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Optimising Marshall Stability of Coir Fiber Reinforced Dense Bituminous Macadam (DBM) Grade-II with VG-40 Bitumen

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Abstract

This study evaluates the effect of coir fiber incorporation on the Marshall properties and volumetric characteristics of Dense Bituminous Macadam (DBM) Grade II mixes at a fixed Optimum Bitumen Content (OBC) of 4.67 %. Coir fibers were chopped into five lengths (5 mm, 10 mm, 15 mm, 20 mm, and 25 mm) and added at contents ranging from 0.1 % to 0.7 % by weight of bitumen. Standard Marshall specimens were prepared and tested for stability, flow, bulk specific gravity, voids in mineral aggregate (VMA), voids filled with bitumen (VFB), and air voids (Vv). Results indicate that Marshall stability increased significantly with fiber addition, peaking at 17.51 kN for 0.4 % content and 15 mm fiber—approximately 31 % higher than the control (13.38 kN). VFB reached a maximum of 76.19 % at 0.5 % content and 15 mm length. Flow values remained near control up to 0.3 % but increased sharply beyond 0.4 %, indicating reduced compatibility. Optimal performance is achieved at 0.4 %–0.5 % fiber content with 15 mm length, balancing strength and volumetric efficiency.

Key Words: Coir fiber, Dense Bituminous Macadam, Marshall stability, Volumetric properties, Voids Filled with Bitumen (VFB), Optimum fiber content, Fiber length

CHAPTER 1: INTRODUCTION

1.1 Background

Bituminous roads form the backbone of modern transportation infrastructure, particularly in developing nations such as India. Dense Bituminous Macadam (DBM) is a commonly used bituminous base layer in road construction due to its excellent load-distribution capacity and durability. However, traditional DBM mixes face performance issues such as rutting, thermal cracking, fatigue failure, and aging under prolonged environmental and traffic stress. To overcome these limitations and improve the service life of flexible pavements, modification of bituminous mixes through the incorporation of reinforcing agents is increasingly gaining importance.

Among various modifiers, **natural fibers** are garnering attention owing to their sustainability, low cost, biodegradability, and availability. Coir fiber, extracted from coconut husk, is one such lignocellulosic waste material widely available in tropical regions. Its high tensile strength, resistance to microbial degradation, and rough surface texture enable good bonding with bituminous matrices, potentially enhancing the mechanical and volumetric properties of the mix.

This study focuses on evaluating the **Marshall Stability, flow, density, air voids (Vv), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB)** of DBM mixes reinforced with coir fibers of varying lengths (5 mm–25 mm) and contents (0.1%–0.7% by weight of bitumen).

1.2 Problem Statement

Despite the advantages of DBM as a base course, it suffers from limitations such as deformation under heavy loads, low resistance to cracking, and early failure in aggressive climatic conditions. Conventional polymer or synthetic fiber additives are expensive and non-biodegradable, limiting their large-scale use. Coir fiber offers a cost-effective and eco-friendly alternative, yet its effect on DBM performance is not adequately documented, particularly regarding the optimization of **fiber content and length**. There is a pressing need to explore the mechanical response of DBM mixes reinforced with coir fiber and identify the **optimal parameters** that ensure performance enhancement without compromising workability and durability.

1.3 Objectives of the Study

The primary objectives of this study are:

- To determine the **Optimum Bitumen Content (OBC)** for a DBM Grade II mix using VG-40 binder through the Marshall Stability method.
- To evaluate the effect of **varying coir fiber contents** (0.1%–0.7%) and **fiber lengths** (5 mm–25 mm) on the Marshall properties of DBM.
- To analyze the trends in **Marshall Stability, flow, bulk density, Vv, VMA, and VFB** with the addition of coir fiber.
- To determine the **Optimum Fiber Content (OFC)** and **Optimum Fiber Length (OFL)** that yield maximum Marshall Stability with acceptable flow values and favourable volumetric characteristics.

1.4 Scope of the Study

This study is limited to laboratory-based investigations on DBM Grade II mixes as per MoRTH specifications. The fiber used is untreated, natural coir fiber, manually cut to predetermined lengths. All testing follows the guidelines of ASTM D6927 and MoRTH Table 500-10. The mix design is carried out using VG-40 binder. The findings are expected to contribute to **pavement design guidelines** for the incorporation of natural fibers in flexible pavement layers.

1.5 Significance of the Study

- **Sustainability:** Promotes the use of agricultural waste (coir) in road construction, reducing environmental burden.
- **Cost-effectiveness:** Coir fibers are locally available and inexpensive, making them viable for low- and middle-income countries.
- **Performance Improvement:** Potential to increase Marshall Stability, reduce deformation, and enhance load-bearing capacity.
- **Research Gap:** Provides experimental evidence for optimal use of coir fiber in DBM, addressing the limited data available in literature.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The performance of flexible pavements is significantly influenced by the material composition and structure of bituminous layers. Traditional dense bituminous macadam (DBM) mixes have proven effective but exhibit limitations under increasing traffic loads and environmental fluctuations. In recent years, fiber-reinforced bituminous mixes have gained attention for improving structural integrity and durability. Among natural fibers, **coir fiber**—derived from coconut husks—offers promising mechanical properties and environmental benefits. This chapter presents a critical review of past studies that have explored fiber-reinforced bituminous mixes, with an emphasis on the use of **coir fiber** in enhancing Marshall properties.

2.2 Fiber Reinforcement in Bituminous Mixes

Several studies have established that incorporating fibers—synthetic or natural—into bituminous mixes improves fatigue life, resistance to permanent deformation, and structural resilience. Fibers enhance the cohesion within the mix and bridge micro-cracks during loading.

- **Huang et al. (2007)** reported that fiber addition improved stability and fatigue resistance of asphalt mixes, particularly when fiber dosage was optimized.
- **Read and Whiteoak (2003)** noted that fibrous reinforcement provides a three-dimensional reinforcement matrix that delays crack propagation and increases resistance to rutting.

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2.3 Use of Natural Fibers in Pavement Engineering

Due to environmental concerns and rising costs of synthetic fibers, attention has shifted to natural alternatives like jute, flax, bamboo, and coir. These fibers are biodegradable, renewable, and cost-effective.

- **Kumar and Gope (2015)** investigated the use of jute and sisal fibers in bitumen mixes and observed improvements in Marshall Stability and resistance to stripping.
- **Sharma et al. (2018)** highlighted that natural fibers improve mix stiffness and moisture resistance, although performance depends heavily on fiber length, content, and distribution.

2.4 Properties and Potential of Coir Fiber

Coir fiber is a lignocellulosic fiber with high tensile strength, low density, and excellent resistance to bacterial degradation. Its rough surface texture enhances bonding with bitumen.

- **Sundaram and Manivannan (2017)** found that coir fiber addition improved Marshall Stability and reduced flow, making mixes more stable under dynamic loads.
- **Nayak and Das (2014)** observed that 0.3% to 0.5% coir fiber content provided the best balance of stiffness and workability in bituminous mixes.
- **Patil and Jadhav (2020)** noted that fiber length plays a crucial role, with 10–20 mm lengths yielding the best mechanical performance.

2.5 Gaps in Existing Literature

Despite multiple studies on fiber-modified bitumen, the following gaps exist:

- Limited comparative analysis of different **fiber lengths** and **contents** in a single experimental framework.
- Lack of **standardized recommendations** for optimum coir fiber parameters in DBM layers.
- Scarcity of data on the influence of coir fiber on **volumetric properties** like VMA, VFB, and air voids (Vv).

2.6 Research Contribution

This study addresses the aforementioned gaps by:

- Investigating coir fibers with **systematic variation in length (5–25 mm)** and **content (0.1%–0.7%)**.
- Analyzing their effect not only on Marshall Stability and flow, but also on **bulk density, Vv, VMA, and VFB**.
- Providing optimized fiber parameters for **maximum structural performance** of DBM Grade-II mixes using VG-40 binder.

CHAPTER 3: MATERIALS, EXPERIMENTAL METHODOLOGY AND TEST RESULTS

3.1 Materials

3.1.1 Aggregates

- **Source and Type:**:Crushed granite aggregates were procured from a local quarry and sieved into the standard size fractions required for DBM Grade II as per MoRTH specifications.
- **Physical Properties:**:Basic characterization tests on aggregates were carried out in accordance with MoRTH Section 500-14. The results (Table 3.0) confirmed compliance with permissible limits:

Table: 3.1 Basic Tests on Aggregates:

SL NO	TESTS	AGGREGATES	PERMISSIBLE LIMIT (as per table 500-14 of MORTH)
1	Crushing value (%)	21.5	24 max
2	Impact value (%)	19.45	27 max
3	Abrasion value (%)	14.15	35 max
4	Combined Elongation & Flakiness Index (%)	7.73	30 max
5	Specific gravity	2.742	2.5-3.0 max
6	Water Absorption (%)	0.74	2.0 max
7	Coating and stripping of bitumen aggregate mix	97%	Minimum retained coating is 95%

These properties indicate that the aggregates possess adequate strength, toughness, and minimal water absorption for use in DBM.

3.1.2 Bitumen

- **Grade and Source:**VG-40 paving bitumen, supplied by a local bitumen terminal Raja reddy &Co, Adoni, was used throughout this study.
- **Fundamental Properties:**All tests were carried out as per IS 73-2013. The measured properties are summarized as following

Table: 3.12 Basic Tests o Bitumen VG 40:

SL NO	TESTS	VG-40	PERMISSIBLE LIMIT AS PER IS : 73-2013
1	Penetration at 25°C, 5sec	40	Minimum 35
2	Softening point,°C	54	Minimum 50
3	Flash point, °C	>220	Minimum 220
4	Ductility at 25°C,	98	Minimum 25
5	Absolute Viscosity @ 60°C, Poise	4250	3200 -4800
6	Specific gravity	1.02	Minimum 0.99

Prior to mixing, the bitumen was heated to 160 ± 5 °C to achieve a workable viscosity.

3.1.3 Coir Fiber

- **Source and Preparation:** Raw coir fiber was obtained from a local coconut processing unit from bharmavara. The fiber was sun-dried for 48 h, manually cleaned to remove dust and pith, then chopped into specified lengths of 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm using a fine cutter.
- **Properties:** Tensile strength of coir fiber (single strand) was determined as 120 ± 15 MPa, with an average diameter of 200 ± 20 μm.

3.2 Aggregate Gradation and Job Mix Formula (JMF)

3.2.1 Aggregate Fractions

The DBM Grade II gradation limits specified by MoRTH (Table 500-10) were adopted. The individual sieve fractions and combined percent passing are listed in Table 3.2 Key sieve sizes and achieved percentages are as follows:

Table:3.2 DBM Grade-II Aggregate Gradation

Sieve Size	lower limit	Uppar limit	Mid	Limit AS per Morth	Achieved combined gradation
37.5	100	100	100	100.0	100.0
26.5	90	100	95	90-100	100.0
19	71	95	83	71-95	81.4
13.2	56	80	68	56-80	70.3
4.75	38	54	46	38-54	43.5
2.36	28	42	35	28-42	32.4
0.3	7	21	14	7 to 21	13.3
0.075	2	8	5	2 to 8	6.0

The gradation curve obtained (Fig. 3.2) indicates that the as-graded aggregate blend lies well within the upper and lower limits prescribed by MoRTH for DBM Grade II.

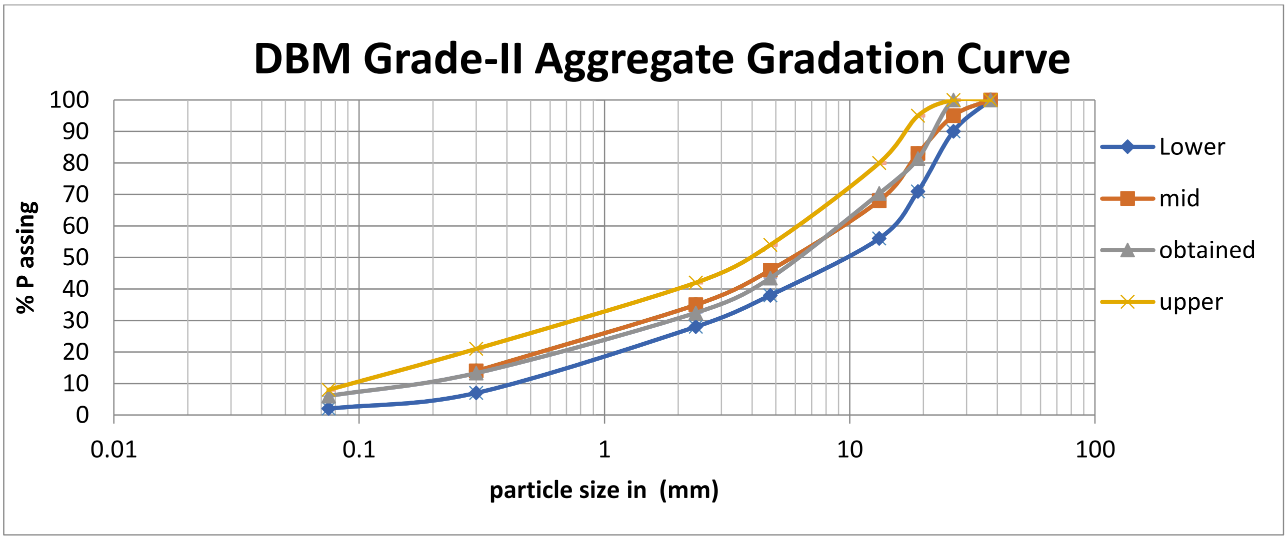

Fig: 3.2 Grade-II Aggregate Gradation Curve

3.3 Marshall Stability Test

- **Target Bitumen Content:** A series of Marshall trials were conducted on bitumen contents of 3.5%, 4.0%, 4.5%, 5.0%, and 5.5% by weight of the total mix.
- **Determination of Optimum Bitumen Content (OBC):**For each trial mix, samples were compacted with 75 blows per face on the Marshall hammer, as per ASTM D6927. Marshall Stability, flow, bulk density, voids in total mix (VTM), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were computed. The graphical plots of stability versus bitumen content, flow versus bitumen content, density versus bitumen content, and VFB versus bitumen content (Fig. 3.3.1) yielded OBC 4.67.

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Table: 3.31 MARSHALL STABILITY TEST FOR CONTROL MIX TO FIND OBC WITHVG 40 BINDERS

sl	% of	Heigh	Stabilit	CF	Correcte	Avg	Flow	Avg	weigh	Avg	weigh	Avg	Gb	Avg	G_T	Vv	Vb	VM	VFB
1	3.5	66.1	5.79	0.9	5.38	6.94	1.81	1.85	1229	1232.0	699	697.5	2.32	2.31	2.47	6.68	7.91	14.59	54.22
2		66.2	9.15	0.9	8.50		1.89		1235		696		2.29						
3	4.0	67.6	10.41	0.8	9.26	9.13	2.18	2.30	1232	1237.0	705	703.5	2.34	2.32	2.45	5.35	9.09	14.45	62.95
4		65.2	9.36	0.9	8.99		2.42		1242		702		2.30						
5	4.5	67	14.69	0.9	13.66	12.99	2.82	2.85	1253	1255.5	715	717.0	2.33	2.33	2.44	4.45	10.29	14.73	69.81
6		66.2	13.24	0.9	12.32		2.88		1258		719		2.33						
7	5.0	65.3	14.88	0.9	14.29	13.62	3.61	3.70	1245	1248.5	715	714.0	2.35	2.34	2.42	3.47	11.45	14.92	76.73
8		67	13.92	0.9	12.95		3.79		1252		713		2.32						
9	5.5	66	14.10	0.9	13.11	12.39	4.12	4.15	1249	1247.0	706	703.5	2.30	2.29	2.37	3.19	12.37	15.56	79.50
10		65.1	12.16	0.9	11.67		4.18		1245		701		2.29						

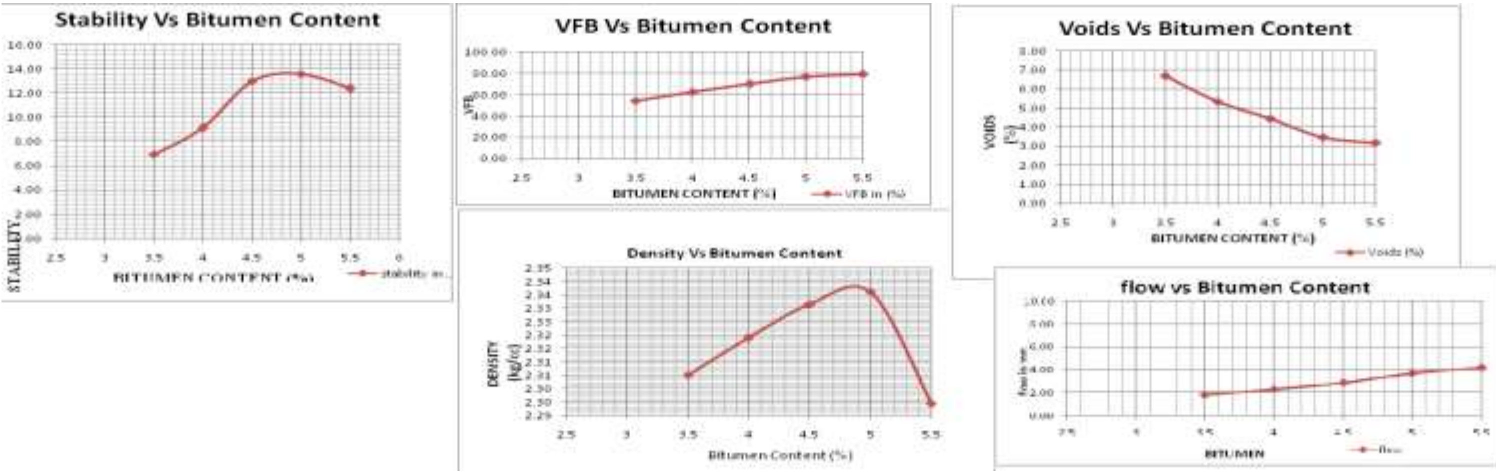

Fig: 3.31 Marshall Properties Graph Vs Various Bitumen Content for Various to find OBC

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- **Compatibility and Volumetric Checks:** At 4.67% bitumen, the mix exhibited:

  By conducting Marshall Test and results are listed

  - **Average Stability:** 13.38 (≥ 9 kN for DBM).
  - **Average Flow:** 3.19 mm (permissible: 2–4 mm; acceptable for DBM).
  - **Bulk Specific Gravity (G_m):** 2.342 g/cm³.
  - **Air Voids (Vv):** 4.28% (target: 3–5%).
  - **VMA:** 14.97 % (minimum required: 14%).
  - **VFB:** 71.42 % (target: 65 ± 5% for DBM, Slightly high acceptable).

Since volumetric properties were within acceptable tolerances, 4.67% bitumen was adopted as OBC for all subsequent fiber-reinforced mixes.

3.4 Specimen Preparation

3.4.1 Control Mix Samples

- Aggregate fractions were oven-dried at 105 ± 5 °C for 4 h to eliminate moisture.
- Heated aggregates were mixed with bitumen at 160 ± 5 °C for 2 min to ensure uniform coating.
- Marshall specimens (100 mm diameter × 63.5 mm height) were prepared by pouring the hot mixture into the mold and compacting 75 blows per side using the standard Marshall hammer.
- Compacted specimens were removed from molds, allowed to cool for 24 h at room temperature (27 ± 2 °C), then tested.

3.4.2 Fiber-Reinforced Mix Samples

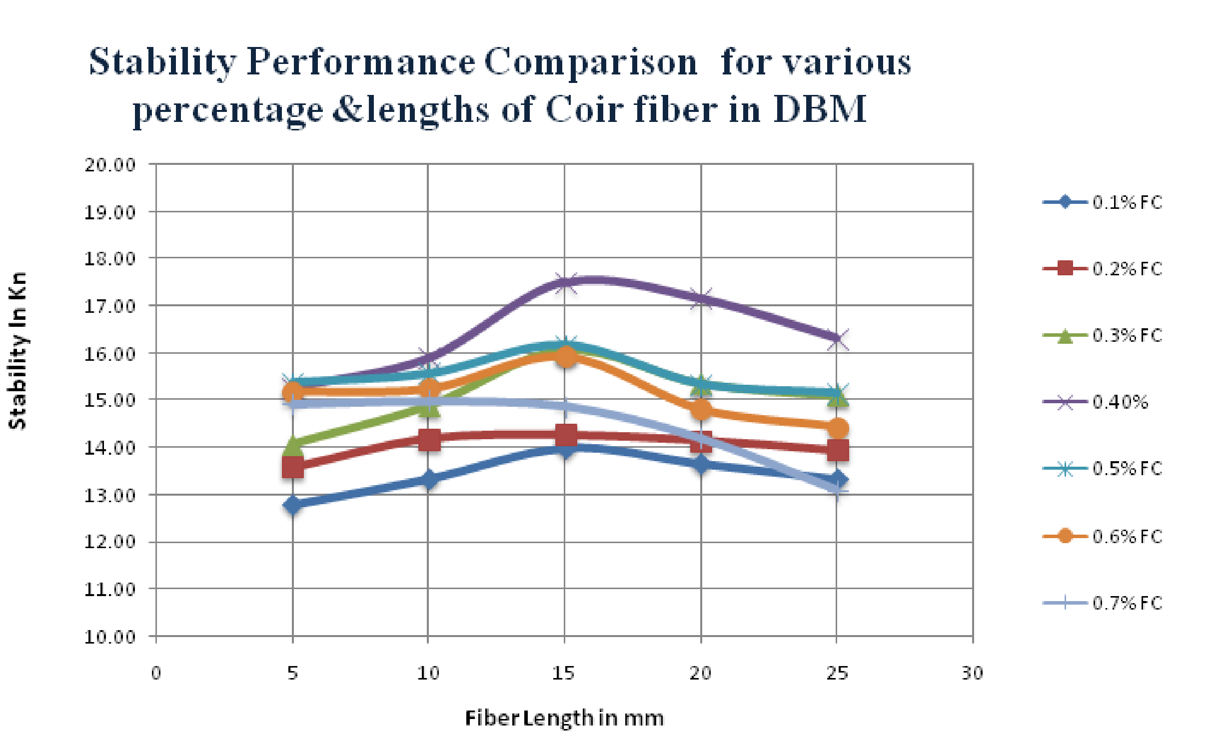
- **Fiber Incorporation:**Pre-weighed coir fibers (0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, and 0.7% by weight of bitumen) were uniformly sprinkled into the heated aggregate-bitumen blend during the mixing stage (at 160 ± 5 °C) and hand-mixed for 2 min to ensure even dispersion.
- **Variation in Fiber Length:**For each fiber content, separate batches were prepared using fiber lengths of 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm.
- **Compaction:**Marshall specimens were compacted similarly (75 blows/face).
- **Curing:**Specimens were cooled and stored for 24 h prior to testing.

4.0 RESULT AND DISCUSSION :

Table 4.1:Comparison Marshall Properties of DBM Without Coir and with Coir Fiber by various Percentage and Lengths

(A) Stability

SL NO	Bitumen Content (%)	Fiber Length in mm	Stabiliy in Kn							
			0%FC	0.1% FC	0.2% FC	0.3% FC	0.4% FC	0.5% FC	0.6% FC	0.7% FC
1	4.67	5	13.38	12.79	13.60	14.08	15.27	15.39	15.19	14.93
2	4.67	10		13.34	14.19	14.90	15.91	15.58	15.25	15.00
3	4.67	15		13.99	14.28	16.06	17.51	16.17	15.94	14.87
4	4.67	20		13.67	14.16	15.37	17.17	15.35	14.83	14.21
5	4.67	25		13.34	13.95	15.11	16.32	15.16	14.44	13.10

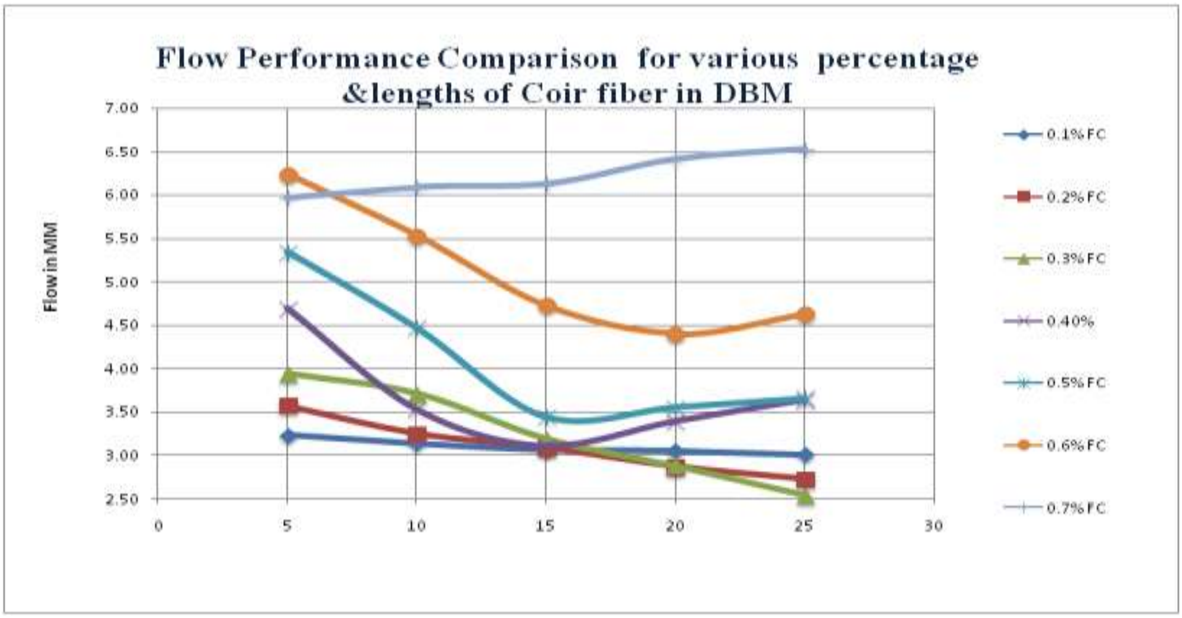


4.1 Variation of Marshall Stability with Fiber Content and Length

- Across all fiber lengths, adding fibers to the mix increases Marshall stability compared to the control OBC mix (13.38 kN).
- At low contents (0.1–0.2 %), stability rises moderately for each length. For instance, at 0.1 % fiber, stability values range from 12.79 kN (5 mm) up to 13.99 kN (15 mm), all already exceeding the control.
- The greatest improvement occurs around 0.3–0.4 % fiber content, particularly for mid-length fibers (15 mm and 20 mm). The peak stability of **17.51 kN** is seen at 0.4 % fiber content with 15 mm length—an increase of 30..86 % over the control. Other lengths follow the same trend, but with lower peak values (e.g., 20 mm yields 17.17 kN at 0.4 %, 10 mm yields 15.91 kN at 0.4 %).
- Beyond 0.4–0.5 % fiber content, stability begins to decline for each length. For example, at 0.6 %–0.7 %, stability for 15 mm drops to ~15.94 kN and 14.87 kN. This suggests an optimal content range before fiber overdosing deteriorates cohesion.

(B) Flow

SL NO	Bitumen Content (%)	Fiber Length in mm	Flow in mm							
			0 % FC	0.1% FC	0.2% FC	0.3% FC	0.4% FC	0.5% FC	0.6% FC	0.7% FC
1	4.67	5	3.11	3.23	3.57	3.94	4.69	5.34	6.24	5.97
2	4.67	10		3.14	3.25	3.71	3.53	4.47	5.53	6.09
3	4.67	15		3.06	3.09	3.19	3.11	3.44	4.73	6.13
4	4.67	20		3.05	2.87	2.88	3.39	3.55	4.40	6.41
5	4.67	25		3.01	2.73	2.54	3.64	3.66	4.63	6.53

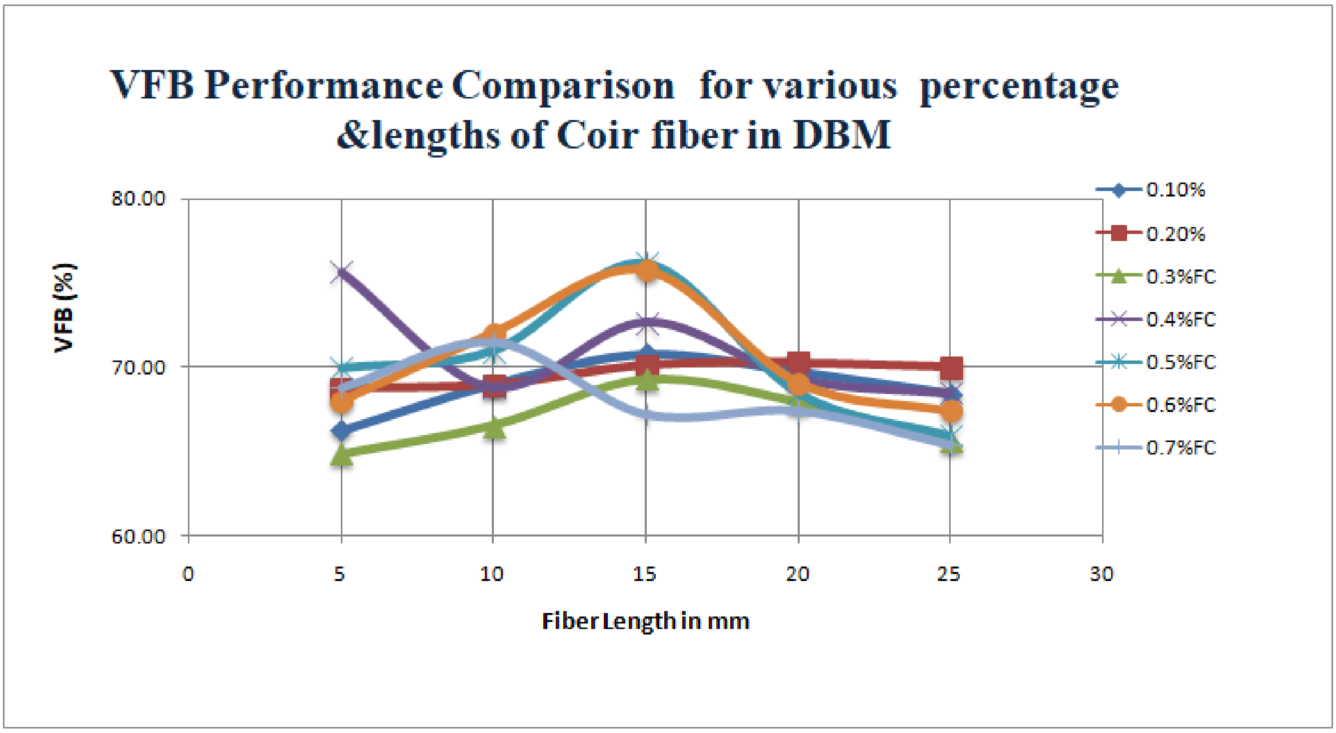


4.2 Variation of Flow with Fiber Content and Length

- Generally, flow increases with fiber content—indicating a reduction in stiffness as fibers prevent tight packing.
- At low fiber contents (0.1 %), flow values are close to the control (3.19 mm)—e.g., 3.06 mm (15 mm) and 3.23 mm (5 mm). As content increases, flow rises nonlinearly: at 0.4 % content, flow for 15 mm is 3.11 mm (still near control), whereas 5 mm is 4.69 mm.
- Beyond 0.4 %, flows escalate sharply—e.g., at 0.6 %, flow for 15 mm is 4.73 mm, and at 0.7 % it reaches 6.13 mm. Longerfibers (25 mm) show lower flow at low contents (2.54 mm at 0.3 %) but catch up to other lengths at higher contents (6.53 mm at 0.7 %).
- The minimum flow across all lengths occurs around 0.2–0.3 %, indicating a more compact, stiffer mix. After that point, excessive fiber leads to poor compaction and rises flow.

(C) VFB

SL NO	Bitumen Content (%)	Fiber Length in mm	VFB in (%)							
			0%FC	0.1% FC	0.2% FC	0.3% FC	0.4% FC	0.5% FC	0.6% FC	0.7% FC
1	4.67	5	71.42	66.28	68.76	64.90	75.7	69.96	68.03	68.83
2	4.67	10		68.98	68.98	66.56	68.82	70.97	72.04	71.52
3	4.67	15		70.82	70.15	69.32	72.67	76.19	75.77	67.22
4	4.67	20		69.72	70.32	67.98	69.37	68.48	69.07	67.42
5	4.67	25		68.45	70.05	65.64	68.51	65.96	67.44	65.42



4.3 Variation of Volumetric Properties (VFB)

- Control Mix (71.42%): Falls within the recommended range, indicating a balanced mix.
- 0.1% to 0.3% FC (69.32%–70.82%): Slightly below or near the control mix, still within acceptable limits but showing no significant improvement.
- 0.4% FC (72.67%): Within the optimal range, showing a slight improvement over the control mix.
- 0.5% FC (76.19%): Slightly above the recommended range, which may suggest excellent durability but risks lower air voids, potentially affecting stability under heavy traffic.
- 0.6% FC (75.77%): Still above the control mix and borderline high, but within acceptable limits for specific conditions.
- 0.7% FC (67.22%): Too low, potentially indicating insufficient bitumen coating or excessive voids due to high fiber content, which could compromise durability.4.4 Suggested Optimum Fiber Content and Length
- The optimum fiber content is 0.4% FC, with a VFB of 72.67%, which is within the recommended 65%–75% range, offering improved durability over the control mix without risking excessive bitumen content.
- The fiber length of 15 mm is suitable based on the results is recommended to confirm the mix's performance under traffic conditions.

o **Optimal combination: 0.4 %–0.5 % fiber content** with **15 mm fiber length**.

- At 0.4 %, stability peaks (17.51 kN) and flow remains acceptable (3.11 mm) and VFB 72.64%

4.5 Effect of Fiber Content

- **Low contents (0.1 %–0.2 %):**
  - Stability increases steadily; flow remains near the control.
  - VFB shows slight fluctuations but roughly parallels the control.
  - These low contents improve fatigue resistance without harming workability.
- **Moderate contents (0.3 %–0.5 %):**
  - Dramatic increases in stability (up to ~31 % higher than control) and VFB.
  - Flow still within acceptable limits (<3.5 mm up to 0.4 % for 15 mm).
  - Mix becomes denser, more cohesive, and better able to resist deformation.
- **High contents (0.6 %–0.7 %):**
  - Stability declines (though still above control) as fiber clusters hinder aggregate interlock.
  - Flow rises sharply (>5.0 mm), indicating a softer mix prone to rutting.
  - VFB begins to fall as fibers occupy excessive space, preventing bitumen from filling voids.

4.6 Effect of Fiber Length

- **Short fibers (5 mm):**
  - Produce moderate stability gains but reach peak stability (~15.39 kN) later (0.5 % content).
  - Flow increases quickly at higher contents (e.g., 6.24 mm at 0.6 %), indicating reduced stiffness.
  - VFB remains on the lower side (66 %–69 %), suggesting less efficient bitumen capture.
- **Mid-length fibers (10–20 mm):**
  - Exhibit the best balance. In particular, **15 mm** yields the highest stability at moderate content and best VFB.
  - **15 mm** also maintains near-control flows up to 0.4 %.
  - **20 mm** is close behind but has slightly lower stability and slightly lower VFB at peak content.
- **Long fibers (25 mm):**
  - Show lower stability at low contents but catch up near 0.3–0.4 %.
  - Flow is lowest at 0.2–0.3 % (2.54 mm), indicating high stiffness, but then increases rapidly beyond 0.4 %.
  - VFB declines steadily beyond 0.3 %, likely due to oversize fibers preventing uniform bitumen distribution.

4.7 Volumetric Trends (Vv, VMA, VFB)

- **Voids in Mineral Aggregate (VMA)** generally decrease slightly up to 0.4 %, then increase or plateau at higher contents—reflecting denser packing around optimum fiber loading.
- **Voids Filled with Bitumen (VFB)** consistently climbs to a maximum at 0.5 % (for 15 mm), indicating improved durability and decreased air voids.
- **Bulk Specific Gravity (G_m)** increases marginally from ~2.30 g/cm³ at low content to ~2.34 g/cm³ at mid-content, then dips slightly at very high fiber contents.
- **Air Voids (Vv)** decrease to a minimum around 0.5 %, then increase again as fiber excess disrupts compaction.

4.8 Comparison with Control OBC Mix Without Fiber

- **Stability**: Control = 13.38 kN. All fiber-reinforced mixes exceed this value even at 0.1 % content. Optimal mixes (0.4 %–0.5 % at 15 mm) reach 17.51 kN and 16.17 kN respectively—a 24 %–31 % improvement.
- **Flow**: Control = 3.19 mm. Fiber mixes have slightly lower or near-control flows at low contents (≤0.3 %), but at higher contents (>0.4 %) they can exceed 4.0–5.0 mm. This shows a trade-off: strength gains vs. stiffness loss.
- **VFB**: Control = 71.42 %. Fiber mixes peak at 76.19 % (0.5 %–15 mm), indicating better bitumen film coverage and potentially greater resistance to moisture damage.
- Overall, fiber addition clearly enhances strength and volumetric efficiency relative to the control, especially when optimized.

4.9 Practical Implications

- **Strength & Durability**: Asphalt pavements reinforced with 0.4 %–0.5 % coir fibers of 15 mm length can better withstand heavy loads and resist rutting due to higher Marshall stability and improved VFB.
- **Fatigue Resistance**: The higher stiffness (lower flow) at moderate contents indicates longer fatigue life—useful for highways and high-traffic roadways.
- **Workability**: Up to 0.4 % fiber content, flow and volumetrics remain close to the control, making mixing and compaction largely unaffected. Contractors can adopt these mixes with standard equipment.
- **Cost–Benefit**: Although fibers add material cost, the improved durability can reduce maintenance intervals. Using 15 mm fibers at 0.4 % optimizes both performance and cost.
- **Limits**: Exceeding 0.6 % fiber content or using fibers>20 mm leads to poor compaction (high flows, reduced VFB), which can increase risk of premature distress (rutting, moisture damage).

5.0 CONCLUSION

This study investigated the effect of varying fiber content (0.1%–0.7%) and fiber length (5 mm–25 mm) on the Marshall properties and volumetric characteristics of bituminous mixes using a fixed Optimum Bitumen Content (OBC) of 4.67%. Based on the experimental results and graphical analysis, the following conclusions can be drawn:

- **Marshall Stability** increased significantly with the inclusion of coir fibers, reaching a peak value of **17.51 kN** at **0.4% fiber content with 15 mm length**, which is approximately **31% higher** than the stability of the control mix (13.38 kN). This demonstrates enhanced load-bearing capacity due to fiber reinforcement.

- **Flow values** remained close to the control (3.19 mm) at lower fiber contents (up to 0.3%), indicating minimal effect on workability. However, at higher contents (≥0.5%), the flow increased substantially, suggesting reduced stiffness due to fiber clustering and reduced compactibility.

- **Volumetric analysis**, particularly **Voids Filled with Bitumen (VFB)**, showed a notable improvement with fiber addition. The maximum VFB value of **76.19%** was achieved at **0.5% fiber content with 15 mm fiber**, indicating denser bitumen coating and improved durability potential but may suffer with minimum Air voids causes bleeding under high temperature and wheel loads.

- The **optimum fiber content** is determined to be **0.4%** while the **optimum fiber length** is **15 mm**, as this combination consistently offered the highest stability, acceptable flow, and superior volumetric properties.

- Fiber reinforcement at moderate levels enhanced both strength and durability without adversely affecting compaction. However, exceeding 0.5% content or using fibers longer than 20 mm led to reduced performance due to poor fiber dispersion and compaction challenges.

- Compared to the control OBC mix without fibers, all fiber-modified mixes showed improved mechanical and volumetric properties, validating the positive contribution of coir fiber reinforcement in bituminous mixtures.

- From a practical standpoint, the use of **0.4% of 15 mm coir fibers** can enhance the structural integrity and longevity of asphalt pavements, making them more resistant to deformation, cracking, and fatigue—especially suitable for high-traffic roads.

REFERENCES

- Bureau of Indian Standards. (2013). *IS 73: Paving bitumen – Specification* (4th Rev.). New Delhi: Bureau of Indian Standards.
- Ministry of Road Transport and Highways (MoRTH). (2013). *Specifications for Road and Bridge Works* (5th Rev.). New Delhi: Indian Roads Congress.
- ASTM International. (2015). *ASTM D6927-15: Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures*. West Conshohocken, PA: ASTM International.
- Huang, Y. H. (2004). *Pavement Analysis and Design* (2nd ed.). Pearson Education.
- Nayak, M., & Das, A. (2014). A study on utilization of coir fiber in bituminous mixes. *International Journal of Engineering Research and Applications*, 4(11), 15–19.
- Patil, P. M., & Jadhav, A. S. (2020). Performance evaluation of coir fiber-modified bituminous mixes. *Materials Today: Proceedings*, 32(Part 2), 443–447. https://doi.org/10.1016/j.matpr.2020.04.676
- Sundaram, N., & Manivannan, R. (2017). Marshall properties of coir fiber modified bituminous mixes. *International Journal of Engineering Trends and Technology (IJETT)*, 48(2), 96–101.
- Sharma, R., Kumar, P., & Singla, S. (2018). Effect of natural fibers on performance characteristics of bituminous concrete. *Construction and Building Materials*, 168, 11–18. https://doi.org/10.1016/j.conbuildmat.2018.02.087
- Kumar, R., & Gope, P. C. (2015). An experimental study on bitumen mix modified with natural fibers. *International Journal of Civil Engineering and Technology (IJCIET)*, 6(6), 27–34.
- Read, J., & Whiteoak, D. (2003). *The Shell Bitumen Handbook* (5th ed.). London: Thomas Telford Publishing.