content at different fiber length

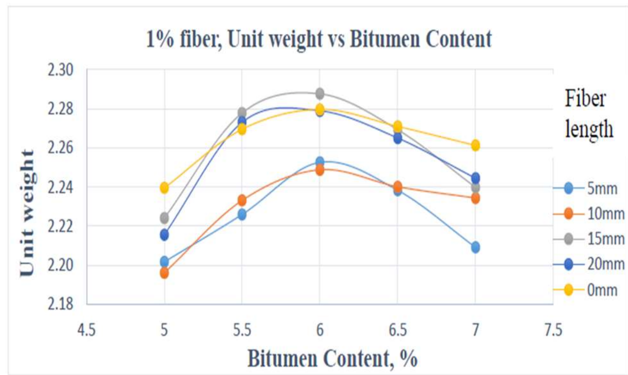

Figure.18 The fluctuation of Unit weight concerning different bitumen content in 1% fiber content at different fiber length

Air Void

Traditionally, Dense Bituminous Macadam (DBM) is characterized by Hot Mix Asphalt (HMA) properties attributed to its well-graded aggregates. However, in the initial phases of this study, DBM samples prepared with coal ash exhibited higher air voids compared to the conventional mix. Consequently, sisal fiber was incorporated to mitigate the air voids. The results, illustrated in figures 19 to 22, unequivocally indicate that an increase in fiber content and length corresponds to a reduction in air voids within the mixture compared to the normal DBM mix. Notably, it was observed that the air voids were 14% less when prepared with optimal coal ash content and sisal fiber properties than the conventional DBM mix.

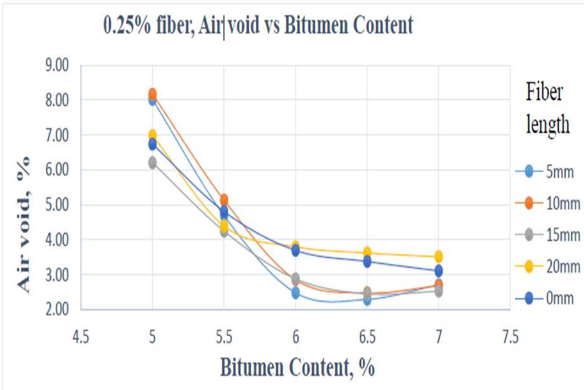

Figure.19 The fluctuation of % air void concerning different bitumen content in 0.25% fiber content at different fiber length

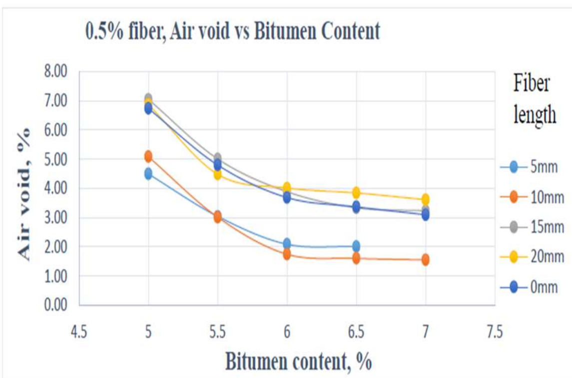

Figure.20 The fluctuation of % air void concerning different bitumen content in 0.5% fiber content at different fiber length

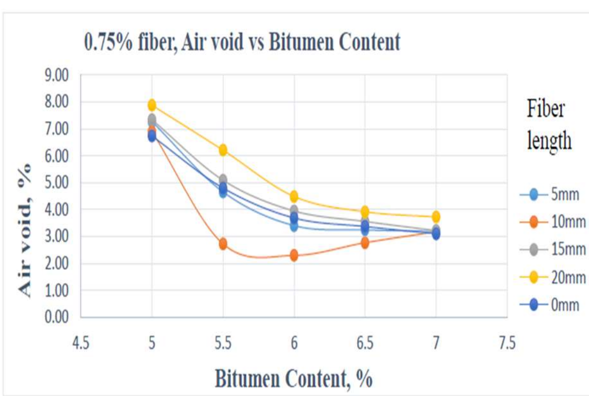

Figure.21 The fluctuation of % air void concerning different bitumen content in 0.75% fiber content at different fiber length

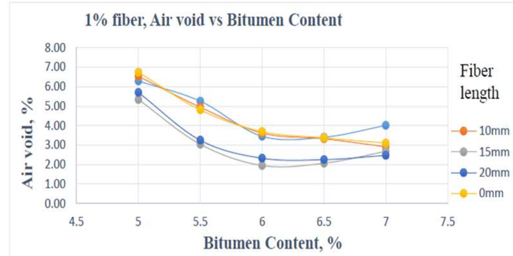

Figure.22 The fluctuation of % air void concerning different bitumen content in 1% fiber content at different fiber length

Voids in Mineral Aggregate (VMA)

The analysis of the Voids in Mineral Aggregates (VMA) and bitumen content, as depicted in figures 5.23 to 5.26, reveals that an increase in fiber length results in an increase in VMA values. The samples prepared with both fiber and coal ash exhibit satisfactory outcomes concerning the design specifications for DBM mixtures.

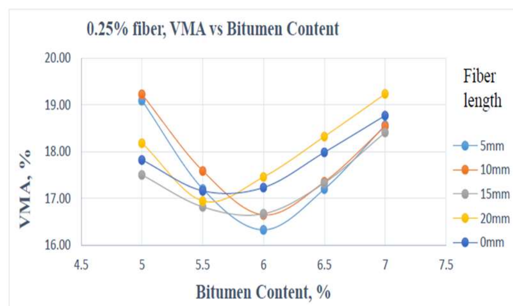

Figure.23 The fluctuation of % VMA concerning different bitumen content in 0.25% fiber content at different fiber length

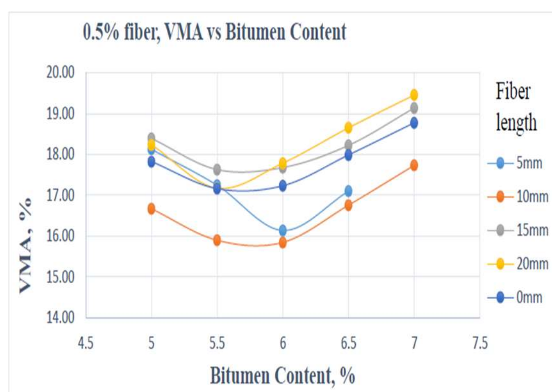

Figure.24 The fluctuation of % VMA concerning different bitumen content in 0.5% fiber content at different fiber length

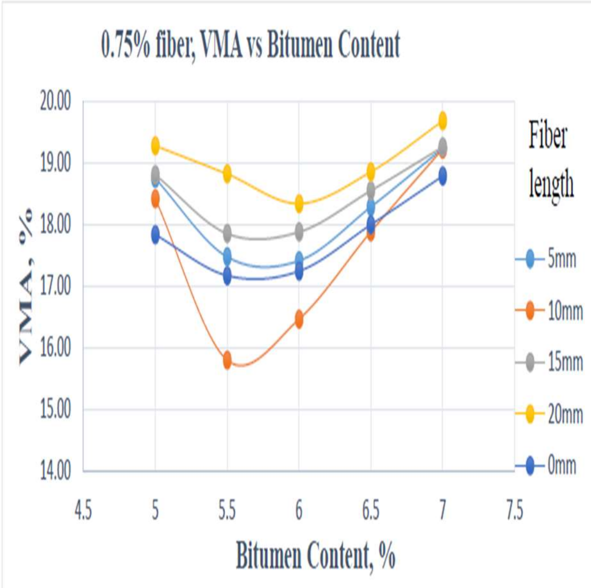

Figure.25 The fluctuation of % VMA concerning different bitumen content in 0.75% fiber content at different fiber length

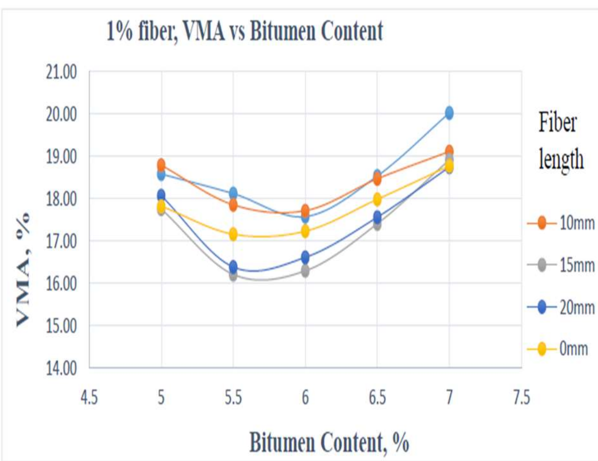

Figure.26 The fluctuation of % VMA concerning different bitumen content in 1% fiber content at different fiber length

Voids Filled with Bitumen (VFB)

The graphs in figures 27 to 30 demonstrate that an increase in binder content corresponds to an increase in Voids Filled with Bitumen (VFB). Additionally, it is observed that, for all fiber content and fiber length variations, the VFB values concerning binder contents show better results compared to the conventional mix.

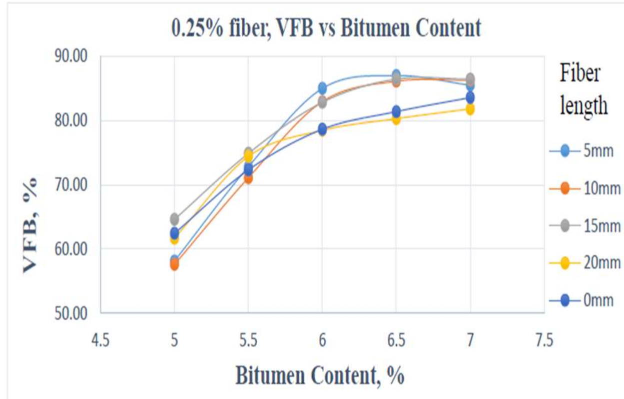

Figure.27 The fluctuation of % VFB concerning different bitumen content in 0.25% fiber content at different fiber length

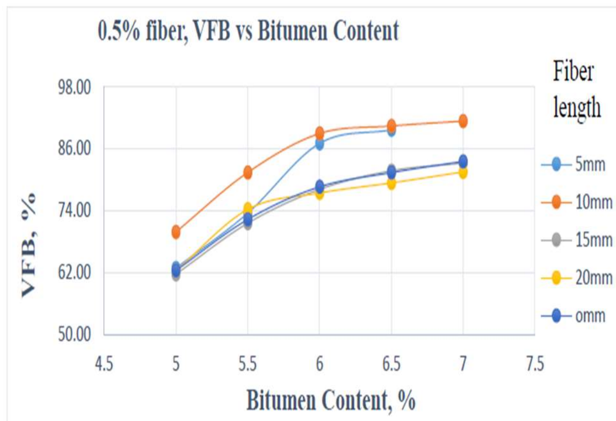

Figure.28 The fluctuation of % VFB concerning different bitumen content in 0.5% fiber content at different fiber length

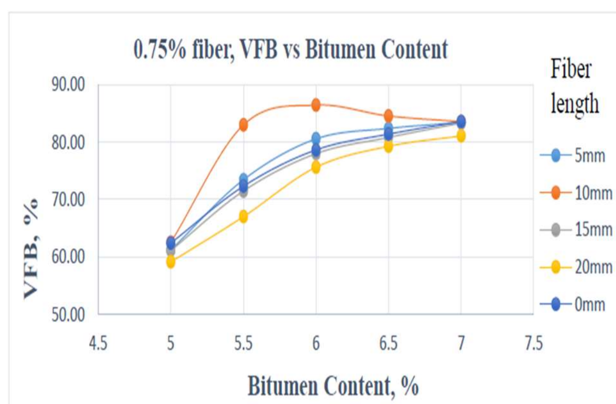

Figure.29 The fluctuation of % VFB concerning different bitumen content in 0.75% fiber content at different fiber length

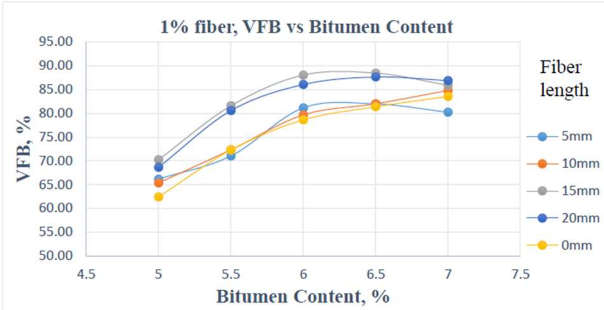

Figure.30 The fluctuation of % VFB concerning different bitumen content in 1% fiber content at different fiber length

Table 1: Marshall property analysis

Fiber content, %	Fiber length, mm	OBC, %	Optimum stability, kN	Flow value, mm	VA, %	VMA, %	VFB, %	Gmb
0.25	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.70	14.20	4.00	3.60	16.70	79.00	2.28
	10	5.78	13.20	3.50	3.60	17.00	76.00	2.28
	15	5.87	12.80	3.80	3.10	16.60	80.00	2.27
	20	5.73	11.90	3.80	4.00	17.00	77.00	2.27
Fiber content, %	Fiber length, mm	OBC, %	Optimum stability, kN	Flow value, mm	VA, %	VMA, %	VFB, %	Gmb
0.5	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.57	13.80	3.85	2.90	17.10	75.00	2.26
	10	5.60	15.00	3.50	2.80	15.80	82.00	2.30
	15	5.80	11.50	3.60	4.30	17.60	76.00	2.25
	20	6.13	12.00	4.90	4.00	17.90	78.00	2.24
Fiber content, %	Fiber length, mm	OBC, %	Optimum stability, kN	Flow value, mm	VA, %	VMA, %	VFB, %	Gmb
0.75	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.90	12.20	3.70	3.60	17.30	80.00	2.26
	10	5.77	13.30	3.10	2.20	15.90	86.00	2.30
	15	6.00	12.50	3.40	4.00	17.90	78.00	2.25
	20	6.13	12.30	3.50	4.30	18.35	77.00	2.24
Fiber content, %	Fiber length, mm	OBC, %	Optimum stability, kN	Flow value, mm	VA, %	VMA, %	VFB, %	Gmb
1	0	5.60	11.40	3.15	2.40	15.30	84.00	2.33
	5	5.93	12.30	4.20	3.70	17.60	80.00	2.24
	10	5.77	12.50	3.40	4.40	17.65	76.00	2.24
	15	5.55	13.40	3.20	2.90	16.10	82.00	2.28
	20	5.63	12.65	3.8	2.40	16.20	83.00	2.28

3:Static Indirect Test

The static indirect tensile test was conducted on four types of samples, including those with fiber and coal ash, with coal ash only, without fiber and coal ash, and with fiber alone. The graph in Figure.32 illustrates the typical trend of a decrease in indirect tensile strength with an increase in temperature. However, the addition of coal ash along with emulsion-coated fiber leads to an increase in the indirect tensile strength of the Dense Bituminous Macadam (DBM) sample compared to the unmodified conventional mix. This enhancement is attributed to the criss-cross pattern of fibers distributed throughout the mixture, resulting in higher tensile strength, as depicted in Figure.31. Additionally, it is noted that coal ash contributes marginally to the increase in tensile strength when compared to the unmodified conventional mix, providing an advantageous effect.

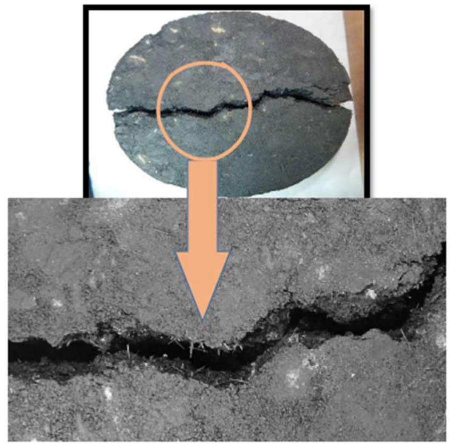

Figure.31 Sisal fiber distribution in a crisscross pattern observed at the point of tensile failure crack.

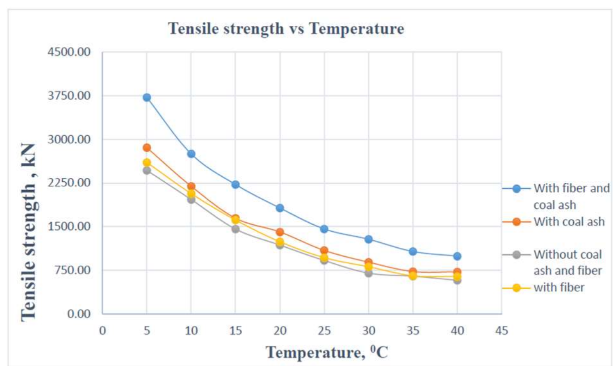

Figure.32 Graph between Tensile strength vs Temperature.

4. Tensile Strength Ratio test

The Tensile Strength Ratio (TSR) test is a method used to evaluate the moisture susceptibility of asphalt mixtures. It involves subjecting cylindrical specimens of the asphalt mix to conditioning in water at an elevated temperature, typically 60°C (140°F), for a specified duration. After conditioning, the specimens are tested to determine their tensile strength both before and after immersion in water. The TSR is calculated as the ratio of the tensile strength after immersion to the tensile strength before immersion. A higher TSR value indicates better resistance to moisture-induced damage, while a lower value indicates greater susceptibility to stripping and degradation of the asphalt mix. This test helps engineers and researchers assess the durability and performance of asphalt mixtures under conditions of moisture infiltration, which is critical for ensuring long-lasting pavement structures.

The table presented in Table 5.2 provides the results of the tensile strength ratio (TSR) for two distinct types of mixes, one being modified and the other unmodified. A notable observation is that the addition of both fiber and coal ash concurrently led to an increased resistance to moisture-induced damage compared to the conventional DBM mixture. This enhancement can be attributed to the reduced amount of air voids in the modified DBM mixture, particularly when prepared with emulsion-coated sisal fiber. Similarly, as per the observations from Table 1, it is noted that a minimal resistance to moisture damage is attained when the mix is prepared with either fiber or coal ash alone.

Table 2: Tensile Strength Ratio (TSR) of DBM mixes with and without the inclusion of fiber and coal ash.

Tensile strength ratio			Design requirement
Type of mixes	DBM With coal ash	DBM Without coal ash	Minimum 80% (as per MORTH specification)
DBM With fiber	84.77%	82.04%	
DBM Without fiber	82.35%	80.26%	

5. Retained Stability test

The Retained Stability test is a method used to evaluate the resistance of asphalt mixtures to permanent deformation or rutting under simulated traffic loading conditions. It is typically conducted as part of performance testing for asphalt pavements. Here's a detailed definition:

Retained Stability refers to the ability of an asphalt mixture to maintain its resistance against permanent deformation after being subjected to repeated loading cycles. The test involves compacting cylindrical specimens of the asphalt mix under controlled conditions to simulate the field compaction process. These specimens are then subjected to repeated compressive loading using a Marshall testing machine or a similar device.

The analysis of retained stability for DBM samples, incorporating fiber, coal ash, and conventional aggregate, is presented in Table 5.3. Remarkably, the samples that included both emulsion-coated fiber and coal ash exhibited superior results compared to the conventional DBM sample. Conversely, the samples prepared solely with coal ash and conventional aggregate demonstrated lower resistance to moisture, resulting in reduced stability below the specified design requirements.

Table 3 Retained Stability of DBM mixes, comparing samples with and without the incorporation of fiber and coal ash.

Retained stability				Design requirement
Type of mixture	Avg. stability after half an hour in water at 60 °c (kN)	Avg. stability after 24 hours in water at 60 °c (kN)	Avg. retained stability (%)	Minimum 75% (as per MORTH specification)
DBM with fiber and Coal ash	14.78	13.21	89.37	
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	

6. Static Creep Test

The static creep test, a measure of permanent deformation under constant loading over an extended period, revealed valuable insights.

In Figure.33, the graph illustrates that the deformation value for the DBM sample, which incorporated 0.5% fiber content, 10mm fiber length, 14% coal ash (comprising 9% bottom ash and 5% fly ash) by weight of the mix, and an optimum binder content of 5.6% by weight of the mixture, exhibited a decrease in deformation compared to other modified and unmodified DBM mixes.

Notably, the addition of either coal ash or fiber in the mixture contributed to a reduction in deformation values when compared to the conventional mixture.

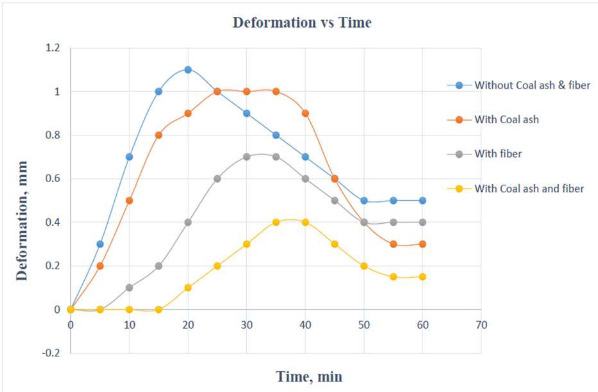

Figure 33 Changes in deformation values at 40°C, over time for the DBM sample.

V. CONCLUSION

1. Optimal Mix Characteristics

The results from the Marshall tests indicated that the Dense Graded Bituminous Macadam (DBM) mixes achieved optimal performance when bottom ash and fly ash were used in particle sizes of 300-75 microns and those passing 75 microns, respectively. The most satisfactory mixes meeting the Marshall criteria were obtained with a bitumen content of 5.6%, a fiber content of 0.5%, and a fiber length of 10mm.

2. Acceptability of Coal Ash Content

The study observed that Marshall stability and flow values remained within acceptable ranges when the coal ash content was maintained at or below 15%. This suggests that coal ash can be effectively utilized in DBM mixes without compromising the essential engineering properties.

3. Influence of Fiber Content and Length

An increase in fiber content and length correlated with a decrease in air-voids and flow, while the Marshall Quotient increased due to higher stability values. This indicates that adjusting fiber parameters can significantly impact the mix's mechanical properties.

4. Optimum Bitumen and Emulsion Requirements

The study revealed that higher fiber content and length necessitated an increased demand for optimum bitumen content and emulsion for effective coating of the fibers. This finding emphasizes the importance of carefully calibrating these components for achieving the desired mix properties.

5. Improved Thermal Cracking Resistance

Indirect tensile strength test results demonstrated that the addition of emulsion-coated fiber and coal ash led to an enhancement in the indirect tensile strength of the samples. This improvement signifies the mix's increased resistance to thermal cracking, thereby enhancing its overall engineering performance.

6. Enhanced Resistance to Moisture-Induced Damages

The incorporation of emulsion-coated fiber, coal ash, or a combination of both in DBM mixes exhibited increased resistance to moisture-induced damages. This was evident in terms of higher tensile strength ratios and retained stability values, emphasizing the mix's durability and longevity under varying environmental conditions.

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