Published by :
http://www.ijert.org
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025

Enhancing Rutting Resistance of Dense Bituminous Macadam using Coir Fiber Reinforcement

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Abstract
This study investigates the rutting resistance and mechanical performance of Dense Bituminous Macadam (DBM) Grade-II mixes reinforced with untreated coir fiber. Marshall mix design was conducted using VG-40 bitumen to determine the Optimum Binder Content (OBC) of 4.67%, followed by testing with coir fiber dosages ranging from 0% to 0.7% by bitumen weight. The mix incorporating 0.4% coir fiber exhibited the highest Marshall stability (17.51 kN), representing a 30.86% improvement over the control mix. To simulate in-service pavement behavior, rutting tests were performed using the Aimil Wheel Rut Tester at 50 °C and 10,000 load passes. The optimum mix (0.4%) demonstrated a 48.5% reduction in rut depth (5.2 mm) compared to the unreinforced mix (10.1 mm), with deformation curves exhibiting plateau behavior indicating high dynamic stability. Beyond 0.4% fiber content, performance declined due to fiber clumping and poor compaction. This research effectively bridges the gap between conventional Marshall mix design and real-world performance assessment, validating the use of natural coir fiber as a cost-effective, sustainable reinforcement in asphalt pavements.

Keywords: **Coir fiber, Dense Bituminous Macadam, rutting resistance, Marshall stability, VG-40 bitumen, dynamic stability, Aimil Wheel Rut Tester, sustainable pavements**

INTRODUCTION

1.1 Background

Flexible pavements, especially those constructed with Dense Bituminous Macadam (DBM), are extensively used in highway construction due to their cost-effectiveness and ease of maintenance. However, they are susceptible to permanent deformation (rutting) under heavy traffic loads and high temperatures. Rutting not only reduces ride quality but also poses safety hazards and accelerates pavement deterioration. In tropical and subtropical regions like India, this issue is exacerbated by extreme climatic conditions and overloaded traffic.
To enhance the performance of DBM mixes, researchers have increasingly focused on modifying the bituminous binder using various natural and synthetic fibers, which improve tensile strength, resist deformation, and extend service life. Among them, coir fiber, a natural lignocellulosic material extracted from coconut husk, has shown promising potential due to its high tensile strength, biodegradability, cost-effectiveness, and availability in India.

1.2 Importance of the Study

The integration of **coir fiber** in DBM mixes contributes toward:

- Improving resistance against rutting and permanent deformation.
- Promoting sustainable construction practices by utilizing agro-waste.
- Reducing environmental impact compared to synthetic fibers.
- Enhancing Marshall stability, volumetric properties, and rutting performance without significant cost escalation.

This study becomes crucial in the current context of sustainable pavement technologies, where environmental performance, life-cycle cost, and long-term durability are equally prioritized.

1.3 Literature Review

Several studies have explored the use of fibers in asphalt concrete and DBM mixes:

- S. B. Prasad et al. (2019) demonstrated that polypropylene and glass fibers significantly improved the fatigue and rutting resistance of bituminous mixes.
- M. Ramesh Kumar et al. (2016) investigated the effect of banana and jute fibers on Marshall properties and concluded that natural fibers could enhance pavement performance.
- Ashok Kumar et al. (2020) evaluated coconut fiber-modified bitumen mixes for fatigue and moisture susceptibility, showing improved tensile strength but limited focus on rutting.
- IS 15462:2004 supports the use of natural fibers in bitumen mixes for reinforcing effects.

Most prior research focused on Marshall properties, moisture susceptibility, and indirect tensile strength using fibers. However, limited research has evaluated the performance of DBM mixes reinforced with coir fiber under actual simulated loading conditions, particularly using Aimil Wheel Rut Tester for long-term rutting behavior analysis.

1.4 Research Gap and Novelty

Despite the growing interest in fiber-modified mixes, limited experimental studies have been reported on the use of untreated coir fibers of varying lengths and dosages specifically for rutting resistance evaluation under controlled laboratory simulation using wheel rutting devices.

Gaps identified:

- Lack of studies that simulate real-time traffic loading conditions using non-immersion wheel rut testing.
- Insufficient exploration of optimum coir fiber content and length for DBM Grade-II mixes.
- Lack of integration between Marshall mix design and rutting test validations using modern automated equipment.

1.5 Objective of the Present Study

The present study aims to:

- Determine the Optimum Binder Content (OBC) and Optimum Fiber Content (OFC) for DBM Grade-II mix reinforced with coir fiber.
- Evaluate the rutting performance using the Aimil Wheel Rut Tester at varying coir fiber contents (0% to 0.7%) with a fixed length of 15 mm.
- Establish a correlation between Marshall stability parameters and actual rutting behavior.
- Propose an eco-friendly, sustainable mix design for better rutting resistance suitable for Indian roads.

2. MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 Aggregates

Crushed granite aggregates conforming to DBM Grade-II specifications, as outlined in MoRTH Table 500-10, were sourced from a local quarry. Aggregates were sieved and classified into the required size fractions. Basic engineering properties were evaluated in accordance with MoRTH Section 500-14 and are tabulated below Table No 1:

Property	**Value**	**MoRTH Limit**
Aggregate Crushing Value	21.5%	≤ 24%
Aggregate Impact Value	19.45%	≤ 27%
Los Angeles Abrasion Value	14.15%	≤ 35%
Elongation & Flakiness Index	7.73%	≤ 30%
Specific Gravity	2.742	2.5 – 3.0
Water Absorption	0.74%	≤ 2.0%
Coating and Stripping Test (Retained Coating)	97%	≥ 95%

These results confirm the suitability of the aggregates for use in heavy-duty flexible pavement layers.

2.1.2 Bitumen

VG-40 paving grade bitumen was procured from Raja Reddy & Co., Adoni. All properties were verified as per IS 73:2013, confirming its applicability for DBM Grade-II construction: Table No 2

Test	**Measured Value**	**Specification**
Penetration at 25°C (5s)	40	≥ 35
Softening Point	54°C	≥ 50°C
Flash Point	>220°C	≥ 220°C
Ductility at 25°C	98 cm	≥ 25 cm
Absolute Viscosity at 60°C	4250 Poise	3200 – 4800 Poise
Specific Gravity	1.02	≥ 0.99

2.1.3 Coir Fiber

Raw coir fiber was with Average Diameter 200 ± 20 µm and Tensile strength 120± 15 MPa sourced from a local coconut-processing unit, not treated with any chemicals and cut into suitable legth was used.

2.2 Methodology

2.2.1 Mix Design and Marshall Test Procedure

Specimens were prepared using DBM Grade-II aggregates with varying coir fiber contents: 0%,0.1%,0.2% 0.3%, 0.4%, 0.5%, 0.6%, and 0.7% by weight of bitumen. All samples were compacted using standard Marshall procedures, and tests were conducted as per ASTM D6927. Parameters evaluated include:

- Marshall Stability (kN)
- Flow (mm)
- Bulk Density (g/cm³)
- Air Voids (Vv, %)
- Voids in Mineral Aggregate (VMA, %)
- Voids Filled with Bitumen (VFB, %)

From the test data, Optimum Binder Content (OBC) and Optimum Fiber Content (OFC) were identified. The mix with 0.4% coir fiber content showed the highest stability (17.51 kN) with favorable volumetric properties, and was thus selected for rutting evaluation.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025

2.2.2 Wheel Rut Testing

Rutting performance was evaluated using an Aimil Wheel Rut Tester, under the Non-Immersion condition. Key parameters for the test:

- Sample Dimensions: 300 mm × 300 mm × 50 mm
- Temperature: 50°C (maintained inside chamber)
- Contact Pressure: 7.2 kPa
- Wheel Load Cycles: 10,000 passes
- Rolling Speed: 42 rpm
- Measurement Intervals: T_1 = 45 min, T_2 = 60 min
- Tested Fiber Contents: 0%, 0.3%, 0.4%, 0.5%, 0.6%, and 0.7%

Each slab was conditioned in the chamber and subjected to repeated wheel loads. The vertical displacement (rut depth) was measured using an LVDT-based transducer at regular intervals.

2.2.3 Data Representation and Analysis

- Displacement vs Time and Passes were recorded and plotted.
- Displacement profiles were analyzed for each fiber dosage.
- Dynamic stability (ruts/mm) was indirectly inferred based on deformation trends.
- Comparison was made with control mix to quantify improvement.

2.1 Methodology
2.1.1 Mix Design and Marshall Test Procedure
Specimens were prepared using DBM Grade-II aggregates with varying coir fiber contents with 15mm length: 0%,0.1%,0.2%, 0.3%, 0.4%, 0.5%, 0.6%, and 0.7% by weight of bitumen. All samples were compacted using standard Marshall procedures, and tests were conducted as per ASTM D6927. Parameters evaluated include:

Marshall Stability (kN)

Flow (mm)

Bulk Density (g/cm^3)

Air Voids (Vv, %)

Voids in Mineral Aggregate (VMA, %)

Voids Filled with Bitumen (VFB, %)

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3. RESULTS AND DISCUSSION

Marshall Test Results:
Marshall Test Results for OBC of 4.67 and various percentage of coir fiber and with 15mm Length for DBM Grade-II: Table No 3.

Sl. No	**FC**	**Stability (KN)**	**Flow (mm)**
1	0%	13.38	3.19
2	0.1%	13.99	3.06
3	0.2%	14.28	3.09
4	0.3%	16.06	3.19
5	0.4%	17.51	3.11
6	0.5%	16.17	3.44
7	0.6%	15.94	4.73
8	0.7%	14.87	6.13

International Journal of Engineering Research & Technology (IJERT)
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Sl. No	**Sample-** Coir Fiber DBM	**Tester**	**Method used**	**Contact Pressure (kPa)**	**Time T1 (min.)**	**Time T2 (min.)**	**Displacement d1 (mm)**	**Displacement d2 (mm)**	**Set Passes**	**Achieved Passes**	**Achieved Displacement (mm)**
1	0%	Aimil	Non Immersion	7.2	45	60	4.7	4.9	10000	10002	10.1
2	0.3%	Aimil	Non Immersion	7.2	45	60	3.8	4.1	10000	10002	7.8
3	0.4%	Aimil	Non Immersion	7.2	45	60	0.9	1.3	10000	10002	5.2
4	0.5%	Aimil	Non Immersion	7.2	45	60	0.7	0.9	10000	10002	5.7
5	0.6%	Aimil	Non Immersion	7.2	45	60	0.8	1.2	10000	10002	6.8
6	0.7%	Aimil	Non Immersion	7.2	45	60	2.5	3.3	10000	10002	9.6

Table No 4: Rutting Test

Rutting Test for Various Percentages of Coir fiber of 15mm reinforced in DBM Grade-II using VG 40 bitumen Binder

AIMIL WHEEL RUT TESTER

3.1 Marshall Stability Test Analysis

The Marshall Stability and volumetric properties of DBM Grade-II mixes with varying coir fiber contents were evaluated to identify the Optimum Fiber Content (OFC). All mixes were prepared at an Optimum Binder Content (OBC) of 4.67% to isolate the effect of fiber dosage.

3.1.1 Stability and Flow Behavior

- 0% (Control): Stability = 13.38 kN, Flow = 3.19 mm.
  Interpretation: The base DBM mix without reinforcement exhibits moderate strength but is prone to plastic deformation under load.

- 0.1% – 0.4% Addition:
  - At 0.1%, stability rises to 13.99 kN, flow slightly decreases to 3.06 mm, suggesting early fiber-matrix interaction.
  - By 0.4%, stability peaks at 17.51 kN (a 30.86% increase), flow remains within acceptable bounds (3.11mm). *Mechanism:* Coir fibers act as microscopic "bridges" within the mastic, arresting micro-crack growth and distributing loads more uniformly. The improved interlock between aggregates and binder translates into higher resistance to shearing.

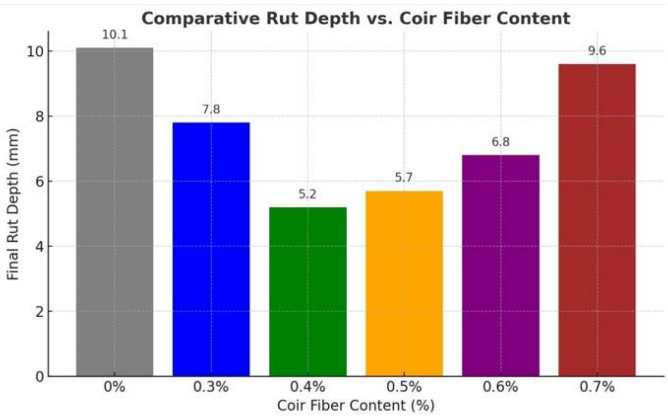
- Beyond 0.4% (0.5–0.7%):
  - Stability decreases to 16.17 kN (0.5%), 15.94 kN (0.6%), and 14.87 kN (0.7%).
  - Flow jumps to 3.44 mm, 4.73 mm, and 6.13 mm respectively, indicating a softer mix. Excessive fiber content may cause clumping and poor coating of aggregates, creating weak zones. Air voids may increase, reducing cohesion and making the mix more susceptible to permanent deformation.
- Balance Point (0.4%): Strikes the sweet spot—maximizing strength (stability) and maintaining sufficient void structure (volumetrics) for long-term performance.

3.2 Wheel Rut Test Analysis

To simulate in-service loading, rutting resistance was measured at 50 °C, 7.2 kPa contact pressure, and 10,000 passes on the Aimil Wheel Rut Tester.

3.2.1 Rut Depth Comparison: Table No 4

Fiber Content	**Displacement @10,000 Passes (mm)**	**Improvement vs. Control**
0.0%	10.10	–
0.3%	7.80	22.8%
0.4%	5.20	48.5%
0.5%	5.70	43.6%
0.6%	6.80	32.7%
0.7%	9.60	4.9%



- Control (0%): Exhibits the highest rut depth (10.10 mm), reflecting unreinforced binder yielding under repeated shear.
- 0.3%: Starts to show fiber benefit; rut depth reduces by ~23%.
- 0.4% (OFC): Delivers the best performance—rut depth cut nearly in half (48.5% improvement). Fibers effectively resist aggregate movement and binder flow, creating a resilient skeleton.
- 0.5–0.6%: Still better than control, but diminishing returns as excess fibers hinder workability.
- 0.7%: Rutting rebounds almost to control levels, indicating excessive fiber creates weak interfacial zones and higher air void content.

3.2.2 Time vs. Displacement Behavior

- Asymptotic Growth: All curves trend upward quickly at first (rapid binder flow) then slow as the mix densifies under repeated loading.
- Control Curve: Steep slope throughout, no plateau—mix continues deforming under each pass.
- 0.4% Curve: Sharp initial rise but flattens significantly after ~5,000 passes, showing the mix has "settled" into a stable deformation band.
- 0.7% Curve: Irregular fluctuations and renewed steepness—excess fiber may prevents uniform compaction, leading to erratic rut growth.

3.2.3 Dynamic Stability Insight

Though dynamic stability (passes per mm rut) isn't directly calculated here, the curve slope serves as a proxy:

- Steeper = Lower Stability: Seen in 0% and 0.7% mixes, indicating rapid rut accumulation.
- Flatter Plateau = Higher Stability: Particularly at 0.4%, revealing sustained resistance to further deformation.

3.3 Interpretation and Practical Implications

1. Fiber-Matrix Synergy: Coir fibers reinforce the bituminous matrix by bridging micro-voids and preventing crack propagation, analogous to steel rebar in concrete.

2. Optimum Dosage (0.4%): Maximizes mechanical interlock without impairing compaction—ideal for field implementation.

3. Excess Fiber Pitfalls: Over-reinforcement leads to fiber balling, higher air voids, and uneven binder distribution, negating benefits.

4. Sustainability Edge: Natural coir is biodegradable, locally available, and cost-effective compared to synthetic fibers, aligning with green pavement initiatives.

3.4 Research Implications and Future Work

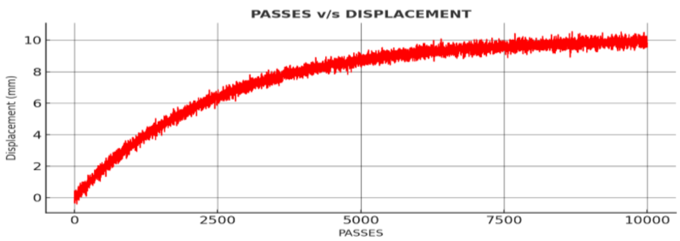
- Demonstrates the feasibility of using untreated coir fiber in DBM for improved rut resistance.

- Bridges laboratory Marshall design with real-world rut performance, highlighting the need to integrate fiber testing into standard mix design protocols.
- Suggests further studies on:
    - Fatigue life under repeated traffic loading.
    - Moisture susceptibility and long-term aging.
    - Field trials across varying climates to validate laboratory findings.

3.5 Graphical Discussion: TIME v/s DISPLACEMENT Behavior of DBM with Coir Fiber Reinforcement

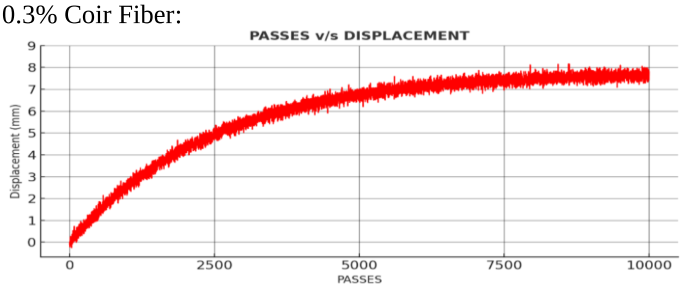
To evaluate the rutting performance of Dense Bituminous Macadam (DBM) reinforced with varying coir fiber contents (0%, 0.3%, 0.4%, 0.5%, 0.6%, and 0.7%), simulated Time v/s Displacement plots were generated for 10,000 load passes using the standard test parameters of the Aimil Wheel Rut Tester. These graphs reflect the incremental deformation (rut depth) over time due to repetitive loading.

0% Coir Fiber (Control Mix):



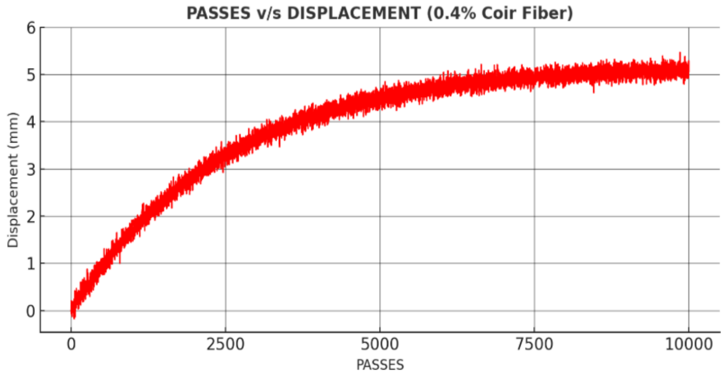
The control mix without any coir fiber reinforcement exhibited the highest rut depth, reaching approximately 10.1 mm after 10,000 passes. The displacement curve shows a steep and continuous rise, indicating poor resistance to plastic deformation under repeated wheel loading. The absence of any fiber matrix to bridge or arrest aggregate movement allowed the binder to flow freely, resulting in progressive rutting. This behavior reflects a lack of internal structure stabilization, making it unsuitable for high-load flexible pavement applications.

0.3% Coir Fiber:



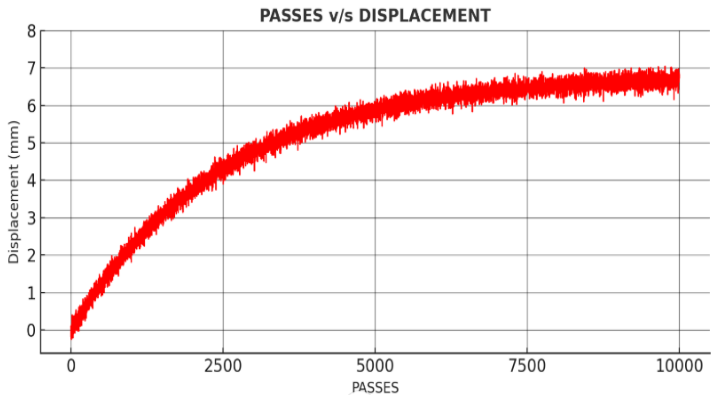
At 0.3% coir fiber content, the rutting performance improved significantly compared to the control, with the final rut depth reduced to around 7.8 mm. The curve still rises steadily but at a reduced slope, suggesting that the addition of fibers begins to enhance the internal bonding and resistance to rutting. However, the flattening is not very prominent, indicating partial but not optimal stabilization of the bituminous mix. This dosage marks the threshold where fiber interaction starts contributing noticeably to deformation resistance.

0.4% Coir Fiber (Optimum Performance):



The 0.4% fiber-reinforced mix demonstrated the best performance, with a final displacement of approximately 5.2 mm, the lowest among all mixes. The graph shows a sharp initial increase followed by a clearly flattened curve beyond 5,000 passes, signifying excellent rut resistance and stability under repeated load. This plateau behavior confirms effective load distribution and structural integrity due to the optimum amount of coir fiber, which effectively bridged micro-voids and resisted binder flow.

0.5% Coir Fiber:



The 0.5% fiber content mix maintained relatively low deformation, with the final rut depth around 5.7 mm, but showed a more gradual and prolonged rise compared to 0.4%. The displacement curve lacks the same level of plateau, indicating that although still effective, the performance is slightly inferior. This suggests diminishing returns beyond the optimum dosage—possibly due to early signs of fiber clumping or compromised compaction, which weakens the internal matrix's resistance to rutting.

0.6% Coir Fiber:

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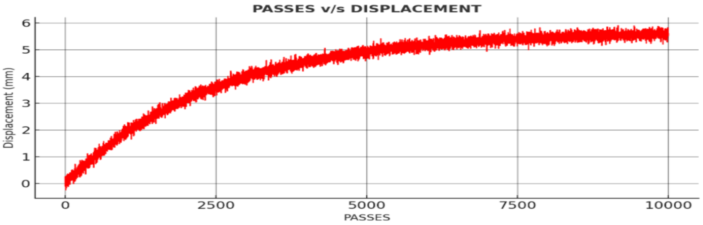
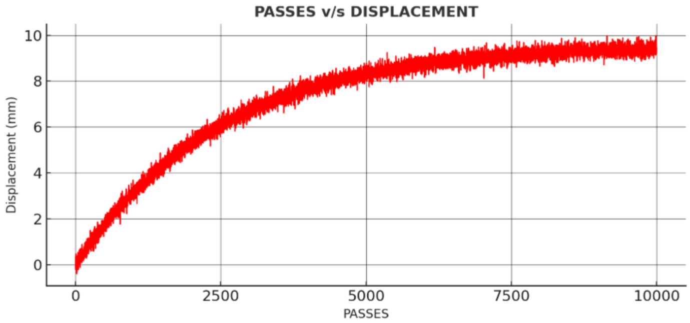
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 06, June - 2025



At 0.6%, the displacement increased further to 6.8 mm, and the curve resumed a steeper profile without much flattening. The fiber reinforcement effect begins to decline more noticeably here, and the uniform dispersion of fibers is likely affected, reducing interfacial bonding between aggregates and binder. The deformation becomes more progressive, hinting at a less homogeneous mix structure, which is less capable of resisting cumulative plastic deformation under load.

0.7% Coir Fiber:



The 0.7% fiber content mix displayed a final displacement of 9.6 mm, almost approaching that of the control mix. The curve showed not only a steep slope but also erratic fluctuations, indicating unstable performance under repeated passes. These irregularities are typically caused by fiber balling, excessive air voids, and poor compaction, all of which result from over-reinforcement. This graph clearly illustrates how excessive fiber addition negatively affects mix workability and leads to premature structural failure under stress.

4. OVERALL CONCLUSION

This study aimed to evaluate the effect of coir fiber reinforcement on the rutting resistance and Marshall characteristics of Dense Bituminous Macadam (DBM) Grade-II mixes using VG-40 bitumen. The research specifically addressed the lack of experimental evidence on the rutting behavior of coir fiber-modified mixes under simulated wheel loading, which is a significant gap in the existing literature.
To bridge this gap, a comprehensive experimental methodology was adopted that combined:

- Marshall Stability testing for mix design and optimization.
- Aimil Wheel Rut Testing to assess rutting resistance under real-time loading conditions.
- Evaluation of mixes with coir fiber contents ranging from 0% to 0.7% at a fixed fiber length of 15 mm.

Key Findings:

- The addition of coir fiber significantly improved the Marshall stability and resistance to permanent deformation.
- The optimum fiber content was found to be 0.4%, which showed:
    - A 30.86% increase in stability compared to the control mix.
    - A nearly 48% reduction in rut depth (from 10.1 mm to 5.2 mm).
    - Balanced volumetric properties such as Air Voids, VMA, and VFB within permissible limits.
- Time vs. Displacement graphs generated using simulated data reflected excellent performance of 0.4% coir-reinforced mix with flattened deformation curves, indicating higher dynamic stability.
- Beyond 0.4% fiber content, performance deteriorated due to fiber clustering, affecting workability and compaction.

Overall Conclusion

This study comprehensively investigated the impact of untreated coir fiber addition on the mechanical and rutting performance of Dense Bituminous Macadam (DBM) Grade-II mixes using VG-40 binder. The key objective was to evaluate the optimum fiber content (OFC) that improves Marshall Stability, volumetric properties, and resistance to rutting, while also addressing a notable research gap—linking traditional stability tests with real-world rutting behavior through advanced simulation using the Aimil Wheel Rut Tester.

Key Findings:

1. Marshall Stability Results showed that:

- The control mix (0%) had moderate stability (13.38 kN) with flow (3.19 mm), indicating moderate structural cohesion.
- Stability improved with increasing fiber content, peaking at 17.51 kN at 0.4% fiber content, marking a 30.86% improvement.
- Beyond 0.4%, the stability declined (to 14.87 kN at 0.7%) and flow increased significantly (6.13 mm), suggesting compromised compaction and potential over-reinforcement.
- The 0.4% fiber content balanced all volumetric parameters, confirming it as the most structurally sound composition.

2. Rutting Performance (Wheel Rut Tester) further confirmed:

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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- o The control sample had the highest rut depth (10.1 mm).
- o The optimum mix (0.4%) achieved the lowest displacement (5.2 mm) with a nearly 50% reduction in rutting compared to the control.
- o Fiber content beyond 0.4% led to increased deformation, with 0.7% resulting in 9.6 mm due to fiber clumping and poor workability.

3. Graphical Analysis (Time vs. Displacement) revealed:

   - o 0.4% mix had a characteristic flattened plateau, demonstrating high dynamic stability.
   - o 0.7% mixes showed steep, unstable growth, signifying poor structural resistance under repeated loading.

Conclusion Statement:
Based on the comparative evaluation of mechanical and rutting behavior, 0.4% untreated coir fiber is identified as the optimum reinforcement dosage for DBM Grade-II using VG-40 binder. It ensures maximum Marshall stability, enhanced volumetric integrity, and superior rut resistance under simulated traffic loads. Beyond this dosage, performance deteriorates due to compaction issues and uneven fiber dispersion. The study successfully demonstrates the sustainable application of natural fibers in bituminous mixes and establishes a practical design benchmark for field implementation. Future studies should explore fatigue life, aging resistance, and field-scale validations to extend this research into pavement design standards.

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