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Original Research

INVESTIGATION OF THE MECHANICAL PERFORMANCE OF STONE MASTIC ASPHALT MIXTURES MODIFIED BY RECYCLED WASTE POLYMERS

Sady A. Tayh*, Doua Yousif Khalif

Highway and Transportation Engineering Department, College of Engineering, Mustansiriayah University, Baghdad, Iraq

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Abstract: The usage of polymer-modified asphalt binders has increased as a result of the significant increase in the number of conventional cars operating on Iraqi roads in recent years. This has resulted in increased strains being placed on pavement structures and materials. Global exploration has focused on the development of stabilizing Stone Mastic Asphalt mixtures for improved pavement behavior. Numerous effective efforts were made to stabilize stone mastic asphalt mixes with polymers and fibers. Iraq produces a considerable amount of waste polymer materials each year. Usually, they are sent to landfills for disposal. These wastes are dumped, occupying a sizable portion of landfill space and creating various serious environmental issues. The study focuses on how waste polymer additions, such as recycled plastic bottles, shopping boxes, and tire crumb rubber, affect the mechanical performance and durability of stone mastic asphalt mixtures. The mechanical performance attributes were assessed. It is evident from the findings that the drain-down amounts were within the permissible requirement range. The findings also showed that the indirect tensile strength, Marshall Stability, moisture damage resistance, and resistance for permanent deformation of stone mastic asphalt mixtures have all increased as a result of the use of waste polymer components. The recycled polymer-modified mixes are the combinations that are most resistant to rutting, according to the results of the repeated load axial creep tests. Iraq may have new options to employ the significant volumes of recycled polymers that are becoming accessible as a result of recycling waste polymers.

Keywords: *Mechanical performance; stone mastic asphalt; drain-down; tensile strength ratio; repeated load axial test; rutting test; Marshall stability*

1. Introduction

The improvement of pavement characteristics is the most essential aim of every pavement behavior investigation. This objective could be realized by altering the mixtures conventionally used with proper additives to boost the characteristics of the

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**Corresponding Author*: sady.tayh75@uomustansiriyah.edu.iq

advanced mixtures. Knowledge from earlier research experiments showed the advantage of stone mastic asphalt (SMA) mixes concerning durability and rutting endurance[1]. Many investigations on enhancing the quality of road materials have been described recently [2-4].

Stone mastic asphalt (SMA) is a hot mixture with a gap-classified aggregate gradation that has gotten worldwide popularity due to its desired properties. SMA was first established in Germany in the 1960s and then began to progress in the United States in the early 1990s. Ever after, it has been utilized widely around the globe. Previous research has reported the potential of SMA mixes to resist permanent deformation, as well as their high durability, reduced skid resistance, and good resistance to fatigue and reflective cracking. Nevertheless, the drain-down of asphalt mastic and higher initial prices might be drawbacks of this sort of mix. SMA mixes need stabilization to prevent the drain-down of asphalt mastic and this could be realized by the addition of polymers or fibers [5-11]. Rutting properties of SMA have been explored by several scholars utilizing various combinations of test protocols and analysis techniques [12-17].

Even though using neat additives in the bituminous mix may enhance the rutting features of the asphalt concrete, in numerous circumstances highway construction prices raises significantly. Therefore, many studies were made concerning asphalt mixes comprising recycled materials as modifiers to enhance bituminous mixture properties and decrease cost due to the utilization of neat materials. Moreover, this could be a substitute to solve ecological problems by the utilization of recycled polymer materials. Steel slag, waste glass, recycled polymers, and waste tires are samples of waste materials that have been utilized in HMA mixes in earlier research [18-21].

Usually, fibers are used as the inhibitor materials for the drain-down of asphalt mastic from SMA mixes. However, several sorts of recycled polymers such as polypropylene (PP), polyethylene terephthalate (PET), crumb rubber (CR), polyvinyl chloride (PVC), or styrene-butadiene-styrene (SBS) modified binders could be utilized as a substitution for the fibrous materials [10, 22-24]. Several explorations have been conducted on adding recycled polymers in asphalt binders to enhance the behavior of asphalt mixtures. The polymer-modified mixes demonstrated higher rutting resistance than the unmodified mixes. The effectiveness of polymeric modifiers was noticed [25-28].

SMA has no application yet in Iraq. Recycled polymers are increasingly used because there is a need for proper alternatives to the additives used in the pavement industry nowadays. The main reason for this research is to explore the effect of adding various sorts of recycled polymers to the conventional SMA asphalt mixture. Thus, this study makes a comprehensive investigation of the mechanical performance of stone matrix asphalt (SMA) mixes enhanced by recycled polymers (PET, PVC, and CR) through laboratory evaluation. The mechanical performance behaviors evaluated include Marshall Stability, indirect tensile strength, moisture resistance, drain-down, and rutting performance.

2. Materials and Methods

2.1. Asphalt binder

The (40-50) penetration grade asphalt cement used in this study is the plain asphalt binder. Since the space does not allow displaying the properties of the modified asphalt binder modified with recycled polymeric materials in different proportions, the physical properties were included only for the optimal addition ratios for each type of recycled material. Based on the outcomes of the preliminary tests conducted on the SMA samples with neat asphalt binder (40-50) and the modified binders, the optimal addition contents for each recycled polymer modifier were (4%) for both RPET and RPVC and (12%) for RCR, as it is shown in Table 1. These results fulfill the requirements as per Iraqi specifications.

The percentages of addition for each type of recycled polymer were chosen based on previous work under publication by choosing the optimum percentage of addition, and this was consistent with previous research published in this field [8, 29-34].

Table 1. Properties of base and polymer-modified bituminous materials.

Type of test	Standard used	Test Results			
		40/50 pen.	**4% PET-modified**	**4% PVC-modified**	**12% CR-modified**
Penetration @ 25 °C	*ASTM D5	44	40.5	40	32
The softening point, °C	ASTM D36	52	55.5	53.5	72
Ductility @ (25°C), (cm)	ASTM D 113	117	125	80	148
Flashpoint, °C	ASTM D92	253	315	339	245
Fire point, °C	ASTM D92	274	323	343	253
Specific Gravity	ASTM D70	1.02			
Viscosity @ 135 °C (cpoise)	ASTM D4402	437	682	672	902
Viscosity @ 165 °C (cpoise)	ASTM D4402	132	312	301	420

*American Society for Testing and Material

2.2. Aggregate

The Al-Nibaae quarry at Al-Taji, Baghdad, provided the crushed aggregates, both fine and coarse. This study chose an aggregate gradation that follows the recommendations of the National Asphalt Pavement Association [35], as can be described in Fig. 1. Table 2 lists the physical characteristics of Al-Nibaee aggregate. Common Portland cement, which has a bulk specific gravity of 3.12, is dry, clump-free, and used as a filler in the creation of SMA Mix.

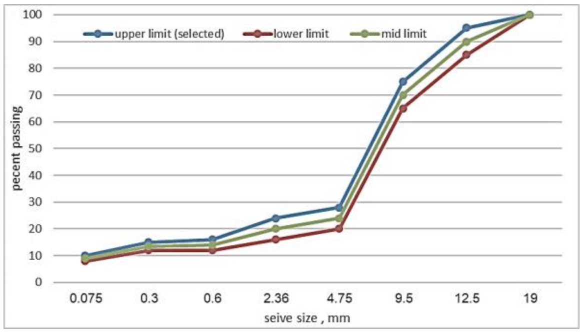

Figure 1. Gradation of the aggregate used.

2.3. Date Palm Fibers

In the present investigations, one type of natural fiber (Date Palm Natural Fiber) was utilized as a stabilizing agent in SMA Mixture. The physical features namely diameter, length, and specific gravity of date palm fibers were 0.1mm, 5 to 10 mm, and 0.5, respectively [61]. The addition of cellulose fiber to the mixture was accomplished using a dry method.

Table 2. Physical properties of the aggregate used

Property	**Specification**	**Coarse Aggregate**	**Fine Aggregate**
Percent Wear (Los-Angeles Abrasion)	(ASTM C131-14)	23.1	……
Bulk Specific Gravity	(ASTM C127-128-15)	2.647	2.63
Specific Gravity (apparent)	(ASTM C127-128-15)	2.653	2.668
Water Absorption (%)	(ASTM C127-128-15)	0.57	0.66

2.4. Recycled Polyethylene Terephthalate (RPET)

Polyester-like polyethylene terephthalate (PET) is frequently used in the food and beverage sectors for packaging. The recycled PET material came from used water bottle trash. PET bottles were broken into tiny bits and then shred by a crushing machine to be used as a modifier in SMA mixes. The PET scraps were then sieved and put through a 2.36 mm sieve to be utilized in this research. The characteristics of PET material are displayed in Table 3.

Table 3. Attributes of recycled PET [21]

Properties	Result
Melting point (°C)	250
Density (g/cm³)	1.35
Tensile strength (psi)	11500
Water absorption (%)	0.1

2.5. Recycled waste polyvinyl chloride (RPVC)

As they were shredded into little bits and placed in the asphalt binder, the used supermarket boxes helped the asphalt binder's qualities. The characteristics of polyvinyl chloride made from recycled waste are shown in Table 4.

Table 4. Attributes of recycled PVC [36]

Attributes	**Results**
Density (g/cm³)	1.3-1.6
Tensile strength (MPa)	40-50
Flexural modulus (GPa)	2.1-3.4
Thermal coefficient expansion	$80*10^{-6}$

2.6. Recycled tire crumb rubber (RCR)

A form of elastomer polymer made from recycled tires is known as recycled crumb rubber [37]. It is blended into the clean asphalt binder in the form of crumbs. Table 5 displays the characteristics of the crumb rubber modifier.

Table 5. Attributes of recycled crumb rubber.

Specifications	**Result**
Physical State	Solid
Color	dark
Density (g/cm³)	0.34–0.35

2.7. Recycled Polymers-Modified Binder Preparation

A medium-speed shear mixer at a shear speed of 1000 rpm for 1h is used to prepare the modified asphalt binders. The blending procedure is done by gradually adding the recycled materials to the base asphalt binder at a moderate speed of rotation while not allowing the temperature to exceed 180°C to avoid losing a lot of volatile substances. The blending process is continued until it is ensured that the additive is dispersed in the asphalt or spreads fairly in it without agglomeration. The compaction and mixing temperatures for every enhanced binder were carried out at various temperature ranges based on the kind of enhanced asphalt, as it is indicated in Table 6, since each modified binder has a distinct viscosity, as shown in Fig. 2. Before being used in the pertinent laboratory experiments, the mixes were then put in metal cans coated with foil. The description of the blends before being evaluated is shown in Table 7.

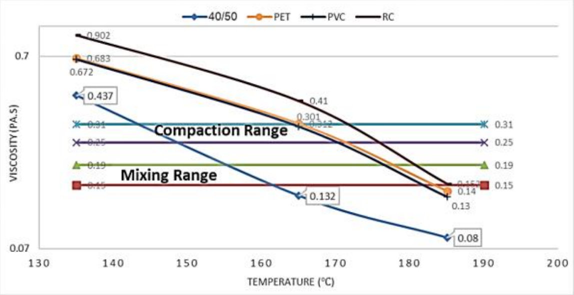

Figure 2. Viscosity-temperature chart for waste polymer-modified asphalts.

Table 6. Temperatures for mixing modified binders that have been pre-treated.

Asphalt type	Temperature range for mixing (°C)	Temperature range for compaction
40/50 pen.	158±5	146±5
Asphalt + PET	180±5	168±5
Asphalt + PVC	179±5	167±5
Asphalt + CR	183±5	175±5

2.8. Design of SMA Mixture

The first step in the design process of SMA mixes is to determine the voids in coarse aggregate using the dry-rodded method (VCADRC) for aggregate compaction according to AASHTO T-19. This parameter is then utilized to determine stone-on-stone contact which can be calculated as in Eq. (1) [38].

Table 7. A description of the enhanced SMA mixes.

Mixture designation	Description
40/50 (control)	40/50 penetration grade asphalt binder
ARPET	40/50 + 4% recycled PET
ARPVC	40/50 + 4% recycled PVC
ARCR	40/50 + 12% recycled CR
AF	40/50 + Fiber
AFRPET	40/50 + Fiber + 4% recycled PET
AFRPVC	40/50 + Fiber + 4% recycled PVC
AFRCR	40/50 + Fiber + 12% recycled CR

$$\mathrm{VCA_{DRC}} = \frac{(\mathrm{G_{CA}} \times \gamma_w) - \gamma_s}{\mathrm{G_{CA}} \times \gamma_w} \times 100 \tag{1}$$

The determination of the voids in the coarse aggregate of the whole mix ($\mathrm{VCA_{mix}}$) can be calculated by utilizing Eq. (2) (AASHTO T19). The stone-on-stone contact can exist in case the $\mathrm{VCA_{mix}}/\mathrm{VCA_{drc}}$ ratio is less than one [39].

$$\mathrm{VCA_{MIX}} = 100 - \left(\frac{\mathrm{Gmb}}{\mathrm{GCA}} \mathrm{P_{CA}}\right) \tag{2}$$

where GCA stands for coarse aggregate bulk specific gravity, γ_s for coarse aggregate unit weight following dry-rodded compaction, γ_w for water unit weight (998 kg/m^3), $\mathrm{G_{mb}}$ for the compacted mix bulk specific gravity, and $\mathrm{P_{ca}}$ for the proportion of coarse aggregates in the whole mixture. The value of $\mathrm{VCA_{DRC}}$ for coarse aggregate fraction was determined to be 44%. The calculation of $\mathrm{VCA_{MIX}}$ was performed for the SMA mixtures at optimum asphalt content (asphalt content that achieves 4% air voids in the SMA mix) and it was found to be 39.56%, which indicates the fulfillment of the stone-on-stone condition in the gradation chosen for this SMA mixture.

The second step is to prepare fifteen cylindrical specimens of 100mm diameter at bitumen percentage ranging from 5%-7% with an increase of 0.5%. Three samples were arranged for every asphalt percent. The optimum binder content is governed by measuring the samples for final air void content of 4%, maximum stability, and maximum specific gravity. To estimate the recycled polymer's effect on mixtures' performances, three replicate samples were prepared to be evaluated through the Marshall stability, Indirect Tensile Strength, moisture-induced performance, and repeated load axial rutting experiments. It was observed that the optimum binder content for the control SMA mixture was found to be 6.2% by weight of the total mix.

2.9. Drain-down

The test technique was recommended by NCHRP Report No. 425 [40]. A typical wire basket with a loose SMA specimen and a flat surface was placed in an oven set at the mixing temperature for one hour for each group of blends. The percent of asphalt mastic drain-down is determined using Equation (3) [41]. The allowed drain-down percent should not be more than 0.3% by the total weight of the mix [42].

$$\text{Draindown} = \left(\frac{B-A}{W}\right) \tag{3}$$

where A is the plate's starting mass, B is the plate's weight after the materials have been drained, and W is the weight of the loose specimen.

2.10. Marshall Stability

Marshall Stability values were determined according to ASTM D6927-06 [43] for the SMA mixes. The high value of Marshall Stability exhibits a higher capacity to withstand heavier traffic loads and better resistance against permanent deformation at high service temperatures [44, 45].

2.11. Indirect Tensile Strength (ITS) Test

A majority of assessments of the relative qualities of materials make use of the indirect tensile test values. In the indirect tensile strength test, a cylindrical specimen is compressed between two loading strips to produce a fairly uniform tensile stress along the vertical diametrical plane. Splitting along this loaded plane almost causes failure [46]. This test was done according to ASTM D6931 [47]. For each SMA Mixture type, three samples with the ideal asphalt content were created. The samples have been loaded at a temperature of 25 °C and a deformation rate of 50 mm/min. The tensile strength value of the asphalt specimen was determined utilizing Equation 4.

$$\text{ITS} = 2P_{max}/\pi Dt \tag{4}$$

where D is the sample diameter (mm), t is the sample thickness (mm), ITS is the indirect tensile strength of the specimen (kPa), P_{max} is the maximum applied load (kN).

2.12. Moisture Damage Resistance Test

Moisture susceptibility test was conducted according to Modified Lottman Test (ASTM D 4867, 1996) [48] or (AASHTO T 283, 2007) [49]. Six samples from each mixture type were prepared. Three of them underwent vacuum saturation conditioning before spending 24 hours in a 60°C warm water bath. Another group of three specimens of each mix type was denoted as unconditioned specimens and tested without being wet but following 40 minutes of submersion in a 25°C water bath. Then, using Equation 5, the indirect tensile strength ratio (TSR) was determined.

$$TSR = (ITS_2/ITS_1)*100 \quad (5)$$

where ITS_1 represents the average indirect tensile strength value of dry specimens (unconditioned) and ITS_2 represents the average indirect tensile strength value of the conditioned specimens (kPa). For SMA mixtures, a TSR of 70% or above is regarded as an acceptable minimum value [45, 50].

2.13. Repeated Load Axial Test Setup

The dynamic creep test, also known as the repeated load axial test, is frequently utilized in experimentation to measure the asphalt mixtures' permanent deformation under certain loading conditions. It is utilized to analyze the rutting possibility for the SMA mixtures in the present study. In this work, cylindrical SMA mixture specimens are subjected to a dynamic creep test that provides uniaxial vertical repeated loads in the form of haversine waves with a stress value of 207 kPa, a loading period of 0.1 seconds, a rest period of 0.9 seconds, and an operating temperature of (50°C). Every sample test is finished after 10,000 load cycles or when the total amount of permanent deformation exceeds 10mm. The amount of repeated load, the average vertical deformation, the number of loading cycles, and the duration of each test were all noted. At Dyala University's College of Engineering's Highway and Transportation Engineering Department, a repeated load test was performed. Using UTM equipment and the Repeated Load Axial Test (RLAT) following NCHRP 465, the resistance of SMA mixes to rutting was evaluated. For each blend, the average of three samples was determined. Fig. 3 shows an example of estimated strain data for the control SMA combination (40-50 asphalt binder) during the RLAT test at a temperature of (50°C).

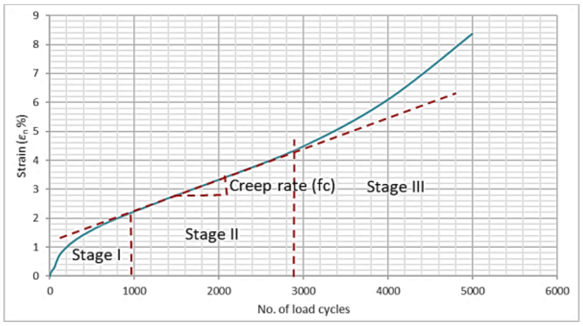

Figure 3. Example of creep strain measurement data from RLAT tests.

Drawing the link between axial creep strain and load repetition cycles often results in three typical phases, which are the primary stage, secondary stage, and tertiary stage, as shown in Fig. 2. The flow number (FN) is a crucial parameter in assessing the asphalt mixtures for rutting resistance, and it can be determined. The primary analysis elements utilized for calculating the resistance to rutting of asphalt mixes examined by the RLAT are (i) the cumulative axial creep strain at the time of failure, (ii) the slope of the steady-state stage (creep rate fc), and (iii) the creep modulus (E_n) at the failure time [51]. The flow number, on the other hand, is the lowest rate of strain buildup recorded throughout the test and is known as the loading cycle number at which the specimen starts to fail rapidly [12].

The slope of the second stage (creep rate *fc*), i.e. the steady state stage, is calculated from a selected segment along the steady state line as in Equation (6) (EN 12697-25, 2016) [52].

$$f_c = \left(\frac{f_{n1} - f_{n2}}{n_1 - n_2}\right).10000 \qquad (6)$$

where *fc* is the creep rate (µm/m/loading cycles), n1 and n2 are the total number of loading cycles, and ε_{n1} and ε_{n2} are the cumulative axial strains at n1 and n2 loading cycles (in percent).

According to Equation (7), the creep modulus (E_n) can be determined for a given loading cycle’s number (n) [53].

$$E_n = \left(\frac{\sigma}{10_{f_n}}\right) \qquad (7)$$

In this equation, E_n is the creep modulus after n cycles of loading (in MPa), ε_n is the cumulative axial strain of the assessed sample at n cycles of loading (in %), and σ (in kPa) is the applied stress.

2.14. Rutting Testing Sample Preparation

As indicated in (NCHRP Report 465, Appendix B) [12], cylindrical specimens with a diameter of (100 mm) and a height of (150 mm) were created, for control and recycled polymer-modified SMA mixes were used with a target air content of 4%. The specimen is compressed using the double piston technique in the Material Laboratory of the Civil Engineering Department, University of Nahrain, with a weight of (15,000 kg) delivered using a hydraulic compression machine. 24 total specimens were produced in this manner.

3. Results and Discussion

3.1. Marshall Stability

The Marshall Stability values for each modified SMA mix type were displayed in Fig. 4. With or without natural fibers, the control group's Marshall Stability was often lower than that of the mixes changed with waste polymers. Due to the presence of polymers that increase the mix's resistance to loading, these results may have helped the creation of a stiffer mix. Nevertheless, there is no noticeable significant difference between the effect of the different types of recycled polymers on the stability values at the optimum addition ratios for each type of additive (4% RPVC and RPET, and 12% RCR). The outcomes of the Marshall stability evaluations display that the kind of reclaimed polymer has minimal effect on how well HMA mixtures resist deformation. To determine the degree of this improvement in rutting performance, more testing using a more complex testing approach is necessary. To learn more about the impact of the reclaimed polymer additions without and with natural fiber, the scientists chose to study the rutting possibility using the repeated loading axial test method.

It is noted that the difference is slight in the increase in the stability values in favor of mixtures that contain natural fibers. This result implies that the addition of natural fiber to HMA mixtures can enhance such mixes’ resistance to permanent deformation. Due to the fibers' adherence to bituminous binders and their ability to interconnect with aggregates, the insertion of fibers into HMA mixes acts as a three-dimensional secondary reinforcement [53, 54]. Therefore, adding natural fiber to HMA mixes has an opportunity to boost such mixes' resistance to rutting.

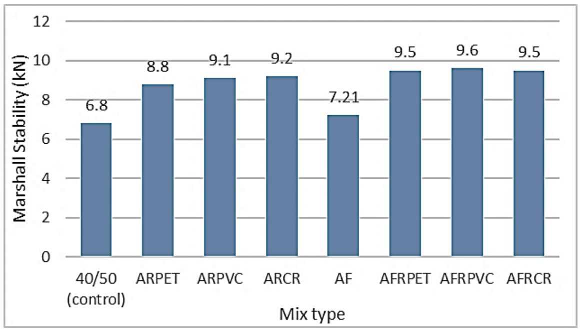

Figure 4. Marshall Stability values for SMA mixes.

3.2. Drain-Down Test

The drain-down testing outcomes for SMA mixes of regular and modified bitumen are presented in Fig. 5. When recycled polymers are used, the drain-down percentage is seen to have improved, especially when fibers are added to SMA mixes at the ideal reclaimed polymer additives proportion (4% for RPVC and RPET mixes and 12% for RCR mixes), while maintaining a constant fiber content of 0.3% by weight of the overall mix. This indicates that the reclaimed polymers added serve their purpose of lowering the proportion of asphalt mastic drain-down from the SMA composition. The rigidity of the mixture has been improved by the recycled components, which prevents the mastic from leaking. Because fibers adhere to asphalt binders, which helps to further reduce the drain-down of the asphalt binder from the mix, the inclusion of fibers into SMA mixes acts as a three-dimensional reinforcing. As required by NAPA [35], the drain-down outcomes were all lower than 0.3% by the weight of the mixture, and there was no discernible difference between the three additions in terms of their resistance to drain-down. The outcomes were satisfactory regardless of the type of addition providing the additions did their function by lowering the percentage of asphalt drain-down from the mix to less than 0.3%.

The findings demonstrated that no stabilizing agent was required in SMA with recycled polymer additions since these recycled materials would act as stabilizing agents on their own if they were added to the combination in an appropriate dose.

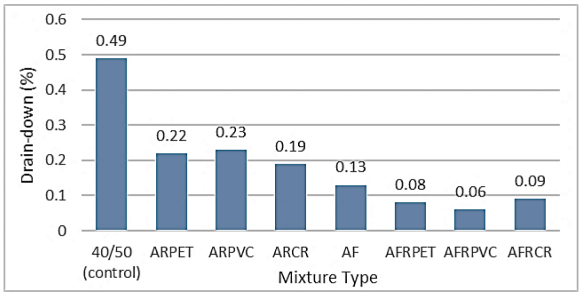

Figure 5. Values for the drain-down test for unaltered and modified SMA mixes.

3.3. Indirect Tensile Strength (ITS) test

As indicated in Fig. 6, three samples were created at the Optimum Asphalt Content (OAC) for each mixture type for both conditioned and unconditioned specimens, and the indirect tensile test was performed on these specimens. According to the findings, SMA Mixes with recycled polymers exhibit greater indirect tensile strength values. This would suggest that the changed mixes seem to have internal resistance, or the capacity to endure greater tensile stresses before cracking [55]. This suggests an improvement in the capacity to withstand static stresses, which enhances the ability of the bituminous mixes including those recycled polymer ingredients to withstand the property of resisting permanent deformation. When polymers are introduced to mixtures, they often cause the bitumen to become stiffer, increasing the mixture's resistance to tensile stresses, which are frequent in hot temperatures [56]. This improvement can be a result of increased bitumen and aggregate cohesion and adhesion [56].

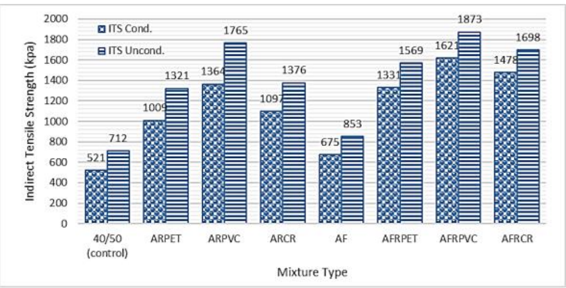

Figure 6. The test's results for indirect tensile strength.

3.4. Moisture Damage Resistance

Fig. 7 illustrates how the recycled polymers affected the moisture damage indicators. The SMA Blends have met the required standard. Nevertheless, it should be noted that the mixes with fibers had greater TSR values, whilst the mixtures without fibers had the lowest TSR values. Additionally, it is noted that the mix enhanced with reclaimed crumb rubber, trailed by reclaimed PVC, and finally reclaimed PET, is the optimum mixture in terms of moisture susceptibility. Nevertheless, regarding resistance to moisture damage, the three additions do not significantly differ from one another. These findings are in line with an earlier study [57], which came to the conclusion that using asphalt modified with recycled polymers had no appreciable impact on how sensitive the SMA mixtures are to moisture.

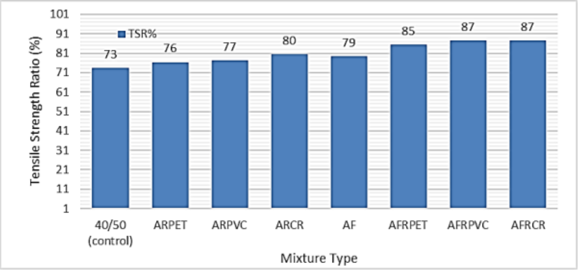

Figure 7. The SMA mixes' Tensile Strength Ratio (TSR) values.

3.5. Permanent Deformation Test

Fig. 8 shows the results of the SMA specimens' permanent deformation test. Because the permanent deformation is influenced by high service temperature, the resultant dynamic creep curves often represent all three creep phases (primary, secondary, and tertiary). Fig. 8 demonstrates how the rut depth (creep strain) grows significantly during the main phase of testing, then gradually and more slowly during the secondary stage, and finally rapidly during the final step (tertiary stage). The values of the creep strain at failure, flow number, and creep modulus at failure for all examined SMA samples could therefore be easily compared. Table 8 displays the results of the dynamic creep test.

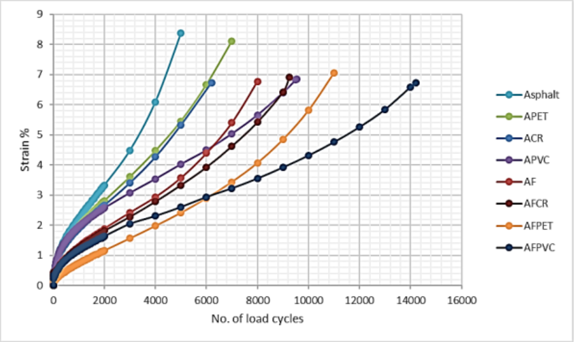

Figure 8. Axial creep strain data from RLAT at 50°C, shown against the number of load repetitions.

Table 8. Results of an RLAT (repeated load axial test) at 50 °C

Mix type	FN	Strain at failure (%)	En at failure (MPa)	DER at failure	fc (µm/m/cycles)
Asphalt	3000	4.4	4.617	13849	11.5
APET	5000	5.46	3.793	18965	8.3
ACR	5000	5.33	3.886	19414	7.96
APVC	8000	5.66	3.656	29248	4.8
AF	5000	3.57	5.799	28996	5.45
AFPET	6000	2.9	7.146	42844	4.2
AFCR	6000	3.92	5.276	31658	5
AFPVC	10000	4.32	4.795	47951	2.95

At the test temperature, it was found that the permanent axial strain values of the SMA mixtures containing reclaimed polymers were lower than those of samples of SMA with a clean binder. These results can be attributed to the formation of stiffer mixtures, which improves the rutting resistance of the asphalt mixture [29,56, 58].

Additionally, it should be noted that mixes with fibers had lower strain values than mixtures without fibers, which had higher strain values. By creating a three-dimensional network to support the mixture and improve adhesion and interconnection between the aggregate and asphalt binder, the use of natural fiber in SMA mixtures has increased the resistance to rutting [53, 54].

The following creep indices following NCHRP 465 were identified for further comparison between the SMA mixes modified with recycled synthetic materials: the axial creep strain at failure, as depicted in Fig. 9, the creep modulus at the breaking point, as displayed in Fig. 10, the creep rate (fc), as displayed in Fig. 11, and the flow number, as displayed in Fig. 12. The modulus corresponding to the number of cycles at failure is the final creep modulus.

With an increase in creep modulus and a decrease in the slope of the second stage of the axial creep curves (creep rate), the integration of recycled polymers in the lithic constitution of the asphalt mixes significantly improved the asphalt mix's resistance to rutting at high service temperatures.

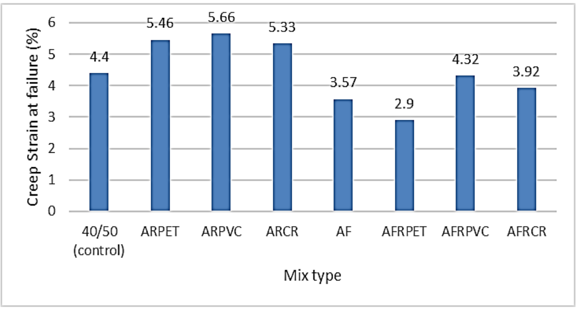

Figure 9. The RLAT test, the tested SMA samples showed axial creep strain at failure.

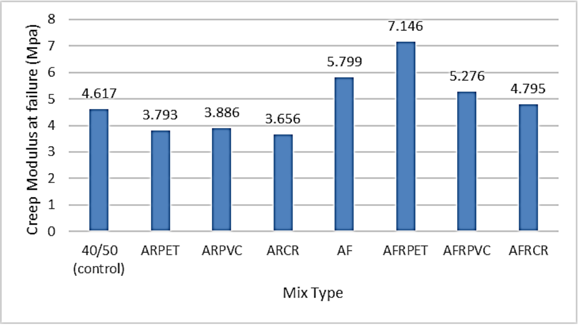

Figure 10. The RLAT test, the tested SMA specimens showing creep modulus at failure**.**

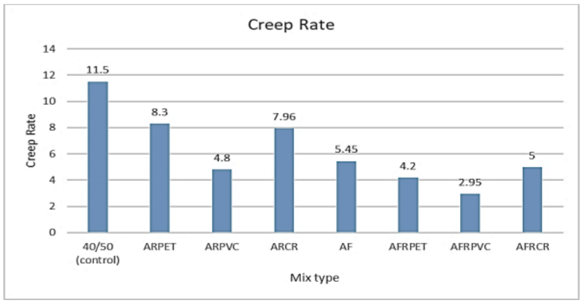

Figure 11. The RLAT test, the tested SMA specimens showing creep rate.

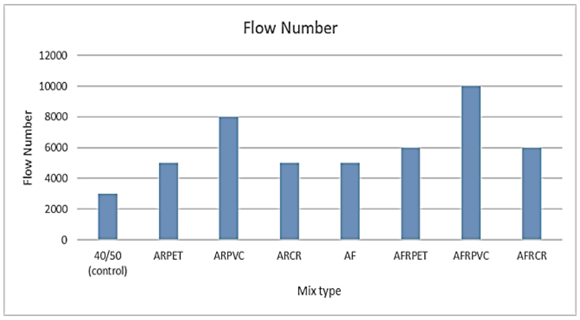

Figure 12. The RLAT test, the tested SMA specimens showing **f**low number.

The RPVC mix had the highest performance in terms of resistance to rutting out of the three recycled polymer mixtures because it had the least cumulative strain and creep rate. These findings are in line with earlier studies [55]. This improvement is almost entirely attributable to the enhanced stiffness and hardness of asphalt mixes as well as the improved viscosity of the asphalt binder made of recycled polymers [59, 60].

4. Conclusions

This study was done to investigate the mechanical performance of SMA mixes consisting of three types of recycled polymer additives (reclaimed Tire Crumb Rubber, reclaimed plastic bottles, and reclaimed grocery boxes). Based on the research outcomes, it was found that the Marshall Stability and Tensile Strength values have enhanced as a result of the use of recycled polymer components in SMA Mixes. All of the reclaimed polymer enhancers used in the SMA mixture for the present investigation functioned as effective stabilizing agents, according to the drain-down test. Utilizing reclaimed polymers can increase the resistance of SMA mixtures to moisture degradation, according to the TSR values of SMA mixtures obtained from the modified Lottman tests. However, every SMA combination that has been created has complied with the strict moisture sensitivity criteria. The dynamic creep test showed that the SMA mixes' rutting capabilities had been improved by the inclusion of recycled polymers; the SMA mixtures that had been changed to contain RPVC were the least prone to rutting, followed by those that contained RPET and RCR, respectively. Last but not least, recycling waste polymers can provide Iraq with new chances to utilize the enormous amounts of recovered polymers that are readily and locally accessible in novel and efficient ways.

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Conflict of Interest

No conflicts of interest exist, according to the authors, with the publishing of this work.

Author Contribution Statement

Author Doua Yousif Khalif: suggested the problem of the research, developed the theory, and conducted the experimental work and calculations.

Author Sady A. Tayh: verified the analytical methods, conducted the structure of the manuscript, and organized the outcomes of this study.

Both authors contributed to the final text and commented on the findings.

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