

EFFECT OF SPEED ON RUTTING BEHAVIOR OF STONE MASTIC ASPHALT (SMA) USING RAP AND WARM MIX ADDITIVES

POORNACHANDRA THEJASWI S

Research Scholar, BMSCE R & D, Affiliated to Visvesvaraya Technological University, Belagavi, Karnataka, India. Assistant Professor, Department of Civil Engineering, Bangalore Institute of Technology, Bengaluru, Karnataka, India.

Dr. K GANESH

Professor, Department of Civil Engineering, BMS College of Engineering, Bengaluru, Karnataka, India.

ADARSH B V

M.Tech Student, Department of Civil Engineering, BMS College of Engineering, Bengaluru, Karnataka, India.

Abstract

This study investigates the rutting performance of Stone Mastic Asphalt (SMA) mixtures incorporating Reclaimed Asphalt Pavement (RAP) and Warm Mix Asphalt (WMA) additives, with a specific focus on the influence of wheel tracking speed under controlled loading conditions. Two SMA gradations were examined: SMA-1 with cellulose fiber and SMA-2 with coconut fiber as the stabilizing agent. The use of coconut fiber was explored as a sustainable alternative to cellulose, aiming to reduce environmental impact while maintaining mechanical stability. RAP content was varied from 40–60%, while WMA additives Zycotherm (0.05–0.15%) and Wetbond (0.3–0.7%) were employed to reduce production temperatures and enhance binder–aggregate adhesion. Marshall mixes design determined the optimum binder content (OBC) for each blend, and Immersion Wheel Tracking Tests were conducted at tire pressure of 1160 kN/m² and wheel speeds of 20, 25, and 30 passes/min to evaluate rutting characteristics. Statistical analysis using ANOVA validated the significance of the observed trends. Results indicated that the SMA-2 mix with 50% RAP and 0.7% Wetbond exhibited the lowest rut depth and highest rutting resistance, outperforming the cellulose fiber mix in both elastic and plastic deformation control. The incorporation of RAP and WMA reduced virgin aggregate demand, lowered mixing and compaction temperatures, and enhanced sustainability by utilizing locally available coconut fibers to prevent binder draindown. The findings demonstrate that optimized RAP–WMA–fiber combinations can produce durable and environmentally responsible SMA pavements, making them highly suitable for high-traffic and heavy-load roadways.

Keywords: Stone Mastic Asphalt, Reclaimed Asphalt Pavement, Warm Mix Additives, Rutting Resistance, Sustainable Pavement Materials.

1. INTRODUCTION

Background and Rationale

Stone Mastic Asphalt (SMA) is a high-performance gap-graded asphalt mixture originally developed in Germany during the late 1960s to withstand rutting caused by studded tires. Its structure, characterized by a coarse aggregate skeleton bound by a mastic of bitumen, filler, and stabilizing fibers, provides superior load distribution, deformation resistance, and durability. SMA's performance is largely attributed to the stone-on-stone contact of coarse aggregates, which transfers loads more effectively than dense-graded mixes.

The stabilizing fibers serve a critical function by immobilizing the binder and preventing draindown during transport and placement.

In recent years, Reclaimed Asphalt Pavement (RAP) has emerged as a key component in sustainable pavement engineering. RAP contains high-quality aggregates and aged binder, enabling cost savings and conservation of natural resources. However, the increased stiffness of RAP binders can adversely affect rutting resistance if not properly rejuvenated. Warm Mix Asphalt (WMA) additives such as Zycotherm and Wetbond provide a solution by lowering production temperatures, improving binder workability, and enhancing aggregate coating, even at high RAP contents.

Sustainability Imperatives

The integration of RAP and WMA in SMA mixtures aligns with circular economy principles by reducing virgin material consumption, lowering greenhouse gas emissions, and conserving energy during production. Furthermore, substituting cellulose fibers with coconut fibers, a renewable agricultural by-product, addresses waste valorization while offering comparable performance in stabilizing the mastic phase.

Existing Research Gaps

Previous studies have examined SMA performance with RAP contents up to 50% and various WMA additives, often focusing on Marshall stability, moisture susceptibility, or fatigue resistance. However, limited research addresses the combined influence of RAP, WMA, and alternative fibers on rutting behavior under varying traffic speeds, particularly using Immersion Wheel Tracking Tests that simulate submerged pavement conditions. This study aims to bridge that gap.



(a) Cellulose fiber

(b) Coconut fiber



(c) Zycotherm



(d) Wetbond



(e) Immersion Wheel Tracking test equipment

Objectives

The specific objectives of this research are to:

1. Evaluate the Marshall properties of SMA mixes with RAP and WMA additives, comparing cellulose and coconut fibers.
2. Assess rutting behavior under different wheel tracking speeds using Immersion Wheel Tracking Tests.
3. Quantify elastic and plastic deformation coefficients for optimized SMA blends.
4. Demonstrate the environmental and economic benefits of using high RAP content, WMA, and coconut fibers in SMA production.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Aggregates

Locally sourced coarse and fine aggregates conforming to MoRTH Table 500-16 specifications for SMA were used.

Gradation followed the Rothfutch method to ensure stone-on-stone contact, a key requirement for rutting resistance.

Physical and mechanical properties met Indian Standard (IS) limits for flakiness, elongation, crushing value, impact value, abrasion resistance, water absorption, and specific gravity

Table 1: Test on Aggregates

Sl.no	Property	Tests	Results	Specification as per MoRT&H Table 500-16	IS CODE
1	Particle Shape	Combined flakiness and elongation test (%)	23.45	Max.3%	IS 2386-part 1
2	Toughness	Crushing value test (%)	20.20	Max. 30%	IS 2386-part 4
3	Strength	Impact test (%)	15.51	Max.24%	IS 2386-part 4
4	Abrasion	Los angeles abrasion test (%)	20.48	Max.30%	IS 2386-part 5
5	Water absorption	Water absorption Test (%)	0.35	Max.02%	IS 2386-part 3
6	Specific Gravity Test	Specific Gravity test	20 mm down=2.6 12 mm down=2.62 6 mm down=2.66 Dust =2.7	Min. 2.6	IS 2386-part 3

2.1.2 Bitumen

VG-30 grade paving bitumen was selected due to its suitability for high-temperature regions, providing improved rutting resistance.

Standard binder tests—including penetration, softening point, ductility, specific gravity, and flash/fire point—confirmed compliance with IS standards (Table 2).

Table 2: Tests on Conventional Bitumen (VG 30)

PROPERTY	IS SPECIFICATION	VG 30	IS CODE
Penetration at 25 °C, mm	60-70	66	IS: 1203-1978
Flash point, °C	Minimum value should be 220°C	260°C	IS: 1209-1978
Softening point, °C	35-70°C	50.82°C	IS: 1205-1978
Ductility at 25°C, cm	Should not be less than 75	100 cm	IS: 1208 -1978
Specific Gravity	0.97-1.02	1.015	IS: 1202-1978

2.1.3 Stabilizing Fibers

Two types of fibers were used to prevent binder draindown and enhance mix stability:

- Cellulose fiber (commercial SMA stabilizer) – high binder absorption capacity, commonly used in SMA worldwide.
- Coconut fiber – a sustainable alternative, sourced locally, offering high tensile strength, biodegradability, and the ability to prevent binder segregation.



Figure 1: presents the fiber types used in this study

Table 3: Results on Bitumen Draindown Test

Fibres used	Bitumen Draindown, %	MoRTH specification Table 500-38
Cellulose	0.03	Max 0.3 %
Coconut	0.02	Max 0.3 %

2.1.4 Reclaimed Asphalt Pavement (RAP)

RAP was obtained from milled asphalt layers of a reclaimed pavement. The material was processed through crushing, sieving, and binder content determination.

RAP particle size distribution was aligned with SMA requirements. The aged binder in RAP necessitated rejuvenation via WMA additives. Figure 2 shows the processed RAP material.

2.1.5 Warm Mix Asphalt (WMA) Additives

Two WMA additives were used:

- Zycotherm – a chemical additive enhancing moisture resistance and enabling lower mixing and compaction temperatures.
- Wetbond – a liquid additive improving aggregate–binder adhesion and reducing stripping potential.



Figure 3: shows the WMA additives used in the study

2.2 Experimental Plan

A schematic flowchart (Figure 4) outlines the research methodology, from material collection to performance evaluation.

Key steps include:

1. Material Characterization – Aggregate and binder testing.
2. Marshall Mix Design – Determination of Optimum Binder Content (OBC) for SMA-1 (cellulose) and SMA-2 (coconut) with varying RAP and WMA dosages.
3. Specimen Preparation – Marshall and wheel tracking specimens with controlled mixing and compaction temperatures.
4. Performance Testing – Marshall Stability test, Immersion Wheel Tracking Test at varying speeds, and determination of rutting coefficients.
5. Statistical Analysis – ANOVA to assess the influence of RAP, WMA, and fiber type.



Figure 4: Flowchart of Experimental Plan for SMA Rutting Evaluation



Figure 5: Immersion Wheel Tracking Test setup

3. EXPERIMENTAL METHODOLOGY

3.1 Overview of Experimental Program

The experimental program was designed to evaluate the rutting resistance of Stone Mastic Asphalt (SMA) mixes incorporating different fiber types (cellulose and coconut), varying proportions of Reclaimed Asphalt Pavement (RAP), and Warm Mix Asphalt (WMA) additives (Zycotherm and Wetbond). A flowchart of the overall experimental plan is presented.

3.2 Mix Design Procedure

3.2.1 Aggregate Gradation and Binder Selection

- Aggregates were combined to achieve the gap-graded SMA gradation as per MoRT&H specifications.
- VG-30 grade bitumen was selected for its high-temperature performance.

3.2.2 RAP Processing and Characterization

- RAP was collected from reclaimed pavement layers, crushed, and sieved.
- The binder content and gradation of RAP were determined before blending.

3.3 Marshall Mix Design

The Marshall method was used to determine the Optimum Binder Content (OBC) for each combination.

- Mixing temperature: 150–155 °C for conventional SMA, reduced by ~15 °C for WMA-modified mixes.
- Compaction temperature: 140–145 °C for conventional SMA, proportionally reduced for WMA mixes.
- RAP proportions tested: 0%, 40%, 50%, and 60%.
- WMA additive dosages: Zycotherm (0.05%, 0.10%, 0.15%), Wetbond (0.3%, 0.5%, 0.7%).

The Marshall Stability, flow, air voids, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were determined according to IS:1201–1220.

Table 4: Marshall Stability Properties for Various SMA mixes

Marshall mixes	OBC (%)	Max stability (kN)	Flow (mm)
SMA 1 (Cellulose Fiber)	6.45	15.8	2.59
SMA 2 (Coconut Fiber)	6.41	17.03	2.59
SMA 1+ RAP 40%	6.4	23.97	4.39
SMA 1+ RAP 50%	6.38	25.65	3.84
SMA 1+ RAP 60%	6.53	24.21	4.24
SMA 2+RAP 40%	6.37	24.6	3.76
SMA 2+ RAP 50%	6.37	25.8	4.14
SMA 2+ RAP 60%	6.43	24.33	4.42
SMA 1+ RAP 50%+Zycotherm 0.05%	6.35	15.31	6.87
SMA 1+ RAP 50%+Zycotherm 0.10%	6.37	15.1	6.99
SMA 1+ RAP 50%+Zycotherm 0.15%	6.37	14.59	9.92
SMA 2+ RAP 50%+ Zycotherm 0.05%	6.33	12.13	6.66
SMA 2+ RAP 50%+ Zycotherm 0.10%	6.35	16.34	7.1
SMA 2+ RAP 50%+ Zycotherm 0.15%	6.35	13.69	7.7
SMA 1+ RAP 50%+WetBond 0.3%	6.37	13.16	7.96
SMA 1+ RAP 50%+WetBond 0.5%	6.37	14.39	7.44
SMA 1+ RAP 50%+WetBond 0.7%	6.37	15.87	7.18
SMA 2+ RAP 50%+ WetBond 0.3%	6.35	13.8	8.38
SMA 2+ RAP 50%+ WetBond 0.5%	6.3	14.54	7.65
SMA 2+ RAP 50%+ WetBond 0.7%	6.32	18.02	6.65

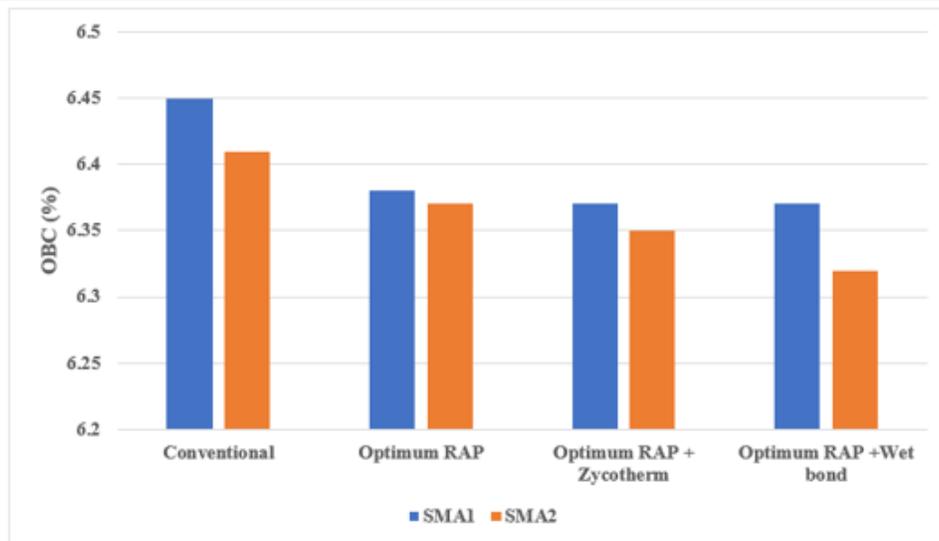


Figure 6: Graph Showing OBC for Various SMA mixes

3.4 Preparation of Wheel Tracking Test Specimens

Slab specimens (600 mm × 100 mm × 50 mm) were prepared using a Universal Testing Machine (UTM) for compaction to achieve target field density. All combinations tested in the Marshall method were also prepared for wheel tracking.

3.5 Immersion Wheel Tracking Test Procedure

- Test conditions: Tire pressure fixed at 1160 kN/m².
- Wheel speeds: 20, 25, and 30 passes/min.
- Loading: Specimens submerged in water and subjected to 10,000 passes.
- Measurements: Rut depth recorded using LVDT sensors at specified intervals.

3.6 Determination of Rutting Coefficients

The rutting coefficient (R) was calculated from the wheel tracking data using:

$$BR=A \cdot B$$

Where:

- **A** = Elastic coefficient (represents recoverable deformation)
- **B** = Plastic coefficient (represents permanent deformation)

Two points on the rut depth vs. number of passes curve were used to determine the coefficients for each test condition.

Table 5: Marshall Stability Properties for Various SMA mixes

Marshall mixes	OBC (%)	Max stability (kN)	Flow (mm)
SMA 1 (Cellulose Fiber)	6.45	15.8	2.59
SMA 2 (Coconut Fiber)	6.41	17.03	2.59
SMA 1+ RAP 40%	6.4	23.97	4.39
SMA 1+ RAP 50%	6.38	25.65	3.84
SMA 1+ RAP 60%	6.53	24.21	4.24
SMA 2+RAP 40%	6.37	24.6	3.76
SMA 2+ RAP 50%	6.37	25.8	4.14
SMA 2+ RAP 60%	6.43	24.33	4.42
SMA 1+ RAP 50%+Zycotherm 0.05%	6.35	15.31	6.87
SMA 1+ RAP 50%+Zycotherm 0.10%	6.37	15.1	6.99
SMA 1+ RAP 50%+Zycotherm 0.15%	6.37	14.59	9.92
SMA 2+ RAP 50%+ Zycotherm 0.05%	6.33	12.13	6.66
SMA 2+ RAP 50%+ Zycotherm 0.10%	6.35	16.34	7.1
SMA 2+ RAP 50%+ Zycotherm 0.15%	6.35	13.69	7.7
SMA 1+ RAP 50%+WetBond 0.3%	6.37	13.16	7.96
SMA 1+ RAP 50%+WetBond 0.5%	6.37	14.39	7.44
SMA 1+ RAP 50%+WetBond 0.7%	6.37	15.87	7.18
SMA 2+ RAP 50%+ WetBond 0.3%	6.35	13.8	8.38
SMA 2+ RAP 50%+ WetBond 0.5%	6.3	14.54	7.65
SMA 2+ RAP 50%+ WetBond 0.7%	6.32	18.02	6.65

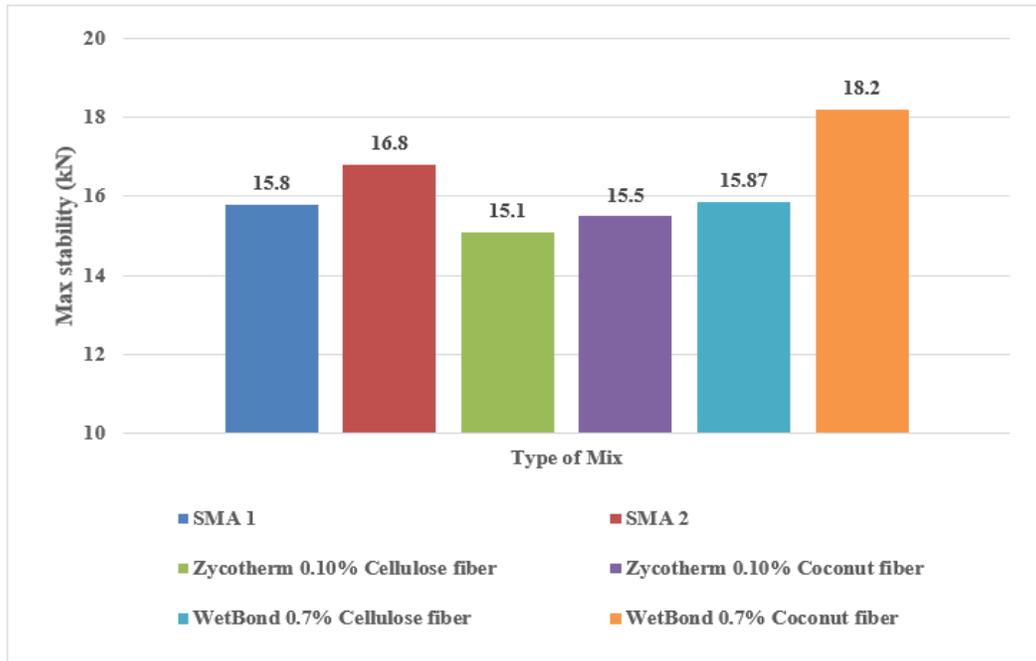


Figure 7: Bar Chart showing Maximum Stability for various SMA mixes

Table 6: Rut depth for various SMA 1 mix for Tyre pressure 1160 kN/m² and varying wheel speed

Type of SMA mix	Wheel speed, ppm	RAP, %	Rut Depth, mm
SMA 1	20	0	7.46
SMA1 + RAP	20	40	6.03
SMA1 + RAP	20	50	5.19
SMA1 + RAP	20	60	5.73
SMA1 + 50% RAP+ ZYCHOTHERM	20	50	4.85
SMA1 + 50% RAP+WET BOND	20	50	4.48
SMA 1	25	0	7.93
SMA1 + RAP	25	40	6.40
SMA1 + RAP	25	50	5.66
SMA1 + RAP	25	60	6.14
SMA1 + 50% RAP+ ZYCHOTHERM	25	50	5.24
SMA1 + 50% RAP+WET BOND	25	50	4.84
SMA 1	30	0	8.4
SMA1 + RAP	30	40	6.77
SMA1 + RAP	30	50	6.13
SMA1 + RAP	30	60	6.54
SMA1 + 50% RAP+ ZYCHOTHERM	30	50	5.63
SMA1 + 50% RAP+WET BOND	30	50	5.21

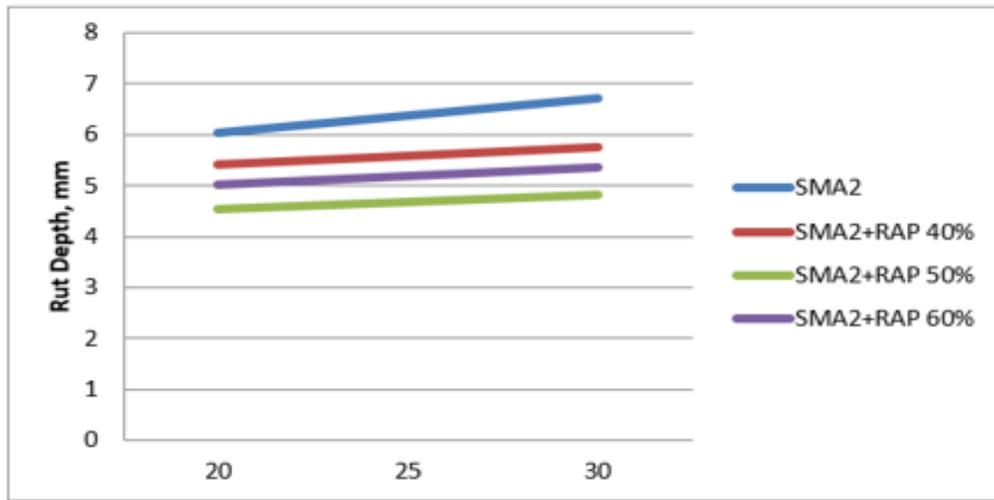


Figure 8: Rut depth Variation for SMA 1 mixes with Tyre pressure 1160 kN/m² and varying wheel speed

Table 7: Rut depth for various SMA 2 mixes for Tyre pressure 1160 kN/m² and varying wheel speed

Type of SMA mix	Wheel speed, ppm	RAP, %	Rut Depth, mm
SMA 2	20	0	6.05
SMA2 + RAP	20	40	5.42
SMA2 + RAP	20	50	4.54
SMA2 + RAP	20	60	5.02
SMA2 + 50% RAP+ ZYCHOTHERM	20	50	4.02
SMA2 + 50% RAP+WET BOND	20	50	3.55
SMA 2	25	0	6.38
SMA2 + RAP	25	40	5.58
SMA2 + RAP	25	50	4.68
SMA2 + RAP	25	60	5.18
SMA2 + 50% RAP+ ZYCHOTHERM	25	50	4.29
SMA2 + 50% RAP+WET BOND	25	50	3.72
SMA 2	30	0	6.72
SMA2 + RAP	30	40	5.74
SMA2 + RAP	30	50	4.81
SMA2 + RAP	30	60	5.35
SMA2 + 50% RAP+ ZYCHOTHERM	30	50	4.56
SMA2 + 50% RAP+WET BOND	30	50	3.90

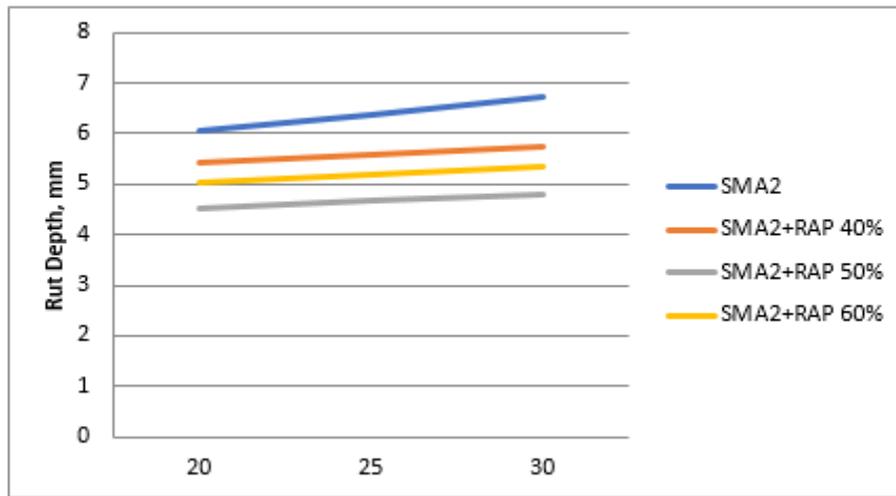


Figure 9: Rut depth Variation for SMA 2 mixes with Tyre pressure 1160 kN/m² and varying wheel speed

3.7 Statistical Analysis (ANOVA)

A one-way ANOVA was conducted for SMA-1 and SMA-2 mixes to determine the statistical significance of rut depth differences across wheel speeds, RAP contents, and WMA types. The significance level was set at $p < 0.05$.

4. ANALYSIS AND DISCUSSIONS ON TEST RESULTS

Table 8: Anova Analysis for SMA 1 mixes for varying wheel speed and fixed Tyre Pressure of 1160 kN/m² at 10000-wheel passes

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	827.2559	4	206.814	40.16939	3.94E-06	3.47805
Within Groups	51.48547	10	5.148547			
Total	878.7414	14				

Table 9: Anova Analysis for SMA 2 mixes for varying wheel speed and fixed Tyre Pressure of 1160 kN/m² at 10000-wheel passes

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	921.4098	4	230.3524	45.73516	2.15E-06	3.47805
Within Groups	50.3666	10	5.03666			
Total	971.7764	14				

4.1 Analysis on Marshall Test Results

The Marshall Stability tests were conducted to evaluate the performance of the SMA mixes with different stabilizing fibers (cellulose and coconut) and varying percentages of bitumen content. The primary aim of the test was to determine the Optimum Binder Content (OBC), which was found by analyzing the stability and flow characteristics of the mix for the conventional SMA mix using cellulose fibers, the stability value increased with

higher bitumen content, reaching an optimum at 6.5% bitumen. The flow values followed a similar trend, with acceptable limits observed between 6.0% and 7.0% binder content. The results showed that cellulose fibers effectively improved the mix's stability, holding the bitumen in place and preventing draindown, as expected in SMA mixes. The performance of the SMA mix using coconut fibre have been improved the stability of the mix, their performance was slightly lower than cellulose fibers at higher bitumen contents. Referring to Figure: 01 the OBC for the coconut fiber mix was identified at 6.37%, slightly lower than the cellulose fiber mix. This difference can be attributed to the natural structure of coconut fibers, which absorb more bitumen and thus require a slightly lower OBC. Coconut fibers, however, offered an environmental advantage due to their biodegradability and their capacity to reduce the overall bitumen consumption.

Overall, the Marshall Stability results indicated that both cellulose and coconut fibers were effective in improving the stability and flow characteristics of SMA mixes. However, the cellulose fiber mix provided marginally better stability results compared to the coconut fiber mix, particularly at higher bitumen contents. The Marshall properties are calculated by using the equations (i) to (vi).

$$G_t = \frac{100}{\left(\frac{W_1}{G_1}\right) + \left(\frac{W_2}{G_2}\right) + \left(\frac{W_3}{G_3}\right) + \left(\frac{W_4}{G_4}\right)} \dots\dots(i)$$

$$G_b = \frac{W_a}{W_a - W_w} \text{ (g/cm}^3\text{)} \dots\dots(ii)$$

$$V_v(\%) = \frac{100(G_t - G_b)}{G_t} \dots\dots(iii)$$

$$V_b(\%) = G_b \times \frac{W_4}{G_4} \dots\dots(iv)$$

$$VMA(\%) = V_v + V_b \dots\dots(v)$$

$$VFB(\%) = 100 \frac{V_b}{VMA} \dots\dots(vi)$$

Where

G_t = theoretical specific gravity

W_1 = weight of the coarse aggregates in the total mix

W_2 = weight of the fine aggregates in the total mix

W_3 = weight of the filler in the total mix

W_4 = weight of the bitumen in the total mix

G_1 = apparent specific gravity of coarse aggregates

G_2 = apparent specific gravity of fine aggregates

G_3 = apparent specific gravity of filler

G_4 = apparent specific gravity of bitumen

G_b = bulk specific gravity

W_a = weight of mix in air

W_w = weight of the mix in the water

V_v = percent of air voids by volume in the specimen

V_b = percent of the volume of bitumen to the total volume

VMA = voids in mineral aggregates

VFB = voids filled with bitumen

4.2 Analysis on Immersion Wheel Tracking Test Results

The Immersion Wheel Tracking Test was conducted to assess the rutting resistance of the SMA mixes under varying wheel loads and speeds. The size of the specimen for study was 600 mm x 100 mm x 50 mm for all SMA mixes is considered. The same specimen with different SMA Mix combinations such as Conventional SMA1 mix, SMA1+RAP variation of 40%-60%, SMA1+ Optimized RAP+Zycotherm, SMA1+ Optimized RAP+Wetbond and same combinations will repeat for SMA2 Mix. The test is done for fixed tire pressure of 1160 kN/m² with a different wheel speed at 20, 25 and 30 passes per minute. All the specimen was tested up to 10,000 number of passes and note down the corresponding rut depth for each specimen. The SMA2 mix demonstrated a higher resistance to rutting compared to the SMA1 mix, particularly when subjected to higher tyre pressures of 1160 kN/m² and 1360 kN/m². Coconut fibers provided better reinforcement within the mix, helping to distribute loads more effectively and reducing permanent deformation. The improved performance of coconut fibers at higher stresses may be attributed to their toughness and natural flexibility, which allows them to accommodate greater strains without breaking down. Under lower tyre pressures (720 kN/m²), referring to Table 05 and Table 06 both SMA1 and SMA2 mixes performed similarly, with only minor differences in rut depth. However, as the tyre pressure increased, the rut depth in the SMA1 mix increased more rapidly, suggesting that cellulose fibers may offer less resistance to deformation under heavy traffic conditions compared to coconut fibers. The results from the wheel tracking test confirmed that both fiber types provided significant rutting resistance, but coconut fibers demonstrated superior performance under higher loads. This makes the SMA2 mix a more suitable option for high-traffic pavements or areas prone to heavy loads, where long-term rutting resistance is critical.

The Rutting Coefficient has been calculated for SMA1, SMA1+Optimized RAP, SMA1+Optimized RAP+Zycotherm, SMA1+Optimized RAP+Wetbond and SMA2, SMA2+Optimized RAP, SMA2+Optimized RAP+Zycotherm, SMA2+Optimized RAP+Wetbond mixes. The Rutting Coefficient has been determined for Tyre pressure of 1160 kN/m² with varying wheel speed of 20, 25 and 30 passes/min. By considering any two values of rut depth along with corresponding to Number of passes. The trend for Elastic Coefficient and Plastic Coefficient for SMA1 is shown in Figure 5 and Figure 6 and SMA2 mixes has shown graphically in Figure 7 and Figure 8. The Elastic coefficient (A)

for SMA mixes will decrease when the tyre pressure is increased, then Plastic coefficient (B) for SMA mixes will be increasing when tyre pressure is increased.

The equation to determine the Rutting Coefficient is given below

$$R=A^B \dots\dots\dots(vii) \text{ Rutting Coefficient}$$

Where,

R= Rut Depth Corresponding to speed in mm

A=Elastic Coefficient

B=Plastic Coefficient

N= Number of Passes

4.3 Analysis of ANOVA results

Anova analysis was carried out for SMA 1 and SMA 2 mixes with 40%, 50% and 60% RAP & two warm mix additives Zycotherm and Wetbond at varying wheel speed and fixed tire pressure of 1160 kN/m² considering the parameter of rut depth. It was found that the P value of SMA 2 mix was relatively less than that of SMA 1 mix as shown. The P value of SMA 1 mix and SMA 2 mix was found to be 0.00000394 and 0.00000215 respectively which is less than 0.05. It can be concluded that SMA 2 mix is performing better as compared to SMA 1 mix statistically.

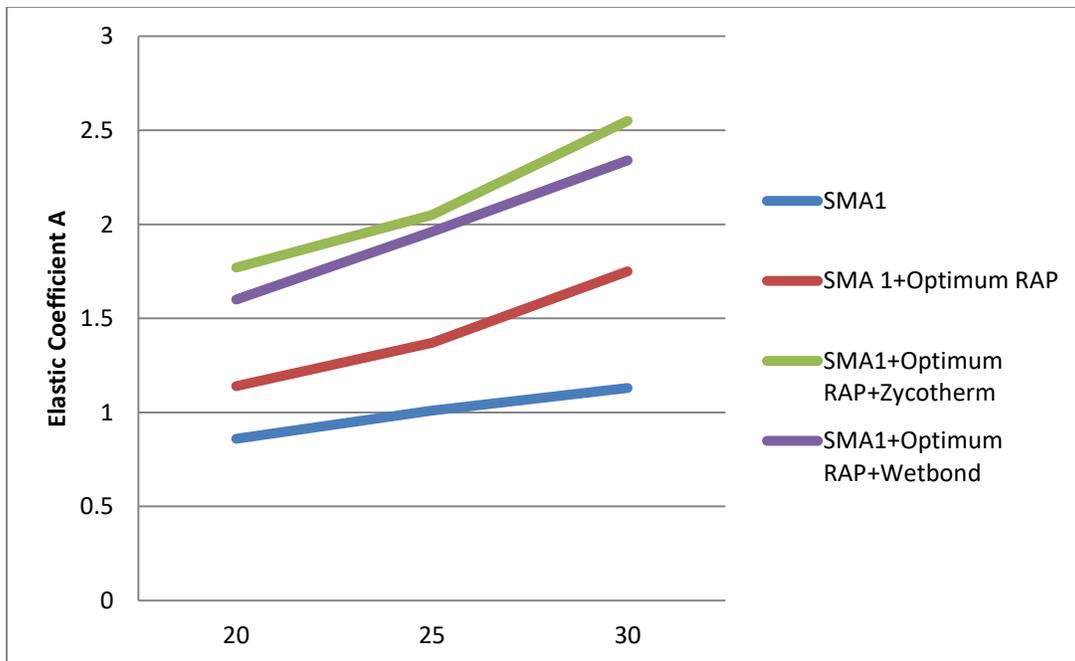


Figure 10: Elastic Coefficient A variation in SMA1 mix at Tyre pressure 1160 kN/m² and varying wheel speed

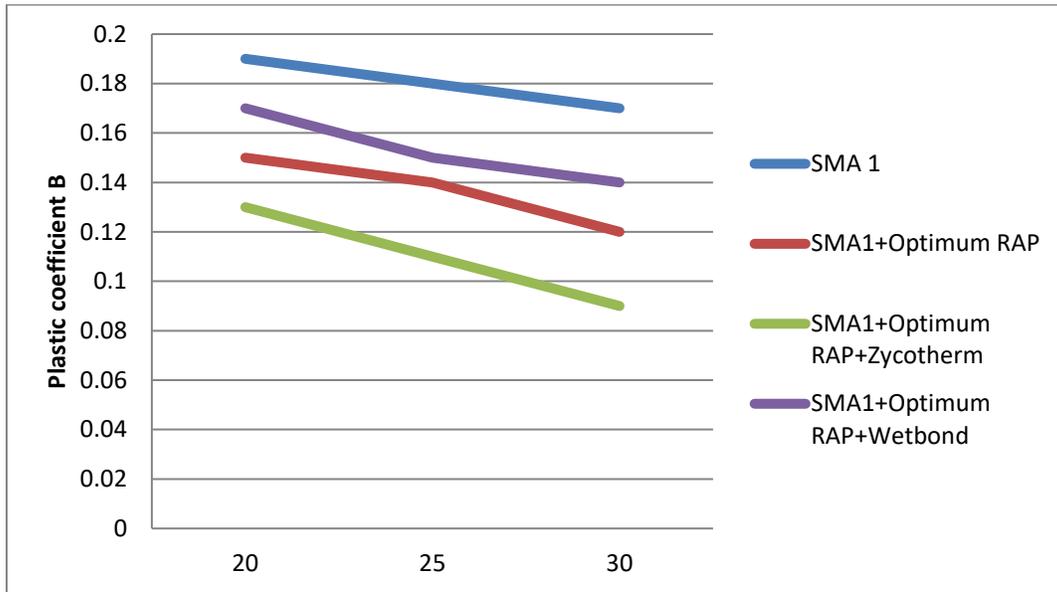


Figure 11: Plastic coefficient B variation in SMA 1 mix at Tyre pressure 1160 kN/m² and varying wheel speed

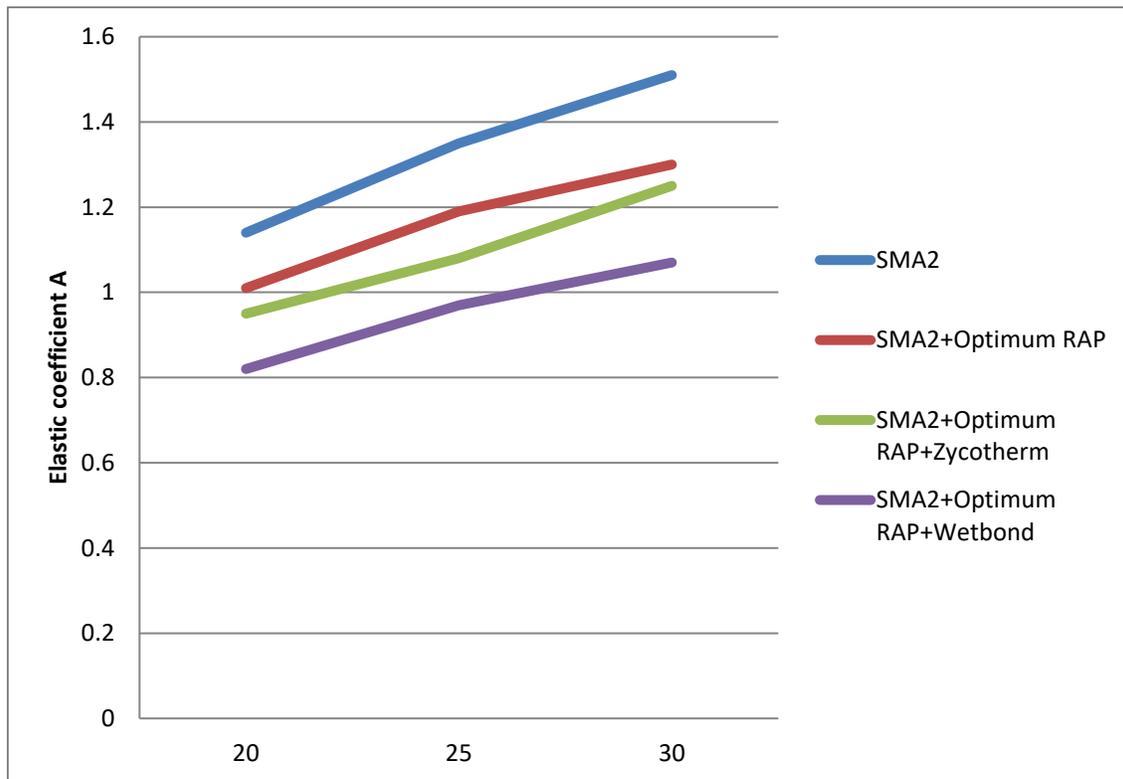


Figure 12: Elastic Coefficient A variation in SMA2 mix at Tyre pressure 1160 kN/m² and varying wheel speed

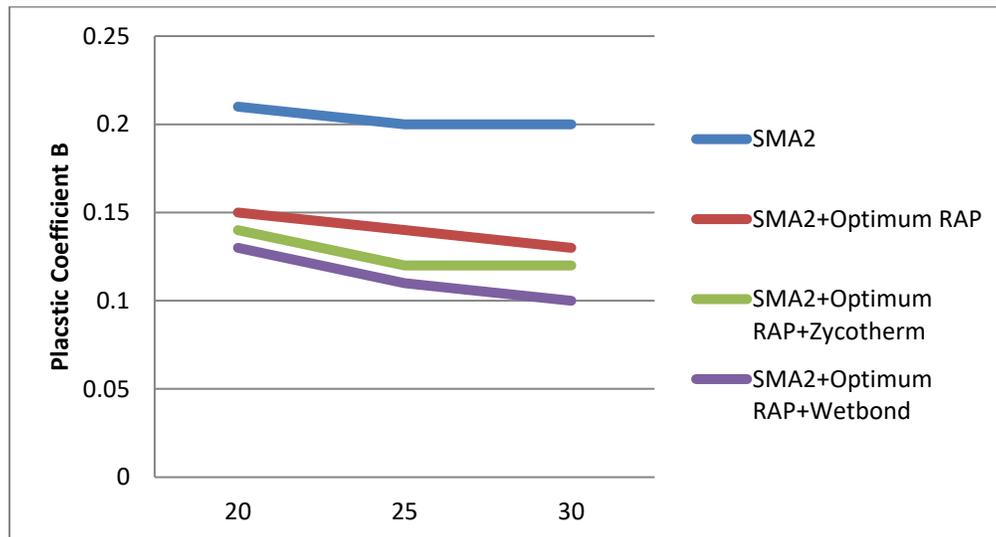


Figure 13: Plastic Coefficient B variation in SMA2 mix at Tyre pressure 1160 kN/m² and varying wheel speed

5. CONCLUSION

This study comprehensively evaluated the rutting performance of Stone Matrix Asphalt (SMA) mixtures incorporating Reclaimed Asphalt Pavement (RAP) and Warm Mix Asphalt (WMA) technologies, with and without coconut fiber reinforcement, under varying wheel speeds. The results revealed clear performance hierarchies and interaction effects that are critical for sustainable pavement design.

Key Findings Include

- 1. Speed–Rutting Relationship** – Across all mix types, rut depth decreased with increasing wheel speed, highlighting the rate-dependent deformation characteristics of asphalt mixtures. At lower speeds, sustained contact time between the wheel and the pavement amplified the viscoplastic response, resulting in deeper ruts.
- 2. RAP/WMA Interactions** – Incorporating RAP enhanced rutting resistance by increasing stiffness, while WMA technologies reduced mixing and compaction temperatures without compromising performance. The combined use of RAP and WMA demonstrated synergistic benefits, contributing to both performance and environmental sustainability through reduced virgin binder usage and lower energy demand.
- 3. Coconut Fiber Reinforcement** – SMA-2 mixes with coconut fiber consistently outperformed SMA-1 counterparts in rutting resistance, especially at low speeds where deformation potential is highest. The fiber network acted as a micro-reinforcement matrix, improving load distribution and restricting binder drainage, which is particularly beneficial in tropical climates.

4. Sustainability Advantage – The integration of RAP, WMA, and natural fiber reinforcement in SMA mixtures offers a triple sustainability benefit—lower lifecycle greenhouse gas emissions, conservation of natural aggregates, and enhanced pavement durability—aligning with modern green infrastructure objectives.

Overall, SMA-2 with RAP, WMA, and coconut fiber presents a high-performance, eco-friendly alternative for heavy traffic pavements in warm regions. The performance improvements observed in this study, particularly under challenging low-speed loading conditions, underscore its suitability for critical roadway applications such as intersections, bus lanes, and port facilities.

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