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Performance enhancement of asphalt mixture through the addition of recycled polymer materials

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Abstract
Enhancing the performance of asphalt binders is essential for ensuring the long-term durability and serviceability of asphalt mixtures, as it can help reduce the frequency of maintenance and repair work, ultimately leading to the development of more sustainable transportation infrastructure. To achieve this goal, this study investigates the effects of incorporating recycled polymer materials, including reclaimed polyvinyl chloride (PVC) and polystyrene (PS) derived from household waste, into hot mix asphalt. The experimental work involved subjecting the polymer-modified asphalt binders to a range of physical tests, such as softening point, penetration, ductility, indirect tensile strength, Marshall stability, and moisture susceptibility, and the results showed that the addition of recycled polymers, with an optimal content of 4%, led to lower penetration values and higher softening point temperatures, indicating improved resistance to temperature changes. Further analysis of the asphalt mixture performance revealed several beneficial outcomes, including a decrease in flow, a boost in the asphalt mixture's resistance to moisture-induced damage, and an improvement in Marshall stability and indirect tensile strength, with the inclusion of 4% recycled polymers yielding increases in Marshall stability of 43.7% and 37.4% for PVC and PS-modified mixes, respectively, and increments in indirect tensile strength of 32.2% and 29.7% for the same mixes. The study concludes that the use of recycled polymers can effectively enhance the performance and durability of asphalt mixtures, contributing to the development of more sustainable asphalt pavement construction practices by utilizing locally available or reused materials, which could lead to the increased knowledge and application of stronger and more weather-resistant asphalt mixes, ultimately promoting the advancement of sustainable transportation infrastructure.

Keywords Recycled polymer materials · Asphalt performance · Retained Marshall stability · Indirect tensile strength · Moisture damage

1 Introduction

Asphalt pavements are essential for global transportation infrastructure, providing critical connectivity that drives economic and social development [1]; however, with time, elements including moisture degradation from ambient conditions in addition to vehicle weights could weaken the longevity of asphalt mixes [2]. When moisture is present in asphalt pavements, it can cause problems such as stripping, deformation, and cracking, which may eventually lead to the collapse

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of the pavement structure [3–6]. Consequently, addressing the challenge of moisture damage is crucial to improving the long-term performance and service life of asphalt pavements.

One approach to enhancing asphalt performance is through the addition of specific modifiers and additives to the asphalt mixture [7–14]. Recycled polymer materials, derived from post-consumer plastics, offer an environmentally sustainable solution for enhancing asphalt performance. Incorporating recycled polymers into asphalt mixtures has been found to enhance the endurance to moisture harm and improve the mechanical features of the pavement [15–17]. The addition of recycled polymers changes the rheological behavior of the asphaltic binder, which makes it last longer, be more flexible, and be less likely to crack or rut [18–21]. Understanding the effects of recycled polymers on asphalt performance is vital for developing sustainable and resilient pavement solutions.

Significant effort was devoted to enhancing the behavior of asphalt mixes to support ever-increasing traffic loadings in a variety of climatic situations and to prevent failures and produce long-lasting asphalt pavements. To improve the asphalt cement properties, specific behavior modifiers have been studied [22]. Currently, the most commonly used modifiers for asphalt are polymers such as styrene-butadiene rubber (SBR), polyethylene (PE), styrene–butadiene–styrene (SBS), ethylene vinyl acetate (EVA), polystyrene (PS), Polyvinyl Chloride (PVC), and crumb rubber [23].

Many academics have looked at the effectiveness and efficiency of asphalt mixtures that include plastic waste. Using cheap polymers, i.e. waste polymers, was suggested by. Ahmadinia et al. [24] as a strategy to lower the price of road construction and make it more feasible. They conducted experiments with varying percentages of polyethylene terephthalate (PET) from recycled plastic bottles to realize how it would affect the engineering attributes of a stone mastic asphalt (SMA) combination, and they concluded that 6% PET by weight of the asphalt was the optimal proportion. The findings indicated that the incorporation of PET has a notable and beneficial impact on the characteristics of SMA and may facilitate the cost-effective and environmentally friendly reutilization of discarded material in the industry.

Recycled polystyrene polymer was employed by Nassar et al. [25] to improve the quality of hot mix asphalt. From 2 to 6 percentages of recycled PS were used with the asphalt binder at varying percentages. Marshall's stability tests on both the modified and unmodified asphalt, as well as its physical parameters such as its penetration value, softening point, and rotational viscosity at 135 °C. Polymer-modified asphalts (PMAs) with the highest performance levels were found to contain (4%).

Using the Marshall mix design approach, Shiva et al. [26] studied the effects of polymer waste in asphalt with 60/70 and 80/100 asphalt. They experimented with varying the quantity of plastic waste to the ideal asphalt content by a range from 2 to 12%. The results demonstrated that the stability improved with a higher percentage of plastic. The optimal percentage of plastic to add was determined to be 8%. They found that the flow increased with plastic content for a 60/70 asphalt mixture but decreased for an 80/100 asphalt mixture.

The addition of plastic to road pavements was studied by Moghaddam et al. [27]. They tested asphalt mixtures with varying amounts of plastic and compared their Marshall characteristics and specific gravities. The addition of ground waste polymeric bottles to asphalt improved its stability and flow properties, as shown by the findings. They also discovered that adding less of the shredded plastic bottles raised the unit weight and stiffness of the combinations, whereas adding more of the polymeric materials caused a lower unit weight and stiffer mixtures.

To make pavements more sustainable and increase their performance, Aboud et al. [28] included polymers as recycled additives acquired from local Iraqi sources of asphalt. Mechanical properties and performance of asphalt mixes with Polyvinyl Chloride (PVC) and Natural Rubber (NR) additives at concentrations of 2, 4, 6, and 8 percent by weight of asphalt binder have been determined. Mixtures were put through a battery of tests, including those for volume, mechanical properties, double punching shear (DPS), and indirect tensile strength (ITS), to see how well they performed. According to the findings, the combinations containing PVC polymer and natural rubber performed better than the control mixture.

Polymer materials play an important role in our modern society thanks to a range of unique properties. They present characteristics such as a very wide range of operating temperatures, high thermal/electrical insulation, corrosion- and light- resistant and sufficient mechanical properties. However, one of the main issues is the environmental impact of the plastic residues accumulated in the natural environment and in landfills, due to their longevity which can reach several decades to degrade [29]. There is an exponential use of thermoplastic materials like PVC and PS in the industrial sector, leading to an increase in global and local polymer consumption and waste generation. Recycling such polymers in the context of the asphalt paving industry would have a significant environmental and economic impact.

From the literature above, it was found that there is an abundance of research that has addressed improving the properties of asphalt mixtures using polymeric materials around the world, but it has been noted that there is a scarcity of research that is interested in investing in recycled polymeric materials in this field, especially locally in Iraq. Therefore, this study examines the effect of adding recycled polymeric materials to asphalt mixtures. Specifically, it investigates how they affect the moisture damage resistance and mechanical properties of the mixtures. To do this, several laboratory tests were conducted on bitumen and asphalt mixtures, in which softening point, penetration, ductility, Marshall and flow stability, indirect tensile strength, tensile strength ratio, and retained Marshall stability tests were conducted.

2 Problem statement

Moisture damage is the term used to describe the deterioration in strength and durability of asphalt pavements caused by water seeping between the particles of the asphalt mixture. In Iraq, the yearly cost of road maintenance accounts for a significant portion of the overall cost of constructing new roads. Iraqi roads often exhibit severe early pavement life problems. Excessively high moisture and temperature are two elements that contributed to the early failures. Following seasonal rains, damaged areas may be noticed on highways and urban roads. These roads may sever from stripping because of the characteristics of the local aggregate. Furthermore, high water table is the cause of the country's serious water damage issues. As a result, the road network is dealing with several issues related to durability, such as pothole development, raveling, and stripping.

3 Materials

Locally accessible recycled materials were used for this investigation. The following sections provide an explanation of the qualities of the materials used, which were as follows: asphalt binder with a grade of 40–50, fine and coarse aggregates brought from Al- Nibaae quarry north of Baghdad, in addition to recycled plastic materials which were PVC and PS.

3.1 Asphalt binder used

The study used 40/50 penetration grade neat bitumen sourced from the Al-Dorah refinery in Baghdad, Iraq. The properties of the neat bitumen were evaluated through traditional asphalt experiments conducted at the Transportation Laboratory, College of Engineering, Mustansiriyah University, Baghdad, Iraq [30]. Table 1 presents a comprehensive overview of the results obtained from these tests, providing valuable insights into the characteristics of the neat asphalt binder.

3.2 Mineral aggregate

The hot mix asphalt relies significantly on the properties of its aggregates. Both fine and coarse aggregates used in this study were obtained from Al-Nibaae quarry located in Al-Taji in Baghdad. The coarse aggregate comprises strong, hard, and durable particles, selected for their robust characteristics. The gradation of the coarse aggregate ranges from 19.0 mm to 4.75 mm sieve size, whereas the fine aggregate gradation ranges from passing the 4.75 mm sieve to retaining on the 0.075 mm sieve, following the guidelines in Iraqi specification of roads and bridges [31].

Table 1 Physical features of the neat asphalt binder used

Tests	Standard	Results	Specification limits	
			Min	Max
Penetration (25 ℃, 5s., 100gm)	ASTM D5	44	40	50
Softening point (℃)	ASTM D36	52	50	60
Ductility at 25 ℃, (cm)	ASTM D113	117	100	
Specific gravity	ASTM D70	1.03	1.01	1.06
Rotational Viscosity at 135 ℃ (Pas.S) Rotational Viscosity at 165 ℃ (Pas.S) Rotational Viscosity at 185 ℃ (Pas.S)	ASTM D4402	0.437 0.132 0.08		
Flashpoint (℃)	ASTM D92	253	≥ 232	
Fire point (℃)	ASTM D92	274	…	

Comprehensive testing of the physical attributes of the Al-Nibaee aggregate was conducted, and the results are presented in Table 2. These assessments were carried out at the National Center for Construction Laboratories and Research in Baghdad, Iraq, providing reliable data on the specifications of the aggregates utilized in hot mix asphalt.

3.3 Mineral fillers

One type of mineral filler, ordinary Portland cement was obtained from local markets for this study. It was thoroughly dry and devoid of lumps or aggregations of fine particles. Table 3 displays its chemical composition, while Table 4 presents its physical properties.

3.4 Recycled polymeric materials

3.4.1 Recycled waste polyvinyl chloride (RPVC)

PVC, or polyvinyl chloride, is a thermoplastic material that is often used in the building sector because of its affordability, toughness, and workability. Additionally, it is used to improve the qualities of the asphalt binder. In this research, waste PVC generated during the production of doors and windows was collected and thoroughly cleaned. The collected PVC was then shredded into small pieces using a shredder. Table 5 provides an overview of the attributes of the reclaimed waste polyvinyl chloride (RPVC) used in this study [30].

3.4.2 Recycled waste polystyrene (RPS)

Polystyrene (PS) polymer is widely used in various applications due to its affordability. It is commonly found in packaging, thermal insulation, and disposable products [33]. In this research, recycled waste polystyrene (PS) was obtained from waste disposable dishes. The physical characteristics of polystyrene are detailed in Table 6 [34]. To ensure a uniform

Table 2 Physical features of the aggregate used

Properties	Specifications	Coarse aggregate	Fine aggregate	Requirement	Remarks
Percent Water Absorption	(ASTM C127-128-15)	0.57	0.66	< 2%	Suitable
Los-Angeles Abrasion	(ASTM C131-14)	23.1	……	< 30%	Suitable
Apparent Specific Gravity	(ASTM C127-128-15)	2.653	2.668		
Bulk Specific Gravity	(ASTM C127-128-15)	2.647	2.63	> 2.60	Suitable

Table 3 The chemical components of the Ordinary Portland cement used

Chemical components	%Content
Silica, SiO_2	21.51
Lime, CaO	62.52
Sulfuric Anhydride, SO_3	1.58
Alumina, Al_2O_3	5.64
Magnesia (MgO)	3.77
Ferric Oxide, Fe_2O_3	3.35
Loss on Ignition (L.O.I.)	1.34
Total	99.44

Table 4 Physical features of the used Ordinary Portland cement

Properties	Result
Passing from Sieve No. 200 (%)	99
Bulk specific gravity	3.15
Surface Area (m^2/kg)	50

Table 5 Physical attributes of recycled waste polyvinyl chloride (PVC) [32]

Properties	Results
Thermal coefficient expansion	$80*10^{-6}$
Flexural modulus (GPa)	2.1–3.4
Tensile strength (MPa)	40–50
Density (g/cm^3)	1.3–1.6

Table 6 Physical properties of recycled polystyrene (PS) [34]

Properties	Results
Density (g/cm^3)	1.05
Tensile strength (MPa)	41.2
Thermal coefficient expansion	80*10–6
Flexural modulus (GPa)	2.84
Softening point (℃)	86

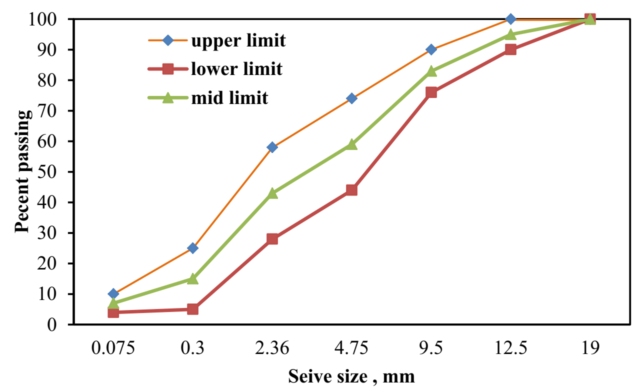


Fig. 1 The selected gradation for the used aggregate [31]

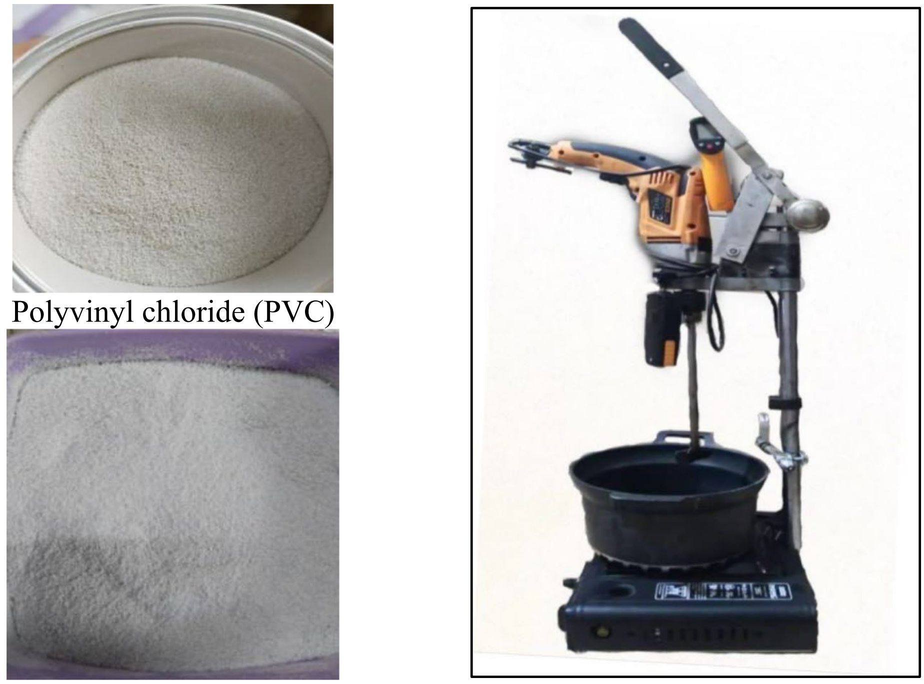
mixture when combined with hot asphalt, the polystyrene polymer was crushed into fine particles using a mechanical crusher in the laboratory.

3.5 Aggregate gradation

The aggregate gradation chosen for this research adheres to the mid-point gradation in order to meet the requirements specified in [31] for the hot mix asphalt-paving mixture. The maximum aggregate size for the surface layer, designated as type IIIA, is 19 mm, with 12.5 mm nominal maximum sieve size. Figure 1 presents a graphical representation of the particle size distribution for the used aggregate, along with the specification limits and the selected mid-point for the surface layer.

4 Manufacturing of polymer-modified asphalt binders

The shredded modifiers, shown in Fig. 2a and b, were first dried at a temperature of 60 ℃ in an oven in order to get the two recycled polymeric ingredients into the asphalt binder. After that, a No. 50 sieve was used to filter each batch of waste polymer. The modifiers were then added to bitumen of grade 40–50 at varying percentages of (2, 4, and 6%) based on the bitumen's weight. The blending equipment utilized in this research was a high-shear mixing device made locally [30], as can be seen in Fig. 2c. The blending process took place by gradually introducing the recycled polymer modifiers to the bitumen using a high-shear mixing device. The blending was conducted at a temperature range of 160–170 ℃ and a shearing rate of 2000 RPM for 1 h. Following the blending process, the blends were stored in metal cans covered with foil until they were used for the relevant laboratory tests.



(a) Polyvinyl chloride (PVC)

(b) polystyrene (PS)

(c) The high shear blending device [30]

Fig. 2 The recycled polymers used and high shear blending device

5 Laboratory testing program

Characterizing the components, assessing their performance, and devising appropriate blending techniques are all important aspects of doing a thorough study on the incorporation of recycled polymer resources into asphalt mixes. To evaluate the physical attributes of the modified asphalt binders and the mechanical characteristics of the modified asphalt mixes, laboratory testing is necessary.

To assess the physical properties of the modified asphalt binder, the penetration and softening tests of asphalt binder were determined. To investigate the susceptibility of the modified asphalt binder to the change in temperature, the Penetration Index (PI) was calculated. It is determined based on the softening point of the bitumen, the penetration test at 25 ℃, and the assumption that the bitumen's penetration at its softening point temperature is 800. The classical approach related to PI calculation has been given in the Shell Bitumen Handbook as in Eq. (1) [35].

$$PI = \frac{1952 - 500 \times log(Pen.25) - 20 \times SP}{50 \times log(Pen.25) - SP - 120} \tag{1}$$

where Pen25 is the penetration at 25 ℃ and SP is the softening point temperature of bituminous binders.

The asphalt mixture was designed using Marshall method to find out the optimum proportion of asphalt binder addition. Then, the asphalt mixture samples were examined to explore their mechanical and volumetric properties.

Moisture damage is one of the main issues influencing the longevity and performance of asphaltic mixes. Damage caused by moisture is often manifested as a decrease in the mixture's cohesiveness or adhesion at the bitumen and aggregate boundary. For asphalt mixes, a TSR value of 80% or over is often regarded as appropriate [36]. Tests typically consist of two stages: conditioned and unconditioned. The goal of the conditioning process is to replicate field exposure conditions. For every test, six Marshall samples were made and compressed to a 7% average percentage of air voids, divided into two groups. The first set of three specimens was evaluated in a dry situation, whereas the other group of samples was examined in a fully wet state. Each mix type's first group had a 30-min test in a water bath set at 25 °C, but without being wet. The second set underwent vacuum saturation conditioning before being submerged in a warm water immersion at 60 ℃ for a whole day. Equation (2) was then used to get the tensile strength ratio (TSR).

$$TSR = \frac{Sw}{Sd} \times 100 \tag{2}$$

The variables Sd and Sw represent the mean indirect tensile strength for the unconditioned and conditioned specimen groups, respectively, in kPa. Figure 3 shows the testing program flowchart for the present study.

6 Results and discussion

6.1 Physical attributes of modified asphalt binders

Tests on the physical qualities of recycled polymer-modified bitumen evaluated attributes such as ductility, softening point, and penetration. These tests provide valuable information about the binder's performance and suitability for specific applications, including its fluidity, hardness, flexibility, and flow resistance. Understanding these properties is essential for designing durable and high-performance asphalt pavements.

The penetration test is a commonly used technique for determining the quality of bitumen. The test results showed the impact of adding recycled waste polymer materials, specifically polyvinyl chloride (PVC) and polystyrene (PS), on the penetration grade of the basic bitumen. Figure 4 illustrates the impact of waste polymers on the penetration values of bitumen. It visually shows the decreasing trend in penetration values as the percentage of recycled polymers increases. This indicates that adding additional polymers made the modified asphalt binders tougher. The decrease rate in penetration reading at 2%, 4%, and 6% of PVC content was 8.5%, 19.1%, and 31.9%, respectively. Comparing PS contents to a clean binder, the differences were 6.4%, 14.9%, and 25.5%, respectively.

Based on this information, it can be concluded that the addition of recycled waste polymers, such as PVC and PS, to the asphalt mix resulted in an increase in the hardness and toughness of the modified asphalt binders. The results of penetration test are consistent with previous research [37–39].

The softening point of asphalt refers to the temperature at which it becomes fluid. Figure 5 indicated that as the percentage of recycled polymers increased in the modified asphalt, the softening point values also increased. This implies that the binder's resistance to temperature rise improved with the addition of recycled polymers. A higher

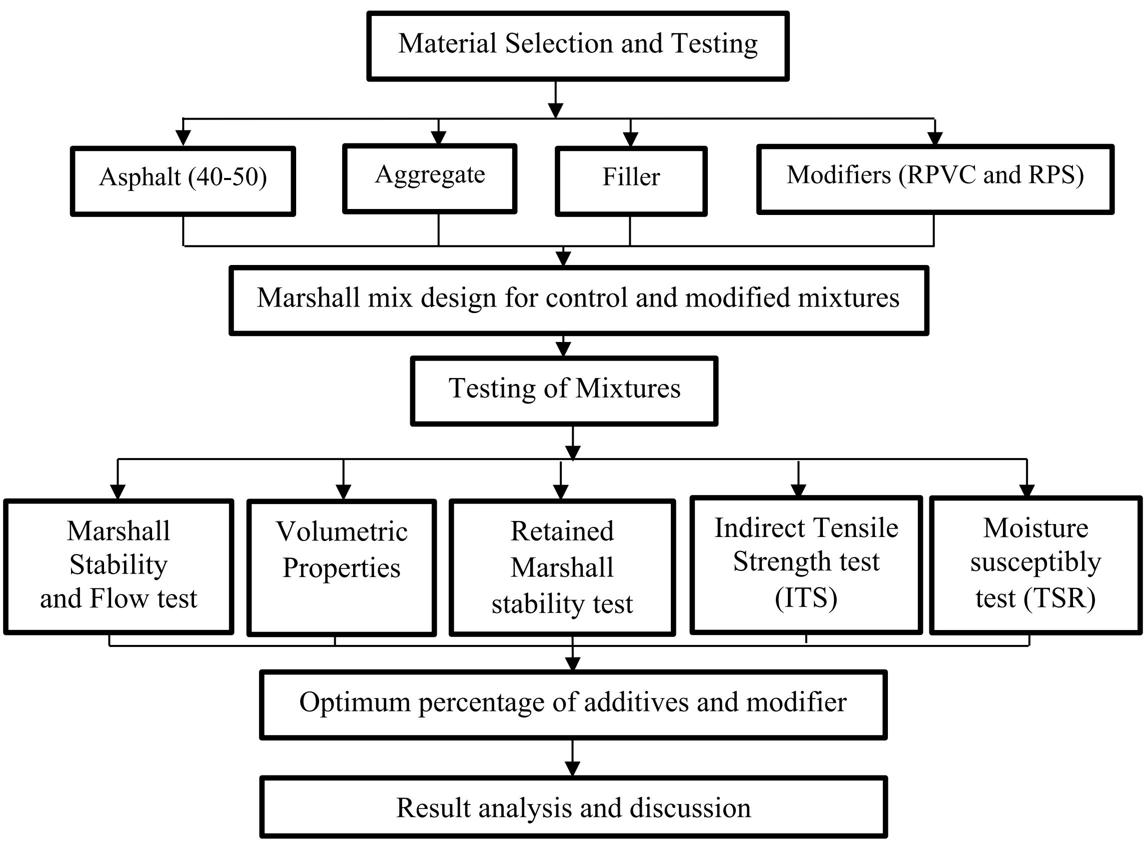


Fig. 3 Testing program flowchart

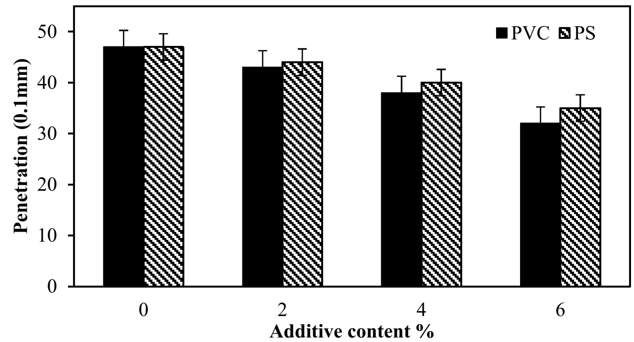


Fig. 4 The impact of waste polymers on penetration values of bitumen

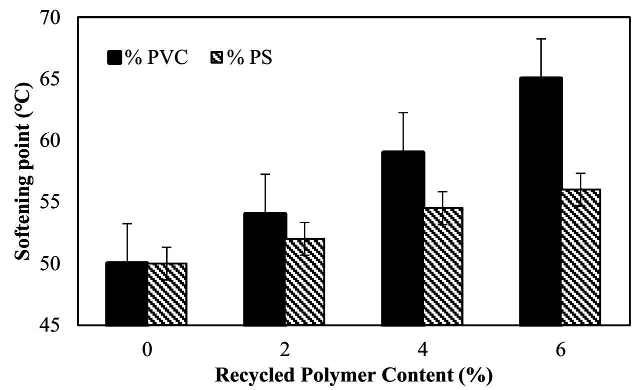


Fig. 5 The impact of recycled waste polymers on the softening point of bitumen

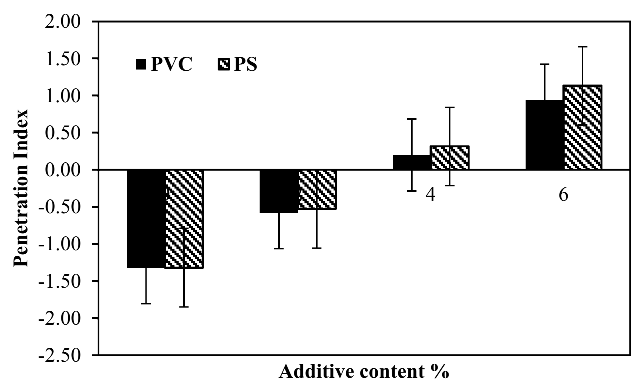


Fig. 6 The impact of waste polymeric materials on the PI of bitumen

softening point lessens the binder's susceptibility to softening in hot weather and lessens irreversible pavement deformation brought on by increased stiffness.

Comparing the modified asphalt samples, those treated with PVC showed a larger drop in penetration values and a greater increase in softening point temperatures compared to the samples treated with PS. This suggests that the PVC-modified samples are less prone to rutting or permanent deformation, which is advantageous for asphalt binders in regions with harsh climates.

The test results for the softening point match those from earlier research studies cited in the paper [37–39]. This supports the conclusion that adding recycled polymers to asphalt binders influences the softening point positively.

Figure 6 shows that as the percentage of recycled polymer increased, the Penetration Index values also increased, following a similar pattern as the softening point. This indicates that the modified binders with higher amounts of recycled polymers were less susceptible to temperature changes compared to the basic bitumen. Furthermore, higher Penetration Index values contribute to improved resilience of asphalt mixes against long-term deformation. It was observed that the PS-modified binder samples produced higher Penetration Index values compared to the PVC-modified samples, particularly at a high polymer level (6%).

Based on these findings, it can be concluded that the addition of recycled polymers, specifically PVC and PS, to the asphalt binder influenced the Penetration Index, indicating a reduced sensitivity to temperature changes and potentially enhanced performance in terms of long-term deformation resistance.

The ductility test measures the adherence and flexibility of bitumen. As can be seen in Fig. 7, with an increase in recycled polymer content, there is a progressive reduction in ductility, making the modified binder harder to flow. This can be attributed to the agglomeration of the additive material, which could disrupt the internal cohesiveness of the bitumen, affecting its ductility. However, even with the addition of PVC and PS, the ductility values of the modified binders remained above the minimum requirement of 100 cm. The results are consistent with studies by Rahman et al. [40] and Anwar et al. [41]. At 2%, 4%, and 6% PVC concentrations, the ductility values decreased by 14.3%, 24.3%, and 32.1%, respectively, compared to the control sample. The reductions in ductility for PS compared to a clean binder were 15.7%, 25%, and 35% at the corresponding polymer concentrations.

6.2 Optimum binder content for mixtures with cement fillers

The optimum asphalt content (OAC) of the asphalt mix was established using the Marshall Mix design procedure. Compaction was performed 75 times to create three samples for each bitumen proportion (4%, 4.5%, 5%, 5.5%, and 6%). Fifteen samples underwent tests to evaluate Marshall stability, flow, unit weight, air voids, and voids in mineral aggregate.

As shown in Fig. 8, the OAC was computed by averaging the bitumen percentages that satisfied the requirements for maximum stability, maximum unit weight, and 4.0% air spaces. The OAC for the asphalt mix with Portland cement filler was found to be 5.2%.

6.3 Volumetric properties

The bulk specific gravity (Gmb) against the proportion of recycled polymers utilized in asphalt concrete manufacture are shown in Fig. 9. As the amount of recycled polymer in the asphalt concrete was raised, so was its unit weight. The reason for this might be because the polymers have a greater specific gravity than the asphalt binder that was utilized. It has been noted that, regardless of the kind of recycled polymer, unit weight rises with increased recycled polymer content up to a certain point (4%) before starting to decrease. With the increment of PS and PVC in the base asphalt binder, better compaction was achieved, as a result, the unit weight was increased. As further increments of modifiers are added to asphalt, the waste polymers segregate from hot asphalt leading to a decrease in the unit weight of the modified mixes. It was noted also that the modified mixes including RPS have a lower bulk specific gravity than those containing RPVC.

As can be seen in Fig. 10, which displays the air void content of the asphalt mixture against different contents of recycled polymers, the proportion of air void in the mixture decreases as the percentage of additives increases for both PS and PVC polymers, but then the curve recovers, i.e., the air void percentage increases, as more additives are added. All the results of air void percentages were found to be within the acceptable range of (3–5%) set by the Asphalt Institute [42].

As can be seen in Fig. 11, as the polymer-modifier proportion in the asphalt cement increases, the proportion of the voids in the mineral aggregates reduces initially. Once the PS and PVC content of the mineral aggregate reaches a minimal value, around 4%, the percentage of voids in the aggregate begins to rise in response to further additions of the modifiers. All VMA percentages of modified materials were above the mandatory minimum value of 14 percent [42].

Fig. 7 The impact of waste polymeric materials on the ductility of bitumen

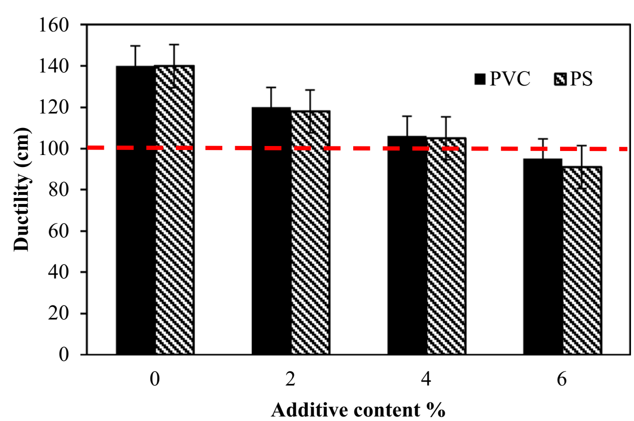
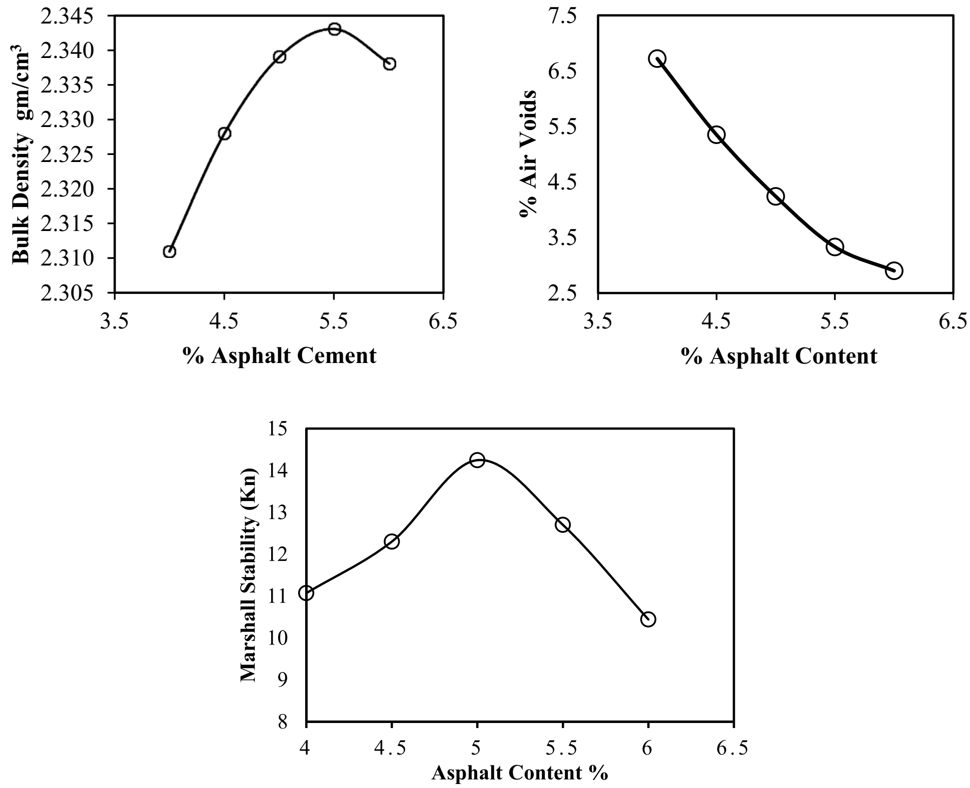


Fig. 8 Optimum asphalt content determination for the control group mix



$$OAC\ for\ cement\ filler\ = \frac{\%AC_{Gmb} + \%AC_{VTM} + \%AC_{M\ Stability}}{3} = \frac{5.5 + 5.1 + 5.0}{3} = 5.2\%$$

Fig. 9 Variations in bulk specific gravity of HMA at various recycled polymer proportions

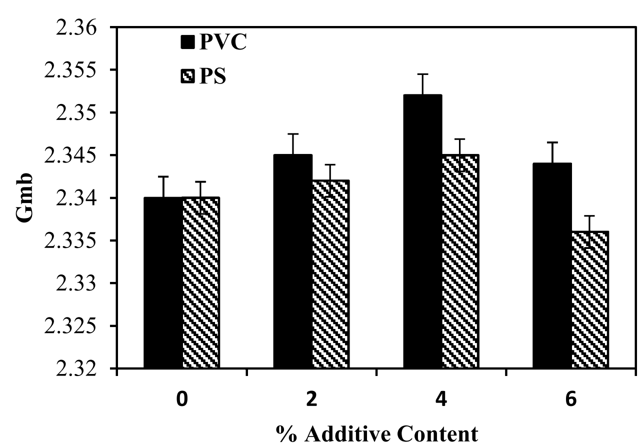
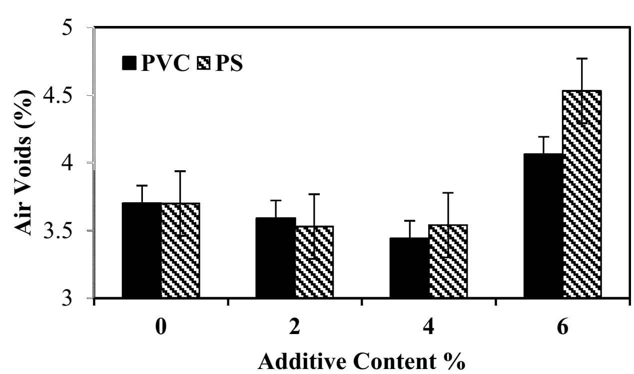


Fig. 10 Relationship between air voids and recycled polymer content



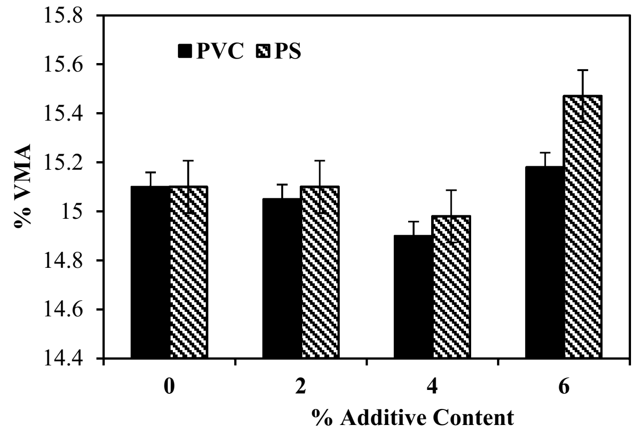


Fig. 11 Relationship between VMA% and recycled polymer content

6.4 Mechanical properties for the modified mixes

After determining the optimal bitumen content (OBC), extra samples were created for seven different mixtures: control, 2% PVC, 4% PVC, 6% PVC, 2% PS, 4% PS, and 6% PS. Figure 12 displays the Marshall stability values for each type of polymer-modified mix, considering the waste polymer content.

Compared to the control group, the mixes treated with waste polymers generally exhibited higher Marshall stability values. The presence of recycled polymers increased the resistance against loading, resulting in a stiffer mix. The addition of polymers to the mix may have caused stronger bonding between the aggregate and binder, contributing to improved stability and cohesiveness.

For both recycled PVC and PS, the Marshall stability values increased up to a certain point (at an additive level of 4%) and then decreased for all the mixes. However, excessive waste polymer content (above 4%) led to increased flow values and reduced stability. The use of recycled PVC and PS with an asphalt binder to produce modified binders showed significant enhancements in Marshall stability and hardness.

In Fig. 12, the maximum stability values for cement filler mixes with RPVC and RPS were 20.12 kN and 19.23 kN, respectively, at an additive content of 4%. These values corresponded to increment values of 43.7% and 37.4%, respectively, compared to the control sample.

In Fig. 13, the impact of recycled polymer additions on Marshall flow values for the polymer-modified asphalt mixes is depicted. The figure shows a significant decrease in flow values with increasing waste polymer content. According to the specifications for roads and bridges in Iraq, the desired flow values for 2%, 4%, and 6% polymer content should be within the 2–4 mm range. This outcome may be attributed to the production of a stiffer mix. These results align with previous research [39, 43, 44]. As the proportion of the additive increases, the flow values continue to decrease. There is a clear turning point at 4% polymer content for both recycled polymers, indicating the optimal proportion for recycled polymer addition.

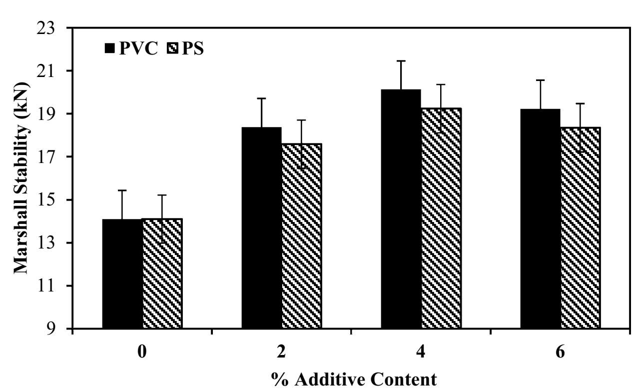


Fig. 12 Marshall Stability values versus waste polymer content for asphalt mix

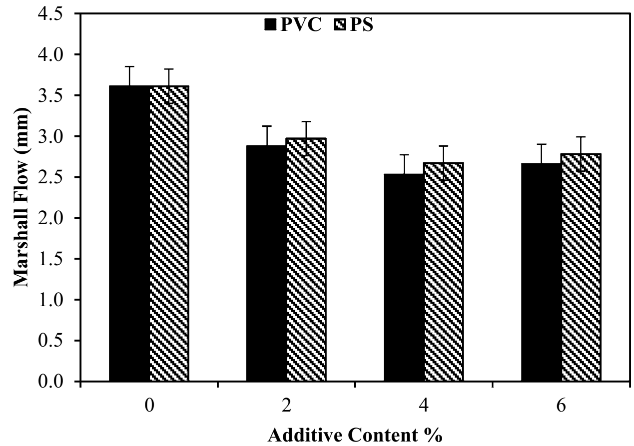


Fig. 13 Marshall flow values against waste polymeric material proportion for asphalt mix

Marshall Stiffness (MS) or Marshall Quotient values assess an asphalt sample's resistance to deformation. Various studies [24, 35, 45–48] have contributed to the development of these values.

Figure 14 demonstrates that asphalt mixes with recycled polymers exhibit higher MS values compared to the control mix. These modified mixes perform similarly to those with Marshall stability. The increased MS suggests that recycled polymer-containing asphalt mixtures are stiffer and more resistant to deformation due to traffic stresses. In other words, higher Marshall stiffness corresponds to improved stability, reduced flow, and enhanced binder stiffness, thereby enhancing the asphalt mixture's resistance to rutting, especially at high service temperatures.

Figure 15 displays the relationship between bulk-specific gravity (G_{mb}) and the quantity of recycled polymers used in asphalt concrete production. Increasing the amount of recycled polymer in the asphalt concrete led to a higher unit weight. This can be attributed to the higher specific gravity of polymers compared to the asphalt binder used. Regardless of the type of recycled polymer, unit weight increased with higher recycled polymer content until reaching a threshold

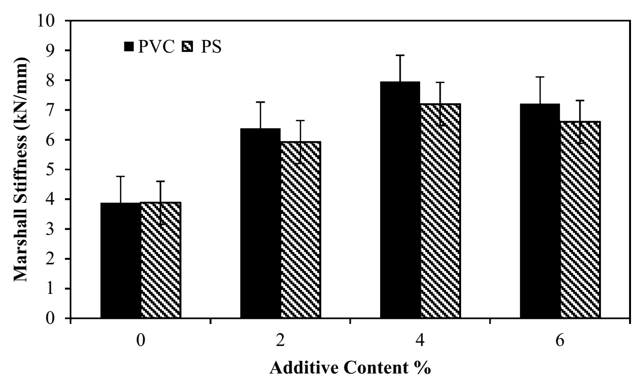


Fig. 14 Marshall Stiffness for the modified mixtures

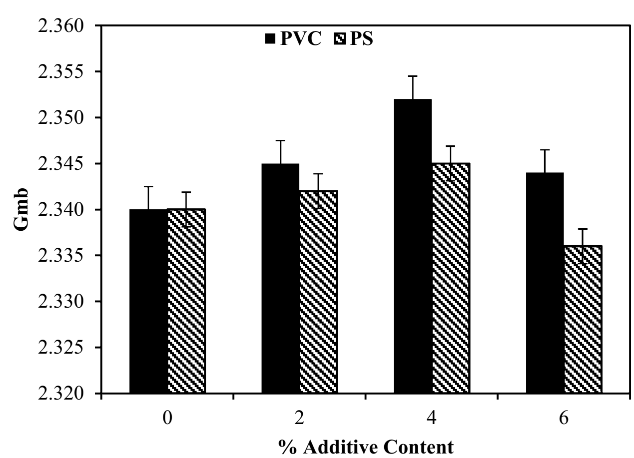


Fig. 15 Variations in bulk specific gravity of HMA at various recycled polymer proportions

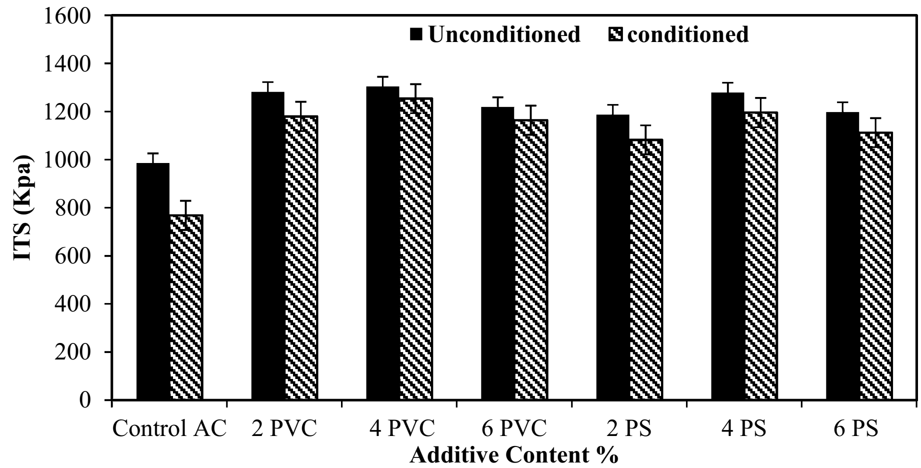


Fig. 16 Results of indirect tensile strength tests of different recycled additive contents

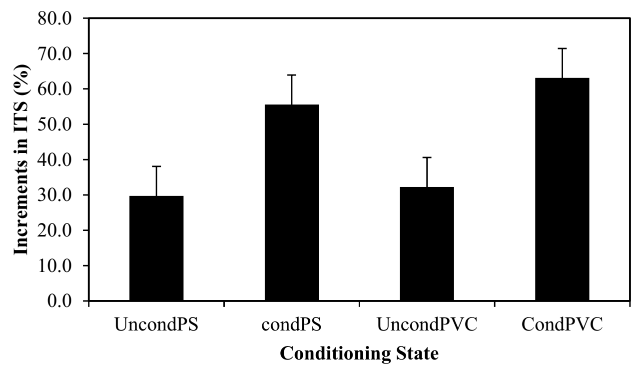


Fig. 17 Increment rate in ITS for polymer-modified asphalt mixes at 4% additive content

of 4%, after which it started to decrease. The addition of PVC and PS to the binder improved compaction, resulting in increased unit weight and stability. However, when a larger amount of additive (greater than 4%) was added, separation of the polymer waste from the hot bitumen occurred, which led to a reduction in its unit weight and stability. Additionally, it was observed that mixes containing RPS had a lower bulk specific gravity compared to those containing RPVC.

Test results for asphalt mixes with recycled polymers were analyzed using the ITS test, as shown in Fig. 16. The modified mixtures showed higher values of indirect tensile strength compared to the control mix, indicating increased resistance to tensile loads. The introduction of polymers stiffened the bitumen, enhancing the mixture's ability to withstand tensile stresses and resist permanent deformation. Improved bitumen and aggregate adhesion and cohesiveness contributed to this enhancement.

Regardless of the type of recycled polymer, the indirect tensile strength (ITS) values increased with higher recycled polymer content until reaching a threshold of 4%, after which they started to decline. For unconditioned asphalt mixes, the ITS increment rate at 4% polymer content was 32.2% and 29.7% for PVC and PS-modified mixes, respectively. In conditioned mixes, the increment rates were 63.1% and 55.6% for PVC and PS-modified mixes, respectively.

Although the ITS values were lower in the conditioned state compared to the unconditioned state, as shown in Fig. 17, the percentage increase in ITS over the control group was significantly higher in the conditioned state. This shows how important recycled polymers are for increasing the tensile strength and adhesion between the aggregate and asphalt binder, which makes the asphalt mixture more resistant to water. Also, mixes containing PVC generally exhibited a higher improvement rate compared to those containing PS.

The results of stability, stiffness, and ITS indicate the improvement of high temperature performance of modified asphalt. Compared to the base mixture, the high temperature stability of the composite is improved resulting from the addition of recycled polymers, but it decreases with the increased content of the modifier content, more than 4%, because of agglomeration of the excess polymers. Accordingly, the engineering properties that are expected to improve in asphalt pavement are resistance to traffic loads at relatively high temperatures, i.e. increased resistance to rutting and permanent deformations.

6.5 Resistance to moisture damage test

The impact of recycled waste polymeric materials on moisture damage indicators in asphalt mixes, represented by the tensile strength ratio (TSR), is shown in Fig. 18. Increasing the percentage of recycled polymers resulted in improved TSR values. While the TSR values of the control group combinations fell below the permissible limit of 80%, the modified mixes met the approved requirement. However, with the increase in the percentage of recycled polymer (more than 4%), the moisture resistance decreases, and this is most likely due to the agglomeration of excess polymers, which leads to a weakening of the bonding forces between the asphalt binder and the aggregate, and thus this causes a greater sensitivity of the asphalt mixture to the presence of moisture.

Additionally, it was noticed that asphalt mixes modified with PVC polymer demonstrated lower sensitivity to moisture conditioning compared to those modified with PS. The stronger bond between the binder and the aggregate in the recycled polymer-modified mixtures led to this improvement. These findings are consistent with previous studies [28, 49]. The maximum TSR values for cement filler mixes with RPVC and RPS were 95.15% and 93.49%, respectively, with increment values of 23.3% and 19.9%, respectively, at a 4% additive content.

6.6 Retained Marshall stability test (RMS)

The asphalt mixture samples were tested using the Marshall Method to evaluate the stability values of asphalt mixes modified with recycled PVC and PS after being soaked in water for different durations (1, 3, and 7 days). PVC-modified mixes exhibited higher stability due to better dispersion in bitumen, indicating increased stiffness and strength. The results shown in Fig. 19 were the same as what was seen in the test for tensile strength ratio (TSR), with the highest levels of stability occurring at a 4% additive content. The findings align with previous research and emphasize the potential of RPVC and RPS as modifiers to enhance the stability of asphalt mixes. These results are consistent with previous research [41].

As the recycled plastic content in the mixtures increased, there was a decrease in the flow values of the polymer-modified asphalt mixtures, as shown in Fig. 20. This behavior pattern was consistent with the findings in the Marshall stability tests, where the flow of the modified mixtures was generally lower than that of the control samples. These results indicate that the presence of polymers in asphalt mixes enhances their resistance to moisture damage by reducing their tendency to deform under the influence of water.

The retained Marshall stability percentage for asphalt mixes with cement filler was calculated and depicted in Fig. 21. The results indicate that both recycled polymers, particularly at a 4% polymer content, contributed to an increase in the retained Marshall stability. However, the retained stability values decreased as the immersion period increased. This can be attributed to the fact that most polymers do not absorb water. By incorporating them into the asphalt binder, they act as a barrier, reducing the amount of water that reaches the interface between the aggregate and binder. This, in turn, protects the adhesion between the two components and prevents separation. These findings are consistent with previous research studies [39, 41, 50].

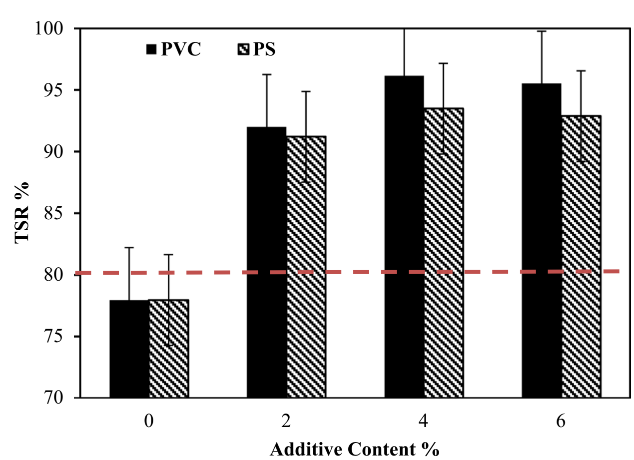


Fig. 18 Tensile strength ratio (TSR) values of the polymer-modified mixes

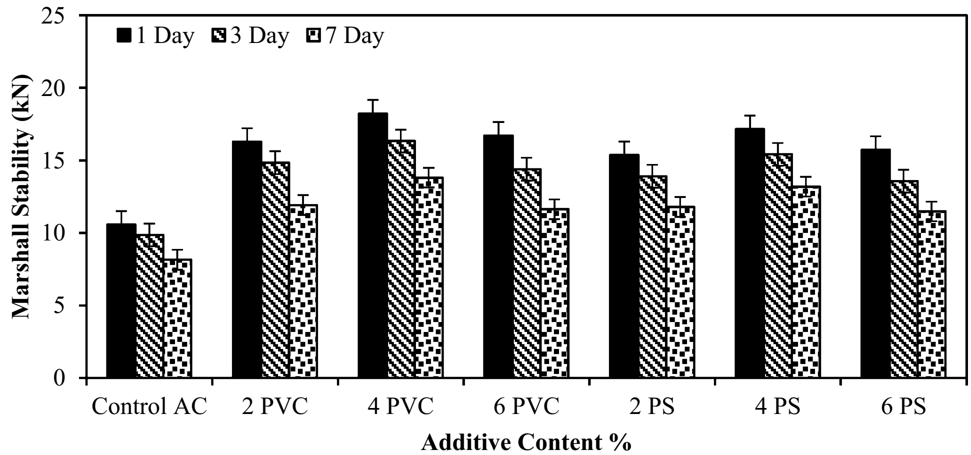


Fig. 19 Stability of recycled plastic-modified asphalt mixes under different immersion periods

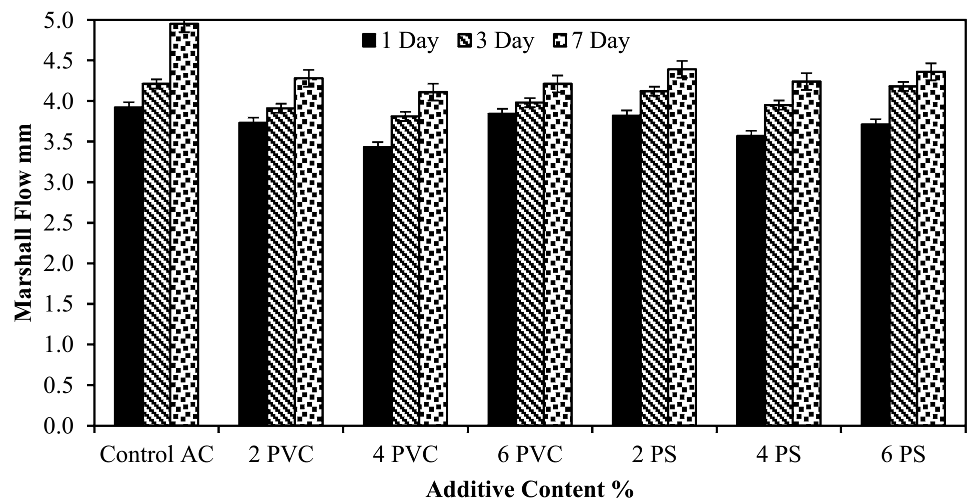


Fig. 20 Results of Marshall flow of mixture with recycled polymers under different immersion periods

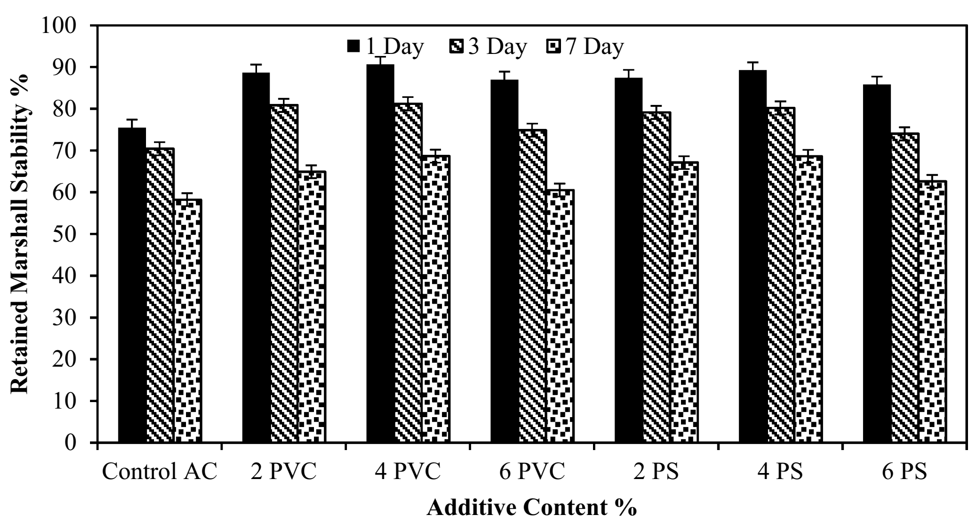


Fig. 21 Results of retained Marshall stability of mixture with recycled additives

For the polymer-modified asphalt mixes, the percentage of maintained Marshall stability increased from 75.5%, 70.4%, and 58.2% (for control mixes) to 90.6%, 81.2%, and 68.6% (for mixes with 4% RPVC), and to 89.2%, 80.2%, and 68.6% (for mixes with 4% RPS) after one, three, and seven days of soaking, respectively.

7 Conclusions

This research examined the impact of adding two different recycled polymeric materials. This research was determined by using one type of asphalt binder (40–50 penetration grade) and only two types of recycled polymeric materials (PVC and PS), in addition to using one type of aggregate (basalt from Al-Nabai quarry north of Baghdad), where the locally available materials and the devices available in the laboratories of the College of Engineering, Mustansiriyah University were utilized as much as possible. The results support a number of conclusions, including:

1. The addition of PS and PVC to the asphalt binder have improved its physical characteristics; this is demonstrated by a decrease in penetration values and an increase in both the degree of softening point and PI.
2. The ideal addition ratio of recycled polymers was 4% by the weight of asphalt binder.
3. Compared to the control mixture, Marshall stability rose significantly with the addition of recycled PVC and PS, increasing by 43.7% and 37.4%, respectively, at an additive level of 4%. This rise suggests that recycled polymer-containing asphalt mixes are stiffer and more resistive to traffic-induced deformation, which improves the mixture's resistance to rutting, especially at high service temperatures.
4. Indirect tensile strength is improved and TSR values are raised by 23.3% and 19.9%, respectively, when 4% PVC and PS polymers by weight of asphalt binder are added in comparison to the control mixture.
5. The retained Marshall stability were increased by 90.6%, 81.2%, and 68.6% for RPVC-modified mixtures, and by 89.2%, 80.2%, and 68.6% for RPS-modified mixtures, at (1, 3, and 7 days of soaking periods), respectively.
6. The recovered Marshall stability decreased with an increase in the immersion time. However, the rate of decrease in the recovered stability was less significant as the immersion period became longer, and the difference between the recovery percentage and stability became insignificant. This suggests that although there was an improvement in the recovered Marshall stability value, damage from the presence of moisture in the asphalt mixture became more severe during longer immersion periods.

To sum up, utilization of waste materials as PVC or PS, extends pavement service life by enhancing pavement properties in terms of mechanical, and physical properties, durability, aging, and provides an economical and eco-friendly paving material and maintain a sustainable environment.

8 Recommendations

1. Depending on their mineral and surface compositions, asphalt mixes made from local aggregates from other sources may have a different moisture damage potential than the aggregates utilized in this research. Thus, the assessment of moisture damage with different aggregate types and the choice of binder aggregate combinations could be the focus of future research.
2. It is advised to employ alternative waste polymer types and adding techniques to assess their impact on mechanical performance of asphalt mixes.
3. Since the major problem facing road performance locally is the types of failure associated with high summer temperatures, and given the outcomes of this research, the researchers support the introduction of recycled polymeric materials in the field of road construction locally due to their expected impact on performance in general and especially in areas that suffer from high temperatures or relatively high humidity or during the rainy season. This is through interest in the field of production of modified asphalt binder subject to sustainability standards.

9 Future research

Possible future research directions could include exploring the use of alternative recycled polymers, optimizing the polymer content, validating laboratory results through field trials, analyzing the mechanical and rheological properties, assessing the environmental and sustainability implications, and evaluating the economic feasibility of incorporating recycled polymers into asphalt mixtures.

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Author contributions Dr. Sady was responsible for developing the research methodology, including the experimental design, procedures, and analysis plan. Dr. Abbas and Dr. Rana reviewed the draft manuscript and provided feedback and revisions to improve the clarity and coherence of the paper. Ahmed conducted the data collection, and analysis, interpreted the results, and wrote the first draft of the manuscript. All authors contributed to the conceptualization of the study, discussed the findings, and approved the final version of the manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Competing interests The authors declare no competing interests.

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