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Synergistic Improvement of Stone Matrix Asphalt Mixtures Incorporating Reclaimed Asphalt Aggregates and Warm Mix Additives Using Multi-variate Analysis

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ABSTRACT

This study focuses on the development of a sustainable and cost-effective road construction process with the use of Reclaimed Asphalt Pavement (RAP), Warm Mix Additives (WMAs), and Waste Cooking Oil (WCO) in Stone Matrix Asphalt (SMA). RAP was used in varying proportions (20%-40%), Sasobit (WMA additive) in 2%-5%, and WCO as a softening agent. Series of laboratory tests, such as SARA fractions, Marshall properties, moisture susceptibility, resilient modulus, and rutting resistance, were carried out to evaluate the mechanical and performance characteristics. A multi-variate analysis approach was employed to rank these mixes based on their performance parameters and to determine the best-performing mix. Among all the mix combinations, the mix containing 30% RAP, 3% Sasobit, and 6% WCO (referred to as WS30R) in Polymer Modified Bitumen (PMB) demonstrated the best performance. Compared to conventional SMA mix (3WS), the WS30R mix improved rutting resistance by 41%, resilient modulus by 15%, and moisture resistance. The findings confirm that the inclusion of RAP, WMA, and WCO enhances the performance of SMA while promoting sustainability. This synergetic improvement provides a practical and eco-friendly solution for modern road construction through the use of sustainable materials.

Keywords: Stone matrix asphalt, Warm mix asphalt, Polymer modified bitumen, Reclaimed asphalt pavement, Moisture susceptibility, Grey relation analysis.

INTRODUCTION

Asphalt pavement performance depends significantly on a well-developed mix design, primarily determined by aggregate gradation and binder content. In addition to mix design parameters, external factors, such as traffic loading, climatic conditions, and construction practices, interact with the pavement over its service life, influencing its overall performance.

Among the various surface course materials, Stone Matrix Asphalt (SMA) stands out due to its superior durability and resistance to cracking and deformation (Manosalvas et al., 2016). SMA typically consists of 70%-80% crushed, cubical, and angular coarse aggregates by weight, forming a strong aggregate skeleton that provides excellent rutting resistance and minimizes permanent deformation under repeated traffic loads (Shahin et al., 2019). The gradation of the aggregate plays a crucial role in enhancing the tensile strength, resilient modulus, and overall rutting resistance of SMA mixes (Ramesh et al., 2019; Sree Ram et al., 2019).

In recent years, the integration of Warm Mix Asphalt (WMA) technology into SMA production has gained traction. WMA is produced at temperatures 20°C-30°C lower than conventional Hot Mix Asphalt (HMA), which reduces binder viscosity and facilitates better mixing and compaction without compromising mechanical performance (Rochishnu et al., 2021; Kalyan et al., 2021; Awazhar et al., 2020; Sterling, 2012; Kim, 2013). When SMA is produced using WMA techniques, it demonstrates improved low- and medium-temperature performance, enhanced resistance to oxidative aging, and significant environmental benefits, such as reduced energy consumption and greenhouse gas emissions (Norouzi et al., 2021; Hamzah et al., 2015). Leng et al. (2014) emphasized the importance of selecting suitable aggregates, binders, and additives, along with controlling production parameters, to ensure the quality of SMA-WMA mixes. Additionally, studies by Durga et al. (2019) and Ameli et al. (2020) reported enhanced workability, superior aggregate coating, and better compaction in SMA-WMA mixtures.

To further improve the performance of SMA mixtures, various modifiers and recycled materials are being incorporated. Polymer-modified binders enhance flexibility and cohesion, offering improved resistance to deformation and cracking under traffic and thermal stresses (Riran et al., 2021). The use of Crum Rubber Modified Bitumen (CRMB) in SMA has been shown to provide superior resistance to moisture damage, rutting, and fatigue, compared to conventional fiber-reinforced mixes (Shiva Kumar et al., 2023).

The inclusion of Reclaimed Asphalt Pavement (RAP) and other industrial by-products in SMA-WMA mixes is increasingly explored to address sustainability and resource constraints (Büchler et al., 2018). RAP offers environmental and economic benefits by conserving natural aggregates and reducing the demand for virgin asphalt (Goli et al., 2022). Mohiud (2020) demonstrated that SMA-WMA mixes containing RAP exhibit reliable performance across a range of service temperatures, along with improved strength and durability (Yang et al., 2022; Adepu et al., 2022). Binder modification techniques, as studied by Sandeep et al. (2021) and Ramayya et al. (2016), further enhance the mechanical performance and longevity of RAP-containing SMA mixtures.

Moreover, the use of additives and rejuvenators plays a critical role in restoring aged binder properties and improving mixture performance. High RAP contents, when combined with fibers, such as glass or basalt, have been shown to enhance fracture resistance, Marshall stability, and rutting resistance (Sandeep et al., 2020; Mamatha et al., 2023). Rejuvenators, such as aromatic oils, help restore binder workability and reduce the effects of oxidative aging (Devulapalli et al., 2020). The above literature highlights advancements in SMA mix design through the integration of WMA technology, RAP, and performance-enhancing additives. However, there remains a need to optimize these blends to develop sustainable, durable, and high-performing asphalt pavements suited to modern infrastructure demands.

Research Gap

This study investigates the combined effects of RAP, WMA technologies, and modified binders in SMA mixtures to promote sustainable and high-performance pavement design. While previous research has examined RAP, WMA, and polymer binders individually, their synergistic impact within SMA remains under-explored. To address this gap, the study aims to evaluate performance and identify optimal RAP-WMA blends. Grey Relational Analysis (GRA), developed by Ju-Long (1982), is employed to rank the mixtures based on key performance indicators.

Objectives of the Study

This study explores the incorporation of RAP in modified SMA mixtures produced using WMA technology to enhance performance and sustainability. The study objectives are:

- To optimize the dosage of warm mix additives in polymer-modified binder.
- To evaluate the mechanical and performance characteristics of Stone Matrix Asphalt mixtures incorporating Sasobit, varying percentages of Reclaimed Asphalt Pavement (RAP), and Waste Cooking Oil (WCO) as a softening agent.

MATERIALS AND METHODS

Materials

Aggregates

Two different types of aggregate have been used in this study; RAP collected from Nehru Outer Ring Road, Hyderabad, India and natural aggregates collected from a nearby quarry. SMA mix gradation was prepared satisfying the requirements as per IRC SP: 79-2008. Figure 1(a) depicts the aggregate gradation of the SMA mix with RAP proportions ranging from 20% to 40%. The white curve in Figure 1(b) was determined using EN 933-1 (2013), whereas the black curve (with RAP and its binder) was determined using EN 12697-3 (2012). This is critical for sieving, because the binder in RAP causes particles to stick together, unlike the white curve. A high amount of RAP is effective when mixed with rejuvenators or softening agents. Rejuvenators help restore the asphaltene-to-maltene ratio, while softening agents reduce binder viscosity.

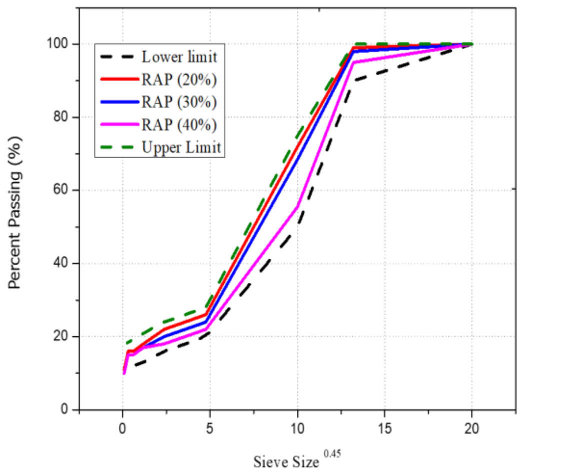

Figure 1(a). Aggregate gradation (JMF) used in the study

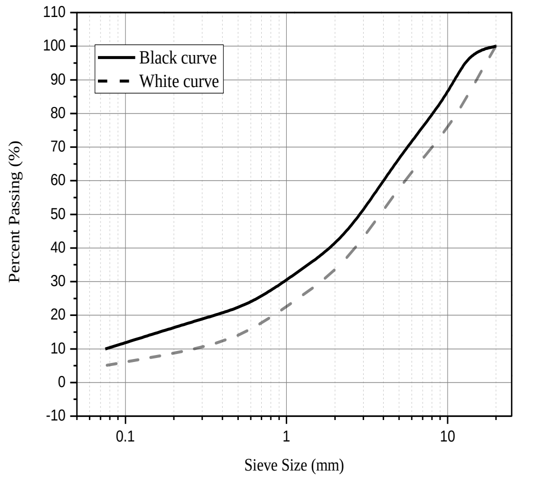

Figure 1(b). White and black curves for RAP

Modified Asphalt

Polymer Modified Binder (PMB 70) collected from M/s. Mega Engineering and Infrastructure, Ltd., Hyderabad, was used in this study. The physical properties of modified binder were studied and found to be satisfied in accordance with IS: 15462-2019 (2019).

Warm Mix Asphalt

Sasobit modifier was used for the development of Warm Mix Asphalt (WMA) in this study. It was procured from M/s. KPL International, Ltd., New Delhi, and is supplied in the form of solid pellets with a diameter of 2 mm and a melting point range of 80°C-110°C. The addition of Sasobit to the binder reduces its viscosity, thereby facilitating the production of WMA mixtures (Sandeep et al., 2023; Meng Guo et al., 2020). In the current investigation, PMB 70 binder was modified by adding Sasobit additive at varying proportions of 2%, 3%, 4%, and 5% by weight of the binder. The penetration index values were presented in Figure 2. The PI values were observed to increase gradually with the increase in dosage of Sasobit, suggesting the change of structure of sol to sol-gel, which is desirable. Beyond 3% dosage of Sasobit, the PI has become positive. In this research, the optimum dosage of Sasobit is taken as 3 percent based on past research (Adepu et al., 2022; Ameri et al., 2018), while a good number of research works reported the optimum dosage to be in the range 2%-4%.

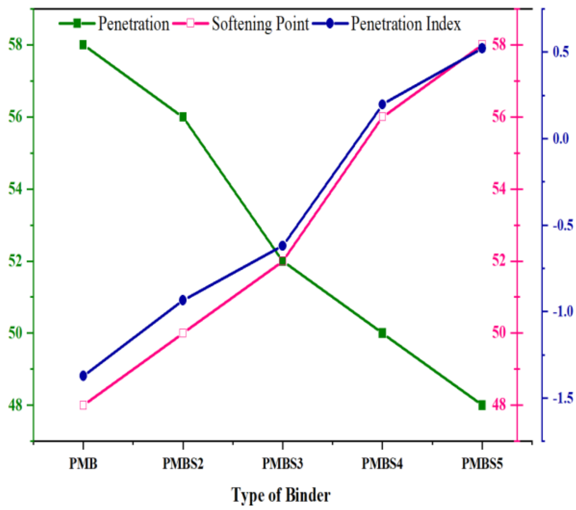

Figure 2. Optimum dosage of Sasobit

Cellulose Fibre

In order to improve aggregate film coating, mix stability and aggregate skeleton interlocking, 2-3 mm long pressed pellets of cellulose were added into SMA mixtures. The palletized cellulose fibre used in the present research fulfils the requirements as specified in IRC: SP: 79-2008 (2008).

Waste Cooking Oil (WCO) as Softening Agent

Oxidation of asphalt in recycled pavements increases its hardness, adversely affecting pavement performance and leading to issues, such as thermal stress and fatigue cracking. In this study, WCO is utilized as a softening agent in combination with RAP to mitigate the stiffness of the mixture and enhance its workability.

Based on existing literature, the recommended dosage range is from 3% to 8%, with 6% adopted for the current investigation (Devulapalli et al., 2020). Saturates, Aromatics, Resins, and Asphaltenes (SARA) analysis was conducted on both the RAP binder and the RAP + WCO binder to evaluate the chemical changes induced by WCO. Results revealed a 10% increase in maltene content and a 7% decrease in asphaltene content in the RAP + WCO binder compared to the RAP binder alone. This reduction in asphaltene content lowers the viscosity of the RAP binder, confirming that WCO is an effective and efficient softening agent (Martins et al., 2022).

Methodology

The study plan is shown in Figure 3. Different materials (natural aggregate, RAP, PMB 70, WMA, and fiber) have been used in this study. The basic physical properties of all different materials were evaluated.

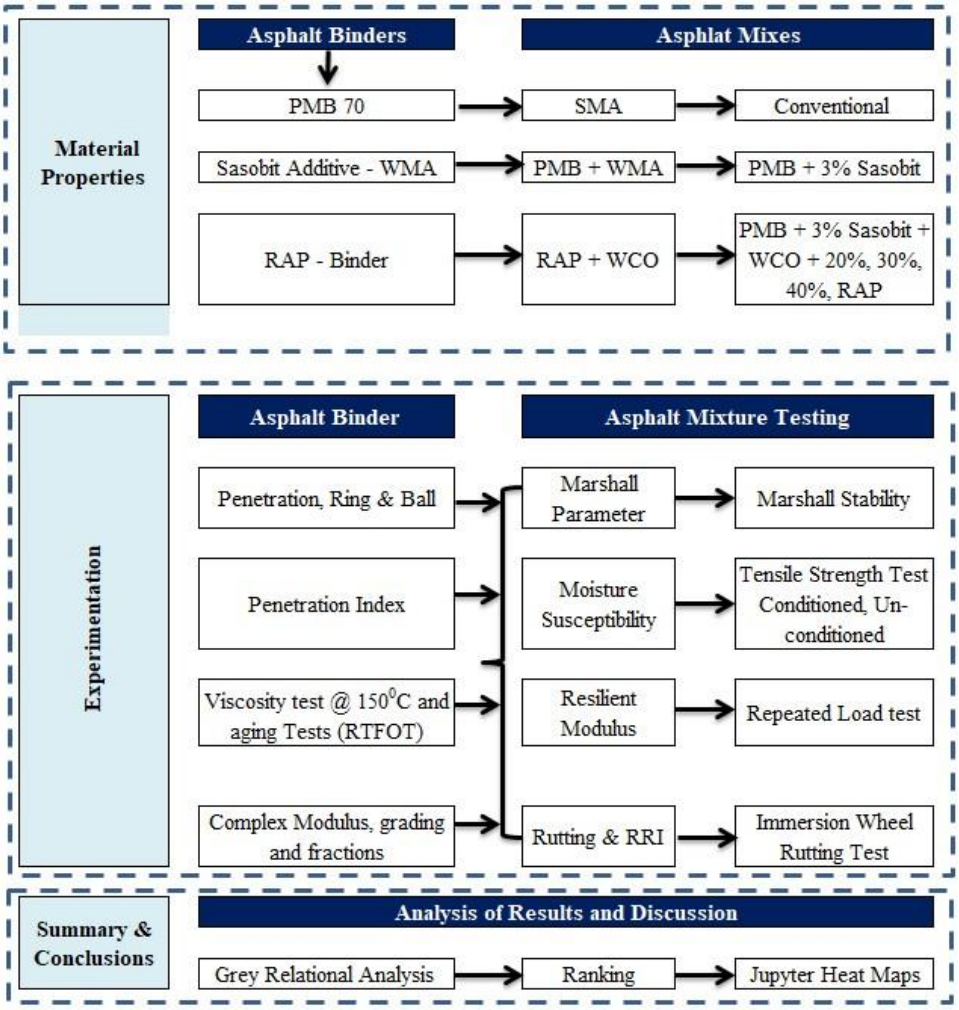

Figure 3. Methodology adopted for the study

Preparation of Modified Binder and Asphalt Mixtures

The PMB 70 binder was pre-heated to 105°C, after which Sasobit pellets were gradually added, and the blend was continuously stirred at 500 rpm-800 rpm until a homogeneous blend was obtained. Aggregates were pre-heated to 140°C for two hours to ensure uniform mixing. The Sasobit-modified binder was then used in the preparation of asphalt mixtures. RAP was incorporated at varying proportions and blended with 6% waste cooking oil, used as a softening agent, to enhance the workability and performance of the final mix.

Test Methods

Binder Fractions - SARA Analysis

Asphalt binders, based on chemical constituents, are classified into four elements *viz*. Saturates, Asphaltenes, Resins and Aromatic hydrocarbons. Maltenes can be classified as resins, aromatics and saturates. Corbett method (1969) of separation was used to determine the asphaltenes and maltenes fractions of the base, modified and RAP binder. The dried residue is weighed for asphaltenes and maltenes fraction and the study results are presented in Figure 4, and the letter '*W*' stands for warm mix, the letter '*S*' for Sasobit, '*UA*' for unaged and '*A*' for aged.

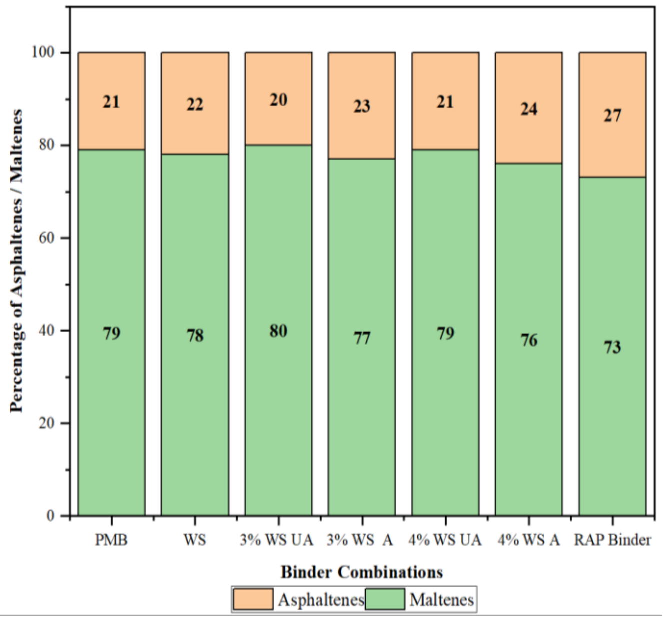

Figure 4. Modified WMA and RAP binder fractions

Viscosity and Ageing

Viscosity was measured using the rotational viscometer (RV) test as per AASHTO T316 (2022) to assess the dynamic viscosity of asphalt binder at mixing and compaction temperatures. The study tested temperatures from 110°C to 160°C, correlating with viscosities of 0.17Pas and 0.28Pas, respectively. The mixing and compaction temperature ranges were reduced by up to 12°C for 3% Sasobit and 8°C for 2% Sasobit, without affecting workability. The rolling thin-film oven (RTFO) test is conducted according to AASHTO T 240 (2023) to simulate the short-term ageing during the mixing and compaction processes.

Test on Conventional and Modified SMA Mixtures

The following tests were used to evaluate the efficacy of SMA mixtures during the study: (i) Marshall stability test, (ii) Drain down test, (iii) Moisture sensitivity test, (iv) Resilient modulus test, and (v) Rutting characteristics test. In each of the abovementioned tests, three specimens were prepared for the assessment of conventional SMA and SMA mixtures containing RAP. The mix combinations adopted during the study are 3WS, 3WS20R, 3WS30R, 3WS40R with 3% sasobit and with 20%, 30% and 40% RAP.

Designing and Preparation of Marshall Specimens

Marshall specimens of 100mm diameter and 63.5mm thickness were prepared in accordance with

ASTM D 6926-20 (2020). Four different mixtures were prepared during the current investigations, as outlined in Table 3. For each trail of mixture mentioned, a total of 1200 g of blended aggregates was taken. Three samples were prepared for all the mix combinations. In addition to volumetric calculations, stability and flow values were measured after the sample was cured at 60^0C or 30 minutes and tested in accordance with ASTM D 5581-07A (2021). The attributes of the mix shall satisfy the requirements listed in Table 500-41 of MoRTH (2015). The optimum SMA binder percentage has been determined and found to be at 7.0%, which corresponds to 4% of air void and the Voids in Total Mix (VTM) is calculated using Eqn. (1).

$$VTM = (1 - \frac{d}{TMD}) x 100 \tag{1}$$

where d- bulk density (g/cm^3), TMD - theoretical maximum density.

Volumetric Properties

Maintaining stone-on-stone contact is a fundamental requirement for SMA mixtures, as the coarse aggregate skeleton significantly contributes to the overall structural strength. Brown et al. (1995) developed the Voids in Coarse Aggregates (VCA) approach to evaluate this contact and is the same as achieved when the voids in coarse aggregates within the compacted mixture (VCA_{MIX}) are lower than those in the dry-rodded condition (VCA_{DRC}).

In the current research, all mixtures exhibit VMA values exceeding 17%, consistent with previous research findings (Jomoor et al., 2019; Manosalvas-Paredes et al., 2016). Additionally, VCA_{MIX} to VCA_{DRC} ratio remains below one for all mixtures, confirming that the gradation successfully retains coarse particles in contact, ensuring required stone-on-stone structure.

Drain Down Test

The bitumen and particles that separate and flow out of the asphalt mix during storage and transportation are referred to as the drain-down of the asphalt mix. To assess the produced SMA mixtures' ability to resist deformation under traffic and the tendency for the asphalt binder to drain from the mixture, a drain down test should be conducted. The test is carried out in accordance with ASTM D 6390 (2011). The test results are within the limits established in IRC: SP: 79-2008 (2008).

Indirect Tensile Strength and Moisture Susceptibility

The indirect tensile strength test was performed in accordance with ASTM D 6931 (2017). Moisture sensitivity is measured in this study using a tensile strength ratio, which is from tensile strength of conditioned and unconditioned samples according to AASHTO T 283 (2014). Six specimens were cast for each mixture. One sub-section (three specimens) was tested at 25°C (unconditioned specimens) in the indirect tension test, while the other sub-section was tested to one cycle of freezing and thawing (16 hrs in −18°C ± 2°C and then 24 hrs in 60°C ± 1°C) and then tested the same as the first sub-section (conditioned specimens). The load is applied to the vertical diametrical plane of the cylindrical specimen at 25^0C to determine indirect tensile strength, and Tensile Strength Ratio(TSR) using Equations (2) & (3).

$$ITS = \frac{2P}{\pi * d * t} \tag{2}$$

where, P= Maximum load applied to the specimen (kN), d=diameter of the sample (mm), t=thickness of the sample (mm).

$$TSR = \frac{ITS_{conditioned}}{ITS_{unconditioned}} \tag{3}$$

where, $ITS_{conditioned}$ and $ITS_{unconditioned}$; Indirect tensile strength of conditioned and unconditioned samples, respectively.

Rutting Characteristics

Rutting, the permanent deformation along the wheel path, was tested as per AASHTO T 324 -23 (2023). Slabs (6000 cm^3) were prepared using a roller compactor to achieve 7% air voids for all mix combinations in the study. The slabs were placed in a wheel tracking apparatus immersed in water at 50°C. A 710N load was applied for 20,000 passes, and rut depth was measured with an LVDT.

Repeated Load Test

The resilient modulus (M_r) is determined for mixtures considered in the study. This test is conducted at 35^0C as per the procedure outlined in ASTM D 4123 (2005). The Marshall samples, prepared at the Optimum Binder Content (OBC), were tested using a repeated haversine load profile. The load period was 0.1 second, followed by a rest period of 0.9 second. On the basis of a 10% failure load derived from the indirect tensile test, the magnitude of the compressive force applied was calculated. The resilient modulus values were calculated after three trials for each combination. The first 100 cycles were used as a conditioning phase, with a total of 1000 cycles being administered. The M_r of the mixtures was determined using Eqn. (4) after 5 cycles.

$$M_r = \frac{P(0.23+\mu)}{t\Delta h} \tag{4}$$

where, Mr-Asphalt mix resilient modulus (MPa); P-Applied load (N); μ- Poisson's ratio; t-Sample thickness (mm); Δh-Horizontal deformation (mm).

RESULTS AND DISCUSSION

The properties of materials; *viz*. natural and RAP aggregates, as well as polymer modified binder used in the current research, are mentioned in the previous section. To develop the best SMA mixture combination, optimum dosage of Sasobit was adopted. The main role of Sasobit is to reduce viscosity, so that it becomes workable at lower temperatures (110^{0}C). Referring to Figure 2, the optimum dosage of Sasobit was fixed at 3% based on Adepu et al. (2022) and Ramesh et al. (2023).

The method of sample preparation to evaluate Marshall properties was previously discussed. The samples were pre-conditioned for 30 minutes at a temperature of 60°C. According to guidelines in Manual Series-2 (MS-2) and MoRTH-5th revision, the optimum binder content was adopted. The trend of bulk density, stability and VTM is presented in Figure 5.

The 3WS30R mix recorded the highest stability of 14.5kN, while flow being the least at 3.8mm demonstrating the ability to withstand deformations caused by moving loads with desired level of 4.01% VTM. A downward trend of stability and increase of flow is observed for RAP greater than 30%, thus signifying the need to optimize RAP dosage.

Tensile Strength Values for Different Mixtures

In order to study the moisture susceptibility behaviour of chosen mixture combinations, the samples were cast at 25^{0}C, as shown in Figure 6, demonstrating that the TSR value was significantly elevated by incorporating 30% RAP to SMA mixtures containing 6% WCO, as a result of better blending (Ameri et al., 2018). The mixture containing 30% RAP and 6% WCO has an outstanding TSR value of 90%, which means a 5.6% increase over the control mixture. This enhancement is probably the result of the 6% WCO dosage activating the aged binder, which improves blending. In case of 40% RAP, the mixture got stiffened, and the reduction of bonding between the RAP and virgin material adversely affected the moisture resistance and decreased TSR due to improper blending (Zhou et al., 2021; Goli et al., 2020).

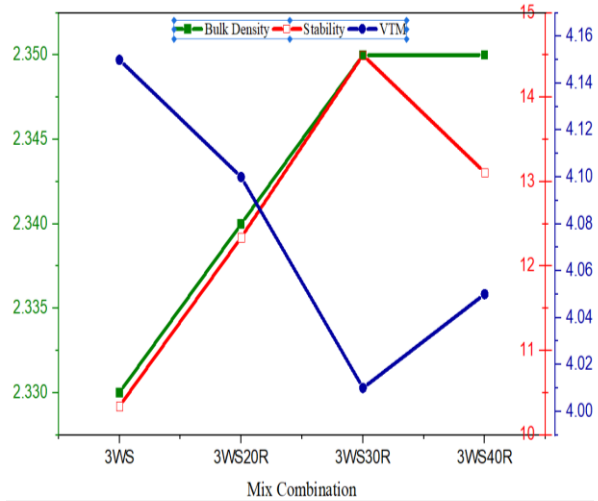

Figure 5. Comparison of different mixtures during the study

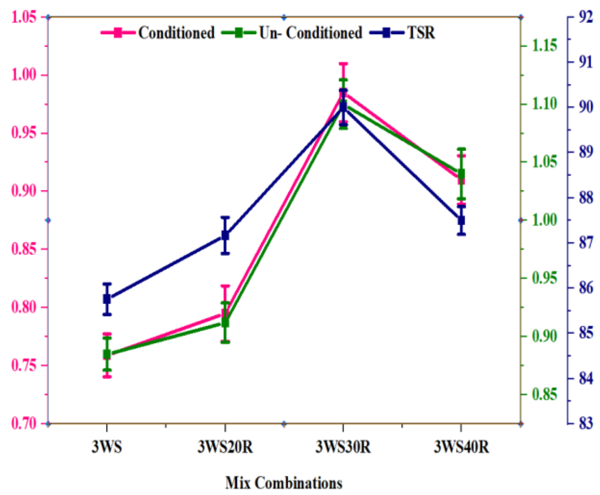

Figure 6. Moisture susceptibility for different mixtures in the study

Immersion Wheel Rutting Test

The rutting test was conducted in compliance with AASHTO-T 324 (2023) to assess the rutting characteristics of the mix. It is noticed from the test results, as presented in Figure 7, that the 3WS30R mixture prepared with WMA, modified binder and RAP exhibited significantly enhanced resistance towards rutting compared to other mix combinations. After 20,000 cycles, 3WS30R demonstrated a remarkable 41% decrease in rutting compared to 3WS mix. However, all mixtures met the study's limiting criterion (12.5 mm) (Wen et al., 2016).

Rutting Resistance Index (RRI)

As shown in Figure 7, at 20000 wheel passes, all four mixtures are far below the rut limit of depth of 12.5mm. It is very essential to consider both rut depth as well as number of passes and arrive at a suitable index for evaluating mixture performance. In order to account for this, Wen et al. (2016) developed the rutting resistance index (RRI) metric, which requires consideration of both rut depth and number of wheel passes at the end of the test. Furthermore, to account for non-linear impact of the number of passes on rutting, Zhou et al. (2021) revised the equation initially proposed by Wen et al. (2016). A study conducted by Vamsikrishna and Singh (2023) presented correlations of different rutting parameters to account for rut depth and number of passes. In the present study, Eqn. (5) was used to calculate the RRI. 3WS, for example, had a final rut depth of 7.3 mm after 20,000 wheel passes; hence, its RRI was calculated to be 13.9. The RRI was computed as 10, indicating its limitation value, in accordance with the established limiting criterion (12.5-mm rut depth at the end of 20,000 passes). The RRI values for the mixtures are calculated and shown in Figure 7.

$$RRI = N^{0.3}\left(1 - \frac{RD}{25.4}\right) \tag{5}$$

where RRI = rutting resistance index; N = 20,000 or number of wheel passes to reach 12.5mm rut depth; and RD = rut depth at 20,000 passes or 12.5 mm for mixtures reaching 12.5mm rut depth before 20,000 passes. The RRIs for all combinations are shown in Figure 7. with higher RRI values indicating improved rutting resistance (lower rut depth). RRI values ranged from 13.9 to 16.23, with 3WS30R mixture exhibiting higher RRI values, demonstrating improved rutting performance. The RRI result for 3WS, 3W20R and 3WS40R was 13.9, 14.8 and 15.42, which met the limitation value of RRI threshold of 10. This implies that the RRI parameter, determined from the immersion wheel rutting equipment by taking both rut depth and number of passes into account, effectively differentiates mixtures investigated.

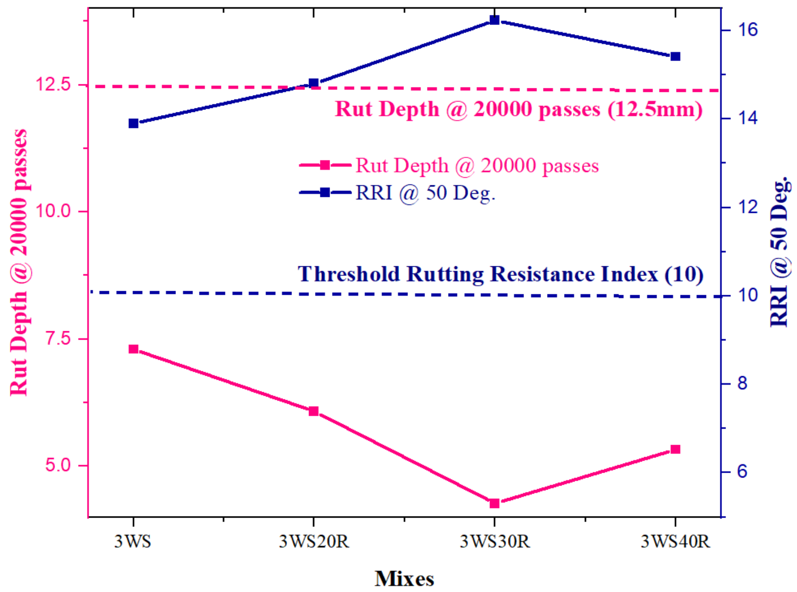

Figure 7. Accumulated rut depths of different mixtures at 20,000 passes & RRI of all mixtures

Resilient Modulus Characteristics

The resilient modulus test assessed the stiffness of SMA mixtures prepared with PMB binder, 3% Sasobit, and 6% WCO in RAP proportions. These additives notably increased the stiffness of the mixture to 3100 MPa, outperforming all other mixtures. The 3WS30R mixture exhibited the highest resilient modulus, suggesting enhanced stiffness and load-bearing capacity compared to the other mixtures in the study. The enhanced stiffness observed with the use of RAP can be attributed to the 6% WCO, which enhances the viscosity and blending of the mixture, leading to improved resilience properties (Zho et al., 2021; Vamsikrishna & Singh, 2023). Additionally, the cellulose fibre contributed to improved aggregate interlock, resulting in a stronger and more durable pavement structure, further enhancing the modulus of the SMA mixtures.

The findings of moisture susceptibility, resilient modulus and rut depth for the various mixtures are presented in Figure 8. According to the findings, 3WS30R had enhanced moisture susceptibility when compared to the other mixtures. Additionally, 3WS30R demonstrated improved resilient modulus. Additionally, 3WS30R exhibited lower rut depth and higher rutting resistance, demonstrating improved performance.

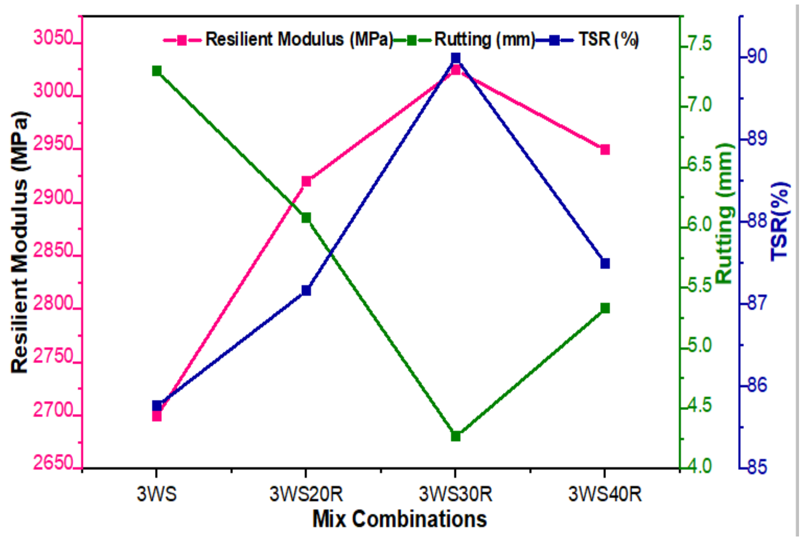

Figure 8. TSR, resilient modulus and rut depth observed for all mixtures

ANALYSIS OF RESULTS

Multi-variate Analysis

Grey Relational Analysis (GRA) is employed in this study to rank SMA and RAP mixtures produced with modified binders containing Sasobit. The ranking is based on their performance when multiple assessment criteria, *viz.* Marshall parameters, moisture susceptibility, resilient modulus and rutting resistance, are involved. The data is normalized to correct for variations in measurement units or ranges and the GR coefficient is calculated using Equations (6) and (7).

Calculation of Dimensionless Column: The data values were normalized based on the maximization and minimization criteria for each parameter. The higher the better (Eqn. (8)) criterion was adopted for TSR, max. bulk density, VMA, stability, Marshal quotient and resilient modulus, while the lower the better criterion (Eqn. 9)) was adopted for flow, VTM and rutting.

$x_i(k) = \frac{x_i^*(k)-x_0(k)min}{x_0(k)max-x_0(k)min}$ where $x_o = \{x_o(1), x_o(2), \ldots \ldots, x_o(n)\}$ (6)

$x_i(k) = \frac{x_0(k)max-x_i^*(k)}{x_0(k)max-x_0(k)min}$ where

$x_o = \{x_o(1), x_o(2), \ldots \ldots, x_o(n)\}$ (7)

Calculation of differences between 2 dimensionless columns:

$\Delta_i = |x_{o(k)} - x_{i(k)}|$ (k=1, 2,.,,,,n) where

$x_o = \{x_o(1), x_o(2), \ldots \ldots, x_o(n)\}$ (8)

Determination of maximum and minimum differences:

$\Delta_{max} = max_i max_k \Delta_k =, \Delta_{maminx} = min_i min_k$ (ASTM, 2021)

Calculation of correlation coefficient

$$x_{oi}(k) = \frac{\Delta min+\rho\Delta max}{\Delta_i(k)+\rho\Delta max} \quad (9)$$

where p is the dynamic distinguishing coefficient, which varies between 0 and 1.

Determination of Grey Relational Level or Grade (GRG) value:

$$x_{oi} = \frac{1}{n}\sum_{k=1}^{n} x_{oi}(k). \quad (10)$$

GRG values for all mixtures have been computed by aggregating the grey relational coefficients across all evaluation criteria (Eqn.10). This grade represents the overall performance ranking of each mixture. Accordingly, mixtures were ranked based on their GRG, from highest to lowest. The mixture with the highest grade indicates superior overall performance, while the mixture with the lowest grade indicates the poorest performance, as summarized in Table 1.

Table 1. GRC and ranks for different mix parameters for p=0.5

Parameter	Mix Type			
	3WS	3WS20R	3WS30R	3WS40R
TSR (%)	0.3333	0.4283	1.0000	0.4589
Max. Bulk Density (gm/cc)	0.3333	0.5000	1.0000	1.0000
VMA (%)	0.3333	0.4390	0.6000	1.0000
Stability (kPa)	0.3333	0.4906	1.0000	0.5994
Flow (mm)	1.0000	0.6269	0.3993	0.3333
VTM (%)	0.3333	0.4375	1.0000	0.6364
Marshall Quotient (kPa/mm)	0.9407	1.0000	0.5749	0.3333
Resilient Modulus (MPa)	0.3333	0.5610	1.0000	0.6598
Rutting (mm)	0.3333	0.4548	1.0000	0.5864
GRG	0.4749	0.5487	0.8416	0.6231
Rank	**4**	**3**	**1**	**2**

Ranking for SMA Mixtures

Heatmaps have been developed to demonstrate the performance ranking of the mix combinations for improved performance characteristics using Python Jupyter Notebook. The mix '3WS30R' ranked first for all parameters investigated in the present study, which was also demonstrated by Grey Relational Analysis. The relative ranking of all mixtures considered in the study is shown in Figure 9.

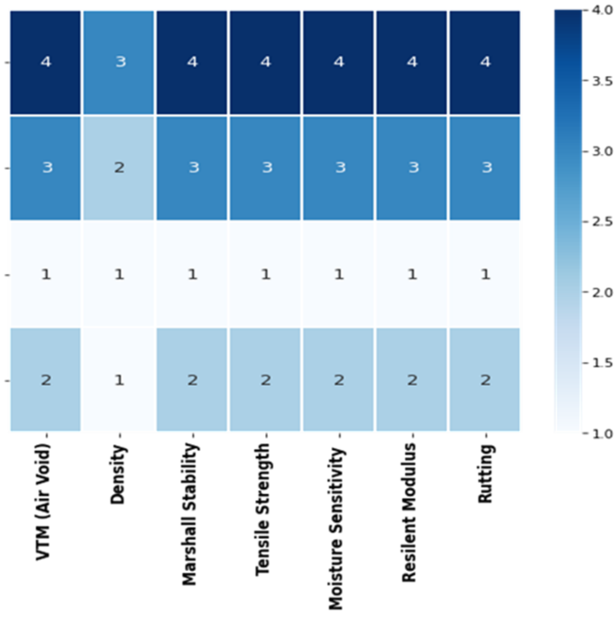

Figure 9. Ranking of performance indices for mixtures in the study

CONCLUSIONS

In the present research, WMA was produced by initially modifying the PMB binder with an optimum 3% Sasobit based on previous studies and also established in the current research. Mixtures containing Sasobit, 6% WCO and RAP with 20%, 30% and 40% dosages were prepared. Further, the efficacy of these mixtures was evaluated in terms of Marshall volumetric properties, rutting, resilient modulus and moisture susceptibility. Based on the experimental investigations, the following conclusions were drawn.

i. The adopted combined aggregate gradation effectively preserved the stone-on-stone contact essential for SMA performance. Therefore, this gradation is recommended for SMA mixtures incorporating RAP.

ii. The inclusion of 3% Sasobit in PMB 70 binder improved viscosity at both mixing and compaction temperatures, enhancing workability. However, the addition of RAP binder to the 3WS mixture increased mixture stiffness. This effect was mitigated by the introduction of a softening agent (waste cooking oil), which reactivated the aged binder, reduced mixture stiffness and moisture susceptibility, and improved binder blending.

iii. The 3WS30R mixture exhibited superior Marshall properties, with the highest stability indicating strong resistance to traffic loads and improved structural integrity. Its flow values were within acceptable limits, ensuring balanced deformation, while optimized VTM provided adequate durability. These results establish 3WS30R as the most mechanically resilient and well-balanced mix among all combinations.

iv. The incorporation of RAP in SMA mixtures resulted in TSR values exceeding 85% across all combinations, indicating good moisture resistance. The 3WS30R mixture, containing 6% waste cooking oil, showed the highest TSR and superior performance due to improved binder activation and blending.

v. The resilient modulus of the 3WS30R mixture improved by 15% compared to the 3WS mixture, indicating enhanced stiffness and load-bearing capacity. In terms of rutting resistance, the 3WS30R mixture outperformed all other tested combinations. While all mixtures met the specified rut depth criterion, the 3WS30R mixture showed a 41% reduction in rut depth relative to 3WS, demonstrating the superior effectiveness of the selected material combination in reducing permanent deformation.

vi. Grey Relational Analysis (GRA) identified the 3WS30R mixture as the most optimal across all evaluated performance parameters. GRA enabled a comprehensive multi-criteria assessment, supporting the superior ranking of the 3WS30R mixture among the tested alternatives.

The findings of this research clearly establish the efficacy of SMA mixtures prepared with WMA technology utilizing WCO for 30% RAP in enhancing pavement performance across various key aspects considered in the study.

Conflict of Interests

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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