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Optimization of Hot Mix Asphalt Using Diesel Engine Waste Oil and Reclaimed Asphalt Pavement to Improve Stability and Durability

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***Abstract* - The demand for conventional pavement materials is increasing daily. This high demand has led to the scarcity and rising prices of materials such as bitumen and virgin aggregates. Consequently, alternatives to conventional (virgin) materials in asphalt mixtures are becoming a growing concern. The primary aim of this research is to evaluate the potential of using diesel engine waste oil (DEWO) as a rejuvenator for hot mix asphalt (HMA) modified with reclaimed asphalt pavement (RAP). The RAP used in this study was rejuvenated with virgin bitumen modified with DEWO in proportions of 2%, 4%, and 6% of the virgin bitumen. The rejuvenated RAP was then added to the HMA in proportions of 20%, 40%, and 60% to assess its mechanical performance. The addition of RAP to the HMA yielded the highest Marshall stability at 40% RAP and 4% DEWO, representing a 41% improvement compared to the unmodified HMA. The Marshall flow decreased by 1% for all RAP proportions, except at 6% DEWO, where it increased by 3%. The air voids and bulk density of the mixture were within the acceptable limits of standard specifications for all RAP proportions. Additionally, the mixture showed a maximum improvement of 19% in resistance to moisture damage and a significant 89% increase in resistance to punching load at 40% RAP and 4% DEWO. Therefore, it is concluded that HMA containing RAP can be effectively modified with DEWO to meet relevant durability and volumetric performance requirements.**
***Keywords:* Hot Mix Asphalt (HMA), Reclaimed Asphalt Pavement (RAP), Diesel Engine Waste Oil (DEWO), Marshall Stability, Mechanical Performance**

I. INTRODUCTION

Recycled asphalt pavement (RAP) is one of the most important materials widely used in the manufacture of new hot mix asphalt (HMA) concrete [1]. Generally, the acceptance of reusing existing pavement materials (RAP) in new HMA is a cost-effective approach that reduces the overall cost associated with pavement construction and encourages the preservation of resources such as aggregates and asphalt binders. It is often necessary to modify RAP to improve its compatibility with new HMA [2].

RAP rejuvenators have been used over time to improve the mechanical properties of RAP. Exploring different waste types, especially waste oils as RAP rejuvenators, is an emerging aspect of pavement research, with several factors motivating these studies [3]. Conventional rejuvenating agents such as virgin binders and polymers pose environmental, technical, and economic challenges. Additionally, the negative environmental impact of indiscriminate disposal of these waste oils, which can contaminate water bodies and land, necessitates innovative investigations.

Diesel engine waste oil (DEWO) is the spent oil from diesel engines after lubricating the engines for a specified period. It is a product derived from crude oil within the distillation range of 200°C to 350°C. DEWO consists of approximately 75% aliphatic hydrocarbons ($C_{10}H_{20}$-$C_{15}H_{28}$) and about 25% aromatic hydrocarbons (e.g., benzene, styrene) [4], [5]. DEWO is highly compatible with the chemistry of bitumen, which contains a complex mixture of aliphatic compounds, cyclic alkanes, aromatic hydrocarbons, PAHs, heterocyclic compounds containing nitrogen, oxygen, sulfur atoms, and metals such as iron, nickel, and vanadium [6].

DEWO is typically drained from the diesel engine when the oil becomes less viscous and can no longer lubricate the engine as required. There is an increasing volume of waste diesel engine oil produced daily from power plants, heavy-duty equipment, etc., which could be used for large-scale HMA production.

Zumanis *et al.,* [7] examined different rejuvenating agents using 100% RAP in HMA concretes. The experiment employed petrochemical end products and bio-recycled substances such as organic oils, hydrocarbon extracts, waste engine oils, distilled tail oils, and waste vegetable oil. The findings consistently indicated the potential of these rejuvenators to improve the durability of RAP.

Datt *et al.,* [8] evaluated the influence of four types of rejuvenators in varying proportions, including cooking oils and crumb rubber. In his research, Asli *et al.,* [9] also contributed by evaluating the effect of different RAP percentages, ranging from 10% to 60%, modified with waste cooking oil. The results showed improvements in Marshall stability and Indirect Tensile Strength tests.

Research by Joni *et al.,* [10] extended asphalt studies to RAP proportions ranging from 10% to 80%, using different rejuvenating oils. Their findings underscored high moisture damage control, establishing a significant advancement in sustainability. In another study, Mamun *et al.,* [11] examined asphalt mixtures containing 25% RAP rejuvenated with condemned engine oil. The results showed that even with low RAP content, the durability of the mixture was improved. This research aims to establish the suitability of DEWO as a rejuvenator for RAP renewal. To achieve this, the study will analyze the effect of adding DEWO to RAP and mixing it with HMA. The mechanical performance of these mixtures will then be evaluated through laboratory tests.

While many studies have thoroughly examined the potential of RAP and RAP rejuvenators [12]-[18], this research seeks to expand the knowledge base on the ever-evolving characteristics of asphalt mixtures by determining the suitability of DEWO as a RAP rejuvenator. This could enhance the sustainability and performance of asphalt pavements, considering both environmental and economic benefits.

II. MATERIALS AND METHOD

A. Reclaimed Asphalt Pavement RAP

The RAP was obtained from a pavement rehabilitation site in Uyo, Nigeria. Characterization of the RAP was conducted using the methods prescribed in the EN 933-1 specification. The RAP aggregates were categorized as fine (0-4.75 mm) RAPF, medium (4.75-12.5 mm) RAPM, and coarse (12.5-19 mm) RAPC.

The RAP fractions were characterized through the tests presented in Table I. The RAP contained 4.4% bitumen.

TABLE I CHARACTERIZATION OF RAP

Test	Specification Code
Sieve analysis	EN 933-1, EN 12697-2
% Bitumen content	EN 12697-1
Bitumen needle penetration and softening point	EN 1426 & EN 1427
Bitumen extraction	EN 12697-3

B. Aggregates

The aggregates for the HMA were obtained clean from a nearby quarry, and the combined aggregate had a particle grading with a nominal maximum sieve size of ¾" (12.5 mm). The physical properties of the aggregate to be investigated are shown in Table II and the gradation of the aggregates is presented in Figure 1.

TABLE II AGGREGATES CHARACTERIZATION

Property	ASTM Code	Coarse Aggregate	Fine Aggregate	Specification
Bulk Specific Gravity	C 127, C128	2.601	2.615	-
Apparent Specific Gravity	C 127, C128	2.622	2.641	-
% Water Absorption	C 127, C128	0.356	0.47	-
Angularity %	D5821	98	-	Min 95%
Toughness %	C535	21.2	-	Max 30%
Soundness %	C88	4.6	-	Max 12%

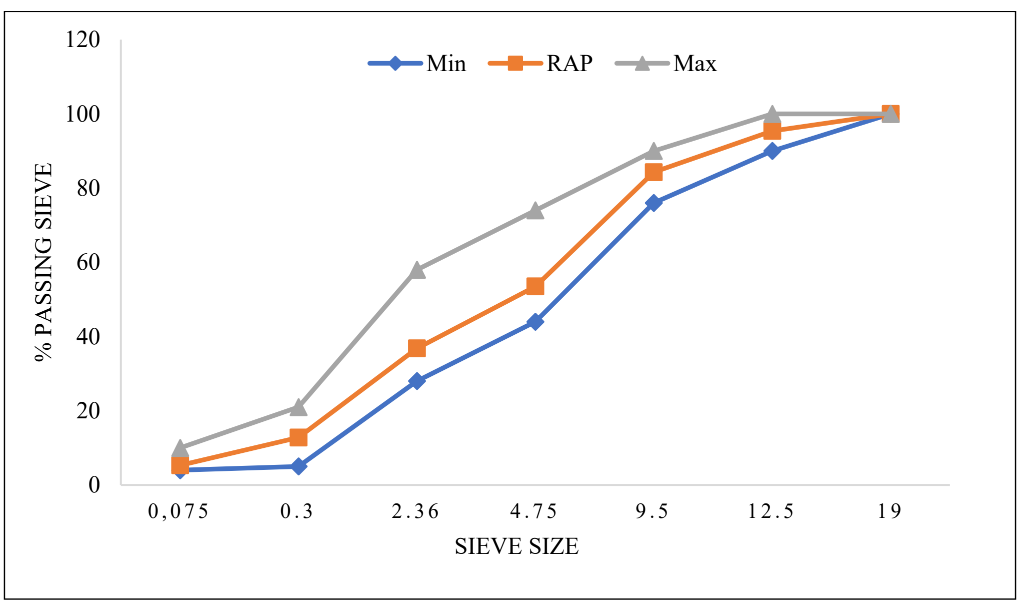

Fig. 1 Particle size distribution of RAP with specification limit

C. Filler

There was a need to add filler to the HMA and RAP mixture. The filler chosen for this study was Ordinary Portland Cement (OPC).

TABLE III CHARACTERIZATION OF OPC

Characterization	Test result
Bulk Specific Gravity	3.2
Passing Sieve # 200(0.075μm) %	97

The cement was obtained from the Dangote Cement depot, and its characterization is presented in Table III.

D. Asphalt Binder

In this study, the characterization of the asphalt binder was conducted using penetration tests, ductility, softening point, and flash and fire point tests, in accordance with the relevant specifications [19]-[22]. The characterization results are presented in Table IV.

TABLE IV CHARACTERIZATION OF ASPHALT BINDER

Test	Standard Test Method	Test Result
Rotational viscosity @ 135^{0}C (mPa=cP)	AASHTO T316, 2011b	655
Rotational viscosity @ 160^{0}C (mPa=cP)	AASHTO T316, 2011b	226
Penetration @ 25^{0}C (mm)	ASTM D5 (2006)	63
Specific gravity @25^{0}C	ASTM D70 (2009)	1.03
Ductility @25^{0}C	ASTM D113 (2007	100+
Flash point ^{0}C	ASTM D92 (2012)	319
Fire point ^{0}C	ASTM D92 (2012)	312
Softening point ^{0}C	ASTM D36 (2018)	60

E. Rejuvenator

The rejuvenator for this study was obtained from a power plant maintenance company.

TABLE V CHARACTERIZATION OF DEWO

Test	Test Result
Viscosity (cP)	168
Specific gravity g/cm^3	0.98
Water content %	0.3

Diesel engine waste oil (DEWO) is the waste oil removed from diesel engines during maintenance procedures, after it has been used to lubricate machine parts for a specified period. The DEWO was characterized as presented in Table V.

F. Modified Bitumen

This study used bitumen grade 60/70 at 5% optimum bitumen content (OBC). It was heated for about 1 hour at 170 °C and stirred with an electric mixer at a stirring speed of 2000 ± 500 rpm to obtain a uniform mixture [23]. The DEWO was added during the heating process in proportions of 2%, 4%, and 6%. Details of its characterization according to specifications [24]-[27] are presented in Table VI.

TABLE VI CHARACTERISTICS OF MODIFIED BITUMEN

Test	0%	2%	4%	6%	ASTM Standard
Penetration @ 25^{0}C	36	39	47	65	D5
Softening point ^{0}C	58	54	52	49	D36
Ductility @ 25^{0}C	100	119	136	142	D113
Flash point ^{0}C	305	298	288	278	D92
Rotational viscosity (cP) @ 160^{0}C	233	215	195	133	D4402
Specific gravity (g/cm^3)	1.070	1.065	1.069	1.041	D70
After thin film oven test ASTM D-1754(2015)					
% of original binder penetration	94.1	91	81.5	88	D1754
Refine ductility @ 25^{0}C (cm)	94	103	111	126	D1754

G. Modified Asphalt Concrete

The asphaltic concrete was prepared using varying proportions (0%, 20%, 40%, and 60%) of RAP and 2% DEWO. The RAP and virgin aggregates were heated together at 160 °C and mixed for 3 minutes, after which the modified bitumen in varying proportions was introduced at room temperature. These steps were repeated for all RAP proportions. Four specimens were produced for each RAP proportion. Details of the sample properties are given in Table VII.

TABLE VII MARSHALL PROPERTIES OF ASPHALT CONCRETE

% RAP	0%	20%	40%	60%
Marshall stability (KN)	10	12	13.3	12.2
Marshall flow (mm)	3.51	3.50	3.49	3.47
Bulk density (g/cm^3)	2.308	2.401	2.511	2.620
Air voids (%)	4.02	3.97	3.88	3.62
% void in mineral aggregate (VMA)	17.30	17.16	17.09	16.99
% void filled with asphalt (VFA)	76	77	80	80.5

III. DURABILITY TEST

A. Marshall Test

The steps described in ASTM D6729 for Marshall stability and its apparatus were employed to conduct this test. The objective of this test is to analyze the strength characteristics of mix proportions. The procedure involved submerging the samples in a water bath for 30-40 minutes at a temperature of 60 ± 10 °C before placing them on the Marshall stability testing apparatus. Load deformation occurred at a constant strain rate of 50.8 mm (2 inches) per minute until failure.
The overall deformation and specimen failure are measured by Marshall flow and Marshall stability tests, respectively [28]. Specimen characterization was performed in accordance with ASTM D2726-17 [29], and ASTM D2041-11 [30], respectively.

B. Indirect Tensile Strength Test ITS

The ITS test was conducted in accordance with the D6931-17 standard procedure [32]. The purpose of the test was to evaluate the influence of moisture on the durability of asphalt concrete. The specimen was prepared with an air void content of 7 ± 1%. For each RAP proportion (0%, 20%, 40%, 60%), six specimens were prepared.

Three specimens for each RAP proportion were tested without any conditioning, while the other three specimens were conditioned before testing by soaking in a water bath for 24 hours at 60 °C, followed by 1 hour at 25 °C (wet condition). The average tensile strength of the conditioned specimens divided by the tensile strength of the unconditioned specimens is called the tensile strength ratio (TSR). TSR is determined in accordance with ASTM D4867, and its minimum value is 80% [33].

C. Double Punch Shear Test

This test was performed in accordance with ASTM C470. The evaluation aimed to determine the effect of binder removal from the aggregates. A specimen from each RAP proportion was prepared and immersed in water for 30 minutes at 60 ± 10 °C. The specimens were then placed between two precisely aligned steel cylinder punches with a diameter of 2.54 cm and were loaded at a rate of 2.54 cm per minute until failure. The highest possible resistance was then determined. Other studies support this procedure [34], [35].

IV. RESULTS AND DISCUSSION

A. Marshall Test

Figures 2-6 present the results of the Marshall stability, Marshall flow, bulk density, and air voids for all RAP and DEWO proportions. It can be seen that Marshall stability and bulk density improved as RAP and DEWO proportions increased. Marshall stability improved from 10 kN at 0% RAP and 2% DEWO to a maximum value of 14.1 kN at 40% RAP and 4% DEWO, representing a 41% improvement. This stability value meets the FMW&H specification of 8 kN for heavy traffic volume pavement wearing courses.

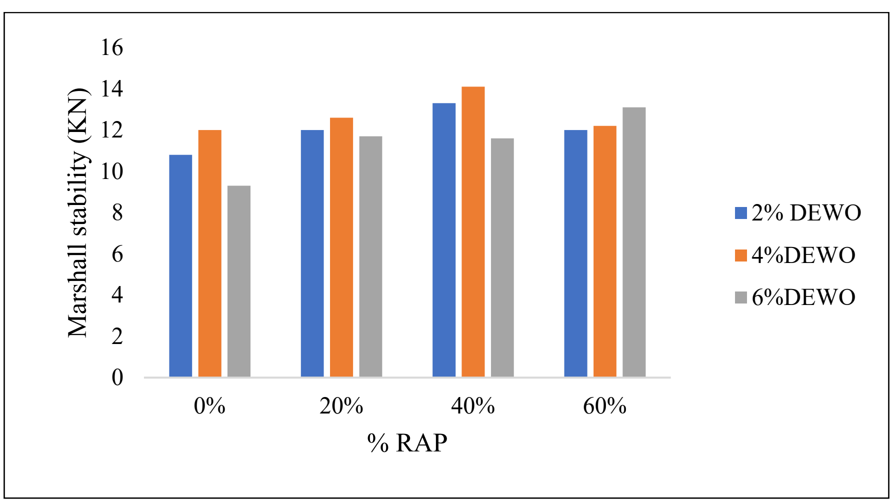

Fig. 2 Effect of RAP and DEWO on Marshall stability

It can also be observed that increasing the DEWO beyond 4% reduces Marshall stability and bulk density in all RAP proportions except at 60%. This reduction may occur because at 60% RAP, the mixture is very stiff with a high void ratio and reduced workability, resulting in low compaction. The 6% DEWO is just sufficient to restore workability and increase compaction, thus improving stability and bulk density. Conversely, in lower RAP proportions (20%, 40%), 6% DEWO reduces the bonding between constituent particles in the mixture and increases its viscosity, thereby reducing stability and causing a slight decline in flow by 1%.

The air voids and bulk density meet allowable standards for all RAP and DEWO proportions, and the results are consistent with other studies [13], [14], [36].

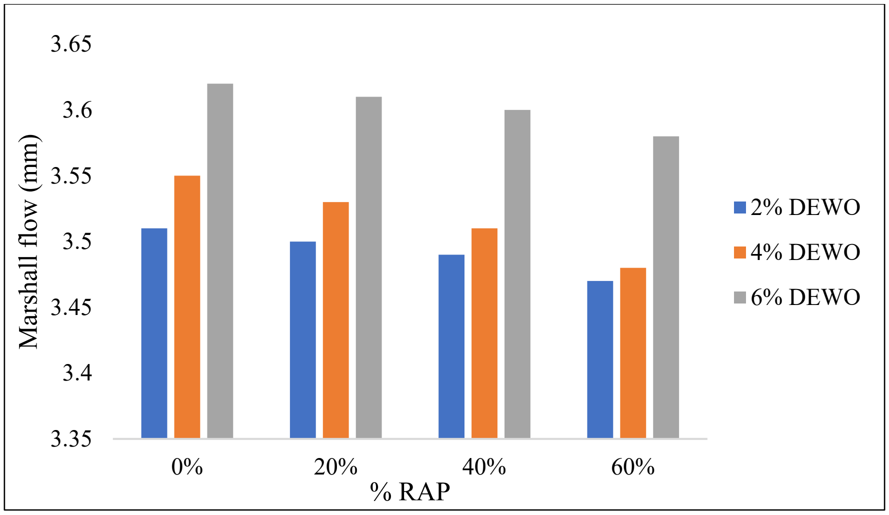

Fig. 3 Effect of RAP and DEWO on Marshall flow

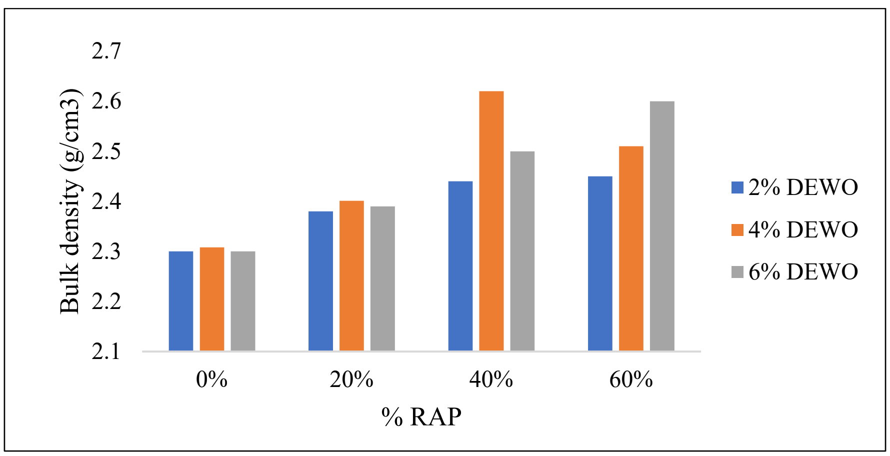

Fig. 4 Effect of RAP and DEWO on Bulk density

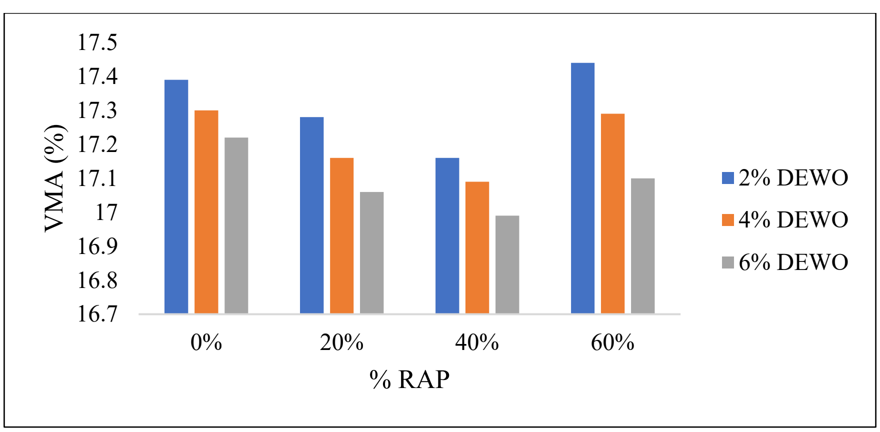

Fig. 5 Effect of RAP and DEWO on VMA

B. Indirect Tensile Test ITS

The tensile characteristics of the HMA are directly linked to the cracking characteristics of asphalt surfaces due to temperature changes. Therefore, the temperature ranges over which the asphalt mixture performed adequately was evaluated in this test. Figures 6 and 7 show the effect of RAP proportions on the ITS for both conditioned and unconditioned specimens. The results show an increase in ITS as RAP proportions increased, peaking at 40% and declining at 60%.

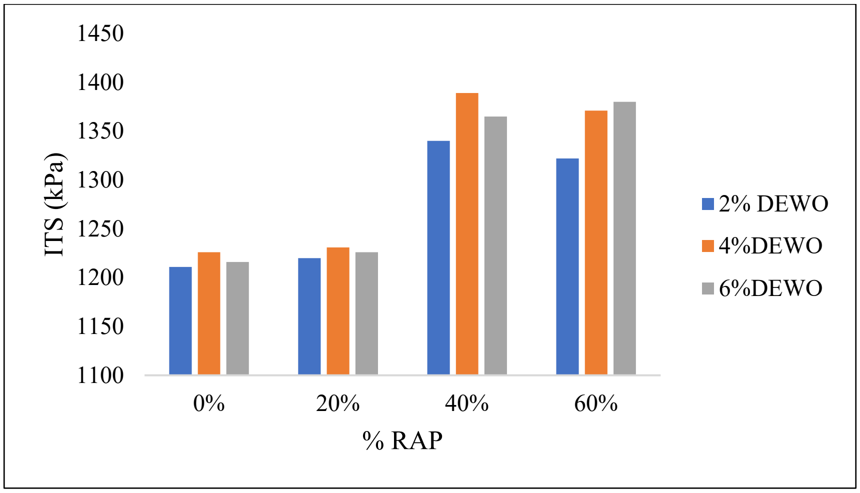

Fig. 6 Effect of RAP and DEWO on ITS (unconditioned)

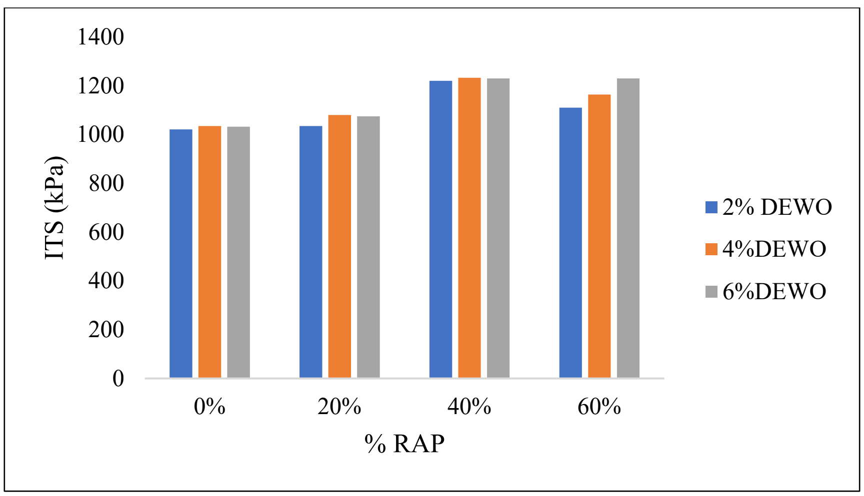

Fig. 7 Effect of RAP and DEWO on ITS (conditioned)

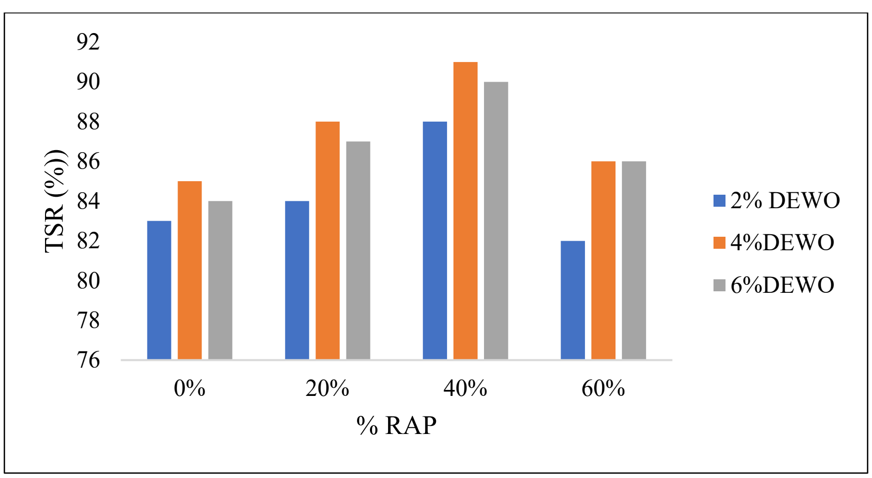

Fig. 8 Effect of RAP and DEWO on TSR

The TSR value in Figure 8 increased with the percentage of RAP and met the minimum specified value for all RAP and DEWO proportions. The improvement in moisture resistance observed in the specimens was due to the addition of DEWO, which reduced the amount of air voids and led to closer bonding of particles in the mixture, thereby improving compaction. Conversely, increasing the RAP content above 40% resulted in reduced ITS and TSR due to increased brittleness, which decreased workability and made it difficult for the aggregates to be adequately coated by the bitumen. This led to higher voids and increased susceptibility to water damage. Similar studies confirmed this outcome [37], [38].

C. Double Punch Shear Test

The results of the punching resistance of the mixture increased as the RAP proportion increased. Figure 9 shows the test results, indicating that mixtures with varying RAP contents outperformed the pure mixture. Additionally, as the percentage of DEWO increased, the punching resistance also increased, suggesting that the addition of DEWO enhances the mixture's bonding characteristics, elasticity, elongation, and binder viscosity, thereby improving resistance to punching load. This is consistent with studies [39], [40], [41].

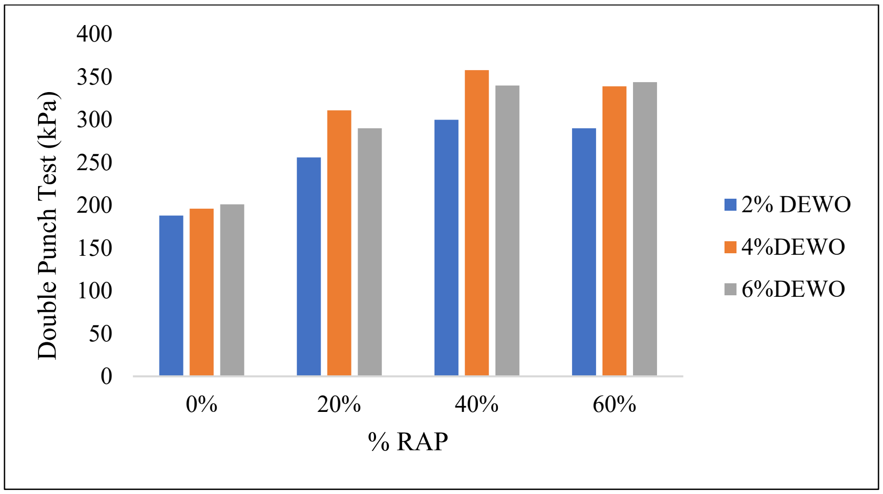

Fig. 9 Effect of RAP and DEWO on double punch shear test

The punching resistance started at 196 kPa at 0% RAP and peaked at 391 kPa at 40% RAP, representing an 89% increase. The punching resistance declined again at 60% RAP, indicating high void content and ease of deformation under applied load. However, with 6% DEWO, the punching resistance increased once more.

IV. CONCLUSION

The findings of this study are summarized as follows:
The addition of DEWO and virgin bitumen to HMA produced with RAP can effectively recover the attributes of RAP and has demonstrated a desirable enhancement in both physical and rheological properties of the HMA. At 60% RAP content in HMA, 6% DEWO is required to optimally enhance the mixture properties. The mixture of DEWO, virgin bitumen, and RAP in HMA production can significantly enhance the mechanical properties of the HMA. DEWO at 4% significantly affects the Marshall and volumetric characteristics of the HMA with 40% RAP. The modified HMA shows improved TSR compared with virgin HMA. The addition of DEWO enhances moisture damage control. The punching resistance of the HMA can be enhanced through the addition of DEWO and RAP. A 40% RAP content is identified as the optimal proportion in the HMA mixture using DEWO as a rejuvenator. Conclusively, this study establishes that the rejuvenation of reclaimed asphalt pavement (RAP)-based hot mix asphalt (HMA) using a combination of virgin bitumen and diesel engine waste oil (DEWO) is sustainable and supports environmental concerns. This study presents a promising approach that will positively impact environmental goals and other imperatives in asphalt research.

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