



EVALUATION OF THE PERFORMANCE OF HOT MIX ASPHALT USING AN ASPHALT BINDER MODIFIED WITH HIGH-DENSITY POLYETHENE WASTE

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ABSTRACT: This study explores the potential of using readily available High-Density Polyethylene (HDPE) waste at 2%, 4%, and 6% by weight of bitumen with a penetration grade of 40–50, to address plastic waste utilization and investigates the effect of modification range on the physical properties of the modified asphalt binder and the mechanical properties of the modified Hot Mix Asphalt (HMA). Penetration, softening point, and ductility tests were conducted to examine the physical properties of the asphalt binder, while measurements such as Marshall Quotient (MQ) using the Marshall stability and flow test, and Tensile Strength Ratio (TSR) using the Indirect Tensile Strength (ITS) test, were performed to evaluate the performance of the HMA. The results indicated that increasing the proportion of finely ground HDPE waste improved the physical properties of the asphalt binder by reducing penetration and raising softening point values; however, a decrease in ductility was observed compared to unmodified bitumen, indicating an enhancement in consistency and temperature susceptibility. Marshall stability tests, along with mix performance criteria including the MQ index, provided positive indications of resistance to deformation and susceptibility to moisture. Stability improved by 50.6%, and TSR by 17.3% compared to the reference samples at a concentration of 6%, which was found to be the optimal concentration for HDPE waste in this study. Overall, HDPE waste concentrations performed better in all laboratory tests than the reference mixtures. This suggests that HDPE waste can contribute to improving the cohesion and bonding strength of asphalt mixture components, thereby increasing durability.

Keywords: High-Density Polyethene (HDPE) waste, Asphalt mixture performance, Marshall stability, Marshall Quotient, Tensile Strength Ratio (TSR)

1. INTRODUCTION

Waste generated by industrial technology has become a major environmental threat, particularly in urban areas. This has prompted the search for solutions to dispose of it effectively and utilize it in various fields, including road paving [1]. Given the challenges of road paving, road engineers have spent decades striving to improve the properties of asphalt mixes, reduce their degradation, and mitigate many road maintenance problems, while simultaneously minimizing pollution and costs. Using recyclable waste is one of the proposed solutions, in the hope of achieving effective and tangible results. These waste includes various types of recycled ceramics, where the use of ceramic waste has shown that the HMA has better values for resilient modulus and creep modulus [2], fibers, where it has been found that rutting resistance and fatigue damage have been improved by using types such as Basalt [3], plastics, where the paving performance has shown greater effectiveness when plastic waste is used in the structure of HMA, and when it is partially replaced by aggregate particles [4], crumb rubber,

which has increased the resistance of asphalt mixture to temperature and water changes [5, 6], steel slag, where the rheological performance of the binder and Marshall properties have been enhanced, as well as the susceptibility of asphalt mixtures to moisture [7, 8], and others.

Polymers are the most commonly used materials for modifying asphalt, imparting desirable properties that improve pavement performance [9, 10]. Plastomers, along with elastomers and rubber, are among the most important polymers successfully used as bitumen modifiers [11]. Polyethylene (PE) is a plastomer that flows when heated and solidifies when cooled. Many road researchers have turned to these flexible plastic materials to improve the performance of asphalt mixtures under high loads and varying weather conditions, particularly at high temperatures, and numerous studies have demonstrated significant improvements in the physical, rheological, and mechanical properties of modified asphalt binder and mixture [12, 13].

Various types of polyethylene are available, including Low-Density Polyethylene (LDPE) and HDPE, which are currently used in asphalt modification [14,

15]. HDPE is the most widely used pure raw material in the manufacture of shopping bags [16]. It is also used in many important applications involving various extrusion processes, including the production of plastic bottles, such as milk, water, and shampoo, as well as pipes [17].

The researchers conducted experiments adding varying proportions of HDPE raw material to different types of bitumen, and the results showed significant improvements in several properties of both the binder and the mixture. It has been shown that adding 3% HDPE to bitumen enhances structural bonding and thus its elastic properties [18], while adding 6% increases resistance to moisture damage [19]. Currently, recycled HDPE is commonly used to produce a wide range of products, including pens and toys. It can also be used in the furniture industry, including chairs, tables, and waste bins, among many other products [20]. It has also become possible to reuse it in pipe manufacturing after mixing it with other materials [21]. The use of recycled HDPE in asphalt modification is a relatively recent trend that requires further research, despite numerous previous studies. These studies suggest the potential to improve the properties of modified asphalt, strengthen mixtures, and reduce their sensitivity to high temperatures [22-24]. The melting point of HDPE waste can be measured and analyzed using Differential Scanning Calorimetry (DSC) to evaluate its thermal properties and composition. Melting values in two separate studies reached 130.72 °C and 131 °C, respectively [25, 26].

The dry method can prepare modified bitumen mixtures by adding the selected proportions of the additive in its dry state as a percentage that replaces the proposed filler portion [27, 28]. This method is more suitable for field applications due to its lower cost and ease of application. However, a homogeneous distribution of the additive particles cannot be guaranteed, resulting in lower consistent mixture performance compared to the wet method [29].

Despite ongoing and intensive research on improving the properties of virgin asphalt using various additives, a significant gap remains in the use of waste-derived materials as sustainable modifiers, particularly regarding their combined effects on both the physical properties of the asphalt binder and the mechanical properties of the mix. Most previous studies have focused on conventional and ready-made polymer modifiers, with limited research on alternative waste-derived materials and their long-term performance. To bridge these gaps, this study proposes using finely ground HDPE waste in the laboratory as a novel asphalt binder modifier. The wet method was used to ensure a well-established

technique for asphalt binder by the optimal distribution of additive particles in the bitumen base [30]. The evaluation not only includes the conventional physical properties of the asphalt binder but also the mechanical behavior, stability, flow, durability, ITS, and moisture sensitivity of the HMA under conditions that simulate real-world applications.

2. RESEARCH SIGNIFICANCE

This study is crucial for advancing sustainable road paving engineering by investigating the use of HDPE waste to improve asphalt binder properties and asphalt mixture performance, enhancing key engineering characteristics such as stiffness, durability, and resistance to moisture damage, while also addressing significant environmental issues related to waste disposal and resource depletion. By converting waste into valuable modified materials, this research helps reduce landfill burdens, lowers construction costs, and decreases dependence on raw materials. Additionally, the findings provide practical insights for transportation agencies and engineers, encouraging the adoption of environmentally friendly and cost-effective paving solutions that support the creation of resilient and sustainable infrastructure systems.

3. MATERIALS AND METHODS

An overview of the research methodology is presented in Figure 1.

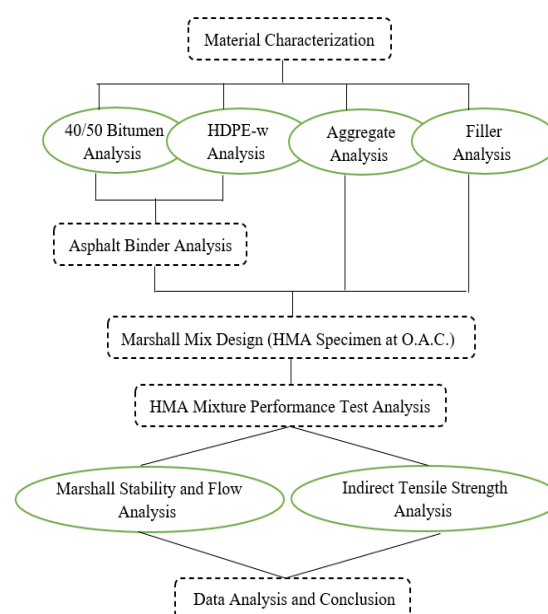


Fig. 1 Flowchart of research methodology

Table 3. Physical properties of both fine and coarse aggregates

Aggregate Properties	Coarse	ASTM Standard	Fine	ASTM Standard	Requirement
Bulk Specific Gravity	2.587	C127	2.632	C128	
Apparent Specific Gravity	2.629	C127	2.656	C128	
Water Absorption (%)	0.82	C127	0.98	C128	
Fractured particles (%)	97	D 5821	----		Min 95%
Wear (Los Angeles Abrasion) (%)	18.8	C535	----		Max 30%
Soundness Loss by Sodium Sulfate Solution (%)	4.1	C88	----		Max 12%

This section of the research presents in detail the experimental work, describes the materials used, verifies their compliance with specified standards, explains the mixing methods, sample preparation, and the testing procedures for both the asphalt binder and mixture samples.

3.1 Asphalt cement

In this study, locally produced Iraqi bitumen with a penetration grade of 40–50 was used. This bitumen is pure asphalt extracted from Al-Daura crude oil refinery. Table 1 presents the properties of bitumen required by the Iraqi State Corporation of Roads and Bridges (SCRB) requirements [31] and based on the listed American Society for Testing and Materials (ASTM) standards.

Table 1. Properties of the virgin bitumen

Properties	ASTM Spec.	Test Result	SCRB Req.
Penetration at 25 °C, 100 gm, 5 sec. (0.1 mm)	D5	47	40 - 50
Softening point; (°C)	D36	53	
Ductility at 25 °C, 5 cm/min. (cm)	D113	141	>100 cm
Flash point; (°C)	D92	330	Min. 232
Viscosity @ 135 °C, (Pa.s)	D4402	0.620	
Viscosity @ 165 °C, (Pa.s)	D4402	0.166	
Specific gravity at 25 °C	D70	1.03	

The aggregate particle size distribution analysis was performed to meet the requirements of (SCRB/R9, 2003) for upper and lower limits. In this important analysis, the aggregate particles were separated using standard sieves into fractions according to their sizes, as shown in Table 4, which shows the surface layer gradation of the aggregate particles, coarse and fine, as well as the Portland cement filler, and Figure 2, which shows the specific gradation with the limits recommended in the local specifications (SORB/R9, 2003).

3.2 HDPE waste

HDPE waste material was used in this study as an additive to virgin bitumen. This plastic waste, consisting of milk and yoghurt bottles with the recycling code 2, was collected from recycling plants in Baghdad Governorate. A series of steps was followed, including tape removal, cleaning, drying, shredding, grinding, and sieving using a No. 200 sieve, before its use as an additive. Table 2 shows the properties of the waste-HDPE.

Table 2. Properties of the waste-HDPE

Property	Results
Temperature of Melting (°C)	130 – 150
Specific Gravity	1.25
Recycle code	2

3.3 Aggregates

In this study, crushed aggregates from the Al-Nibaie quarry in Baghdad were used. Various laboratory tests were conducted on these raw materials, both coarse and fine, to evaluate their physical properties in accordance with the ASTM standards and ensure conformity with the requirements of the SCRB specifications, as shown in Table 3. The aggregate particles were washed and dried before testing to ensure the accuracy of the results.

Table 4. The surface layer gradation of aggregate particles

Sieve size (in)	Sieve size (mm)	Passing (%)	
		Spec. limits	Used
3/4	19	100	100
1/2	12.5	90-100	95
3/8	9.5	76-90	83
No.4	4.75	44-74	59
No.8	2.36	28-58	43
No.50	0.3	5-21	13
No.200	0.075	4-10	7

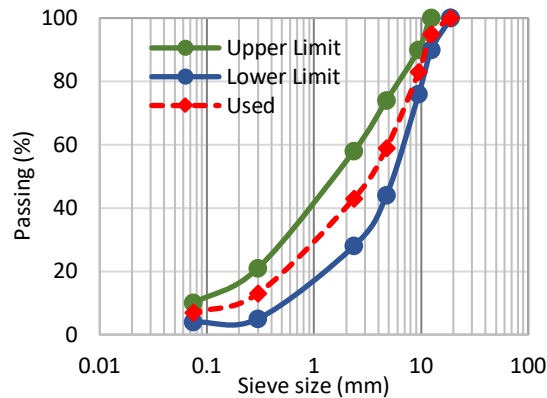


Fig. 2 Gradation curve of aggregate (specification limits and selected) for the wearing course

3.4 Filler

Locally sourced Portland cement was selected in this study as a filler due to its desirable physical properties that improve the performance of the asphalt mixture. The specific gravity of Portland cement passing through a No. 200 sieve was 3.1.

4. PREPARATION OF ASPHALT BINDER AND HMA SAMPLES

4.1 Preparation of asphalt binder samples

Bitumen with a penetration grade of 40–50 was first heated to a mixing temperature of $160 \pm 5^\circ\text{C}$, and then the HDPE waste additive was gradually added. Three sets of modified asphalt binders, each containing a specific percentage of the additive (2%, 4%, and 6% by weight of bitumen), were selected based on previous studies [32], and mixed using a high-shear laboratory mixer at 1000 rpm for 30 minutes. The mixer speed was then increased to 4000 rpm, and the mixing process continued for another 30 minutes at an elevated temperature of $175 \pm 5^\circ\text{C}$ to ensure binder homogeneity.

4.2 Preparation of HMA samples

The Marshall mix design was adopted in this study to produce HMA. The specified gradation aggregate, filler, and binder were mixed according to SCRB/R9 specifications. Five selected asphalt proportions (4%, 4.4%, 5%, 5.5%, and 6%) were used to prepare asphalt mixes to determine the optimum asphalt content. This range was chosen based on levels commonly reported in previous studies, ensuring a systematic assessment of performance trends from low to moderately high modification while avoiding very low contents with minimal

impact and higher contents that might cause mixing difficulties and phase instability. Using a standard Marshall hammer, a sample of the HMA was manufactured and compacted with 75 blows on both sides to simulate a heavy traffic load on site. Subsequently, specimens were prepared at the optimal asphalt content for both standard and modified asphalt to carry out the proposed tests and achieve the objectives of this study.

4.3 Marshall Stability and Flow Test

The Marshall stability and flow test is a destructive test, and all HMA specimens, standard and modified, are subjected to it in accordance with the ASTM D6927 specification [33]. This test evaluates the performance of a cylindrical asphalt mix sample designed according to the Marshall model by measuring its maximum load capacity at a loading rate of 50.8 mm/min. This maximum load represents the sample stability. Simultaneously, the sample's resistance to deformation under load, expressed as its plastic flow, is measured using a gauge mounted on the Marshall test frame and in contact with the sample. The flow value is recorded in 0.25 mm increments concurrently with the maximum load recorded. The MQ index is an important indicator derived from this test and is best suited for measuring the stiffness of mix specimens. It is calculated as the ratio of Marshall stability to Marshall flow [34].

4.4 ITS Test

The tensile strength of HMA samples can be measured in the laboratory using the ITS, which simulates the asphalt pavement's ability to withstand tensile stresses induced by on-site traffic loads. ASTM D6931-15 [35] is used for this test. Two sets of Marshall samples, one control and one modified, were prepared using selected proportions of HDPE waste to achieve an air void ratio of $7\% \pm 1\%$. Each set consisted of three conditioned samples (vacuum-saturated, soaked in water at 60°C for 24 hours, and saturated at 25°C for 1 hour) and three unconditioned samples (saturated at 25°C for 20 minutes) for this test. All samples underwent the ITS at 25°C until failure.

The TSR is a useful indicator for assessing moisture damage in HMA samples using the ITS test, according to ASTM D4867 [36]. To ensure that the asphalt mixture is well resistant to moisture damage, the TSR value must be greater than or equal to 80%. The ITS and TSR values can be determined from equations (1) and (2), respectively:

$$ITS = \frac{2000P}{\pi Dt} \quad (1)$$

Where, ITS is the indirect tensile strength (kPa), P is the maximum load (N), D is the sample diameter (mm), and t is the sample height (mm).

$$TSR = \frac{S_{wet}}{S_{dry}} * 100 \quad (2)$$

Where, TSR is the tensile strength ratio, S_{wet} is the average tensile strength of unconditioned samples, and S_{dry} is the average tensile strength of conditioned samples.

5. RESULTS AND DISCUSSIONS

5.1 Asphalt binder properties

The various physical properties of the control and modified asphalt binder were listed in Table 5.

Table 5. Properties of asphalt binder modified with selected proportions of HDPE waste

Property	Control 0%	HDPE-w 2%	HDPE-w 4%	HDPE-w 6%
Penetration at 25 °C, 100 gm, 5 sec. (0.1 mm)	47	41	38	33
Softening point; (°C)	53	56	61	63
Ductility at 25 °C, 5 cm/min. (cm)	141	125	110	98

Consistency is an important property of bitumen and can be determined by the penetration test. This test showed that samples modified with HDPE waste exhibited a significant improvement in consistency as the percentage of waste increased. This can be attributed to the positive interaction between the HDPE waste and the bitumen. The rigid nature of HDPE, along with its semi-crystalline structure, leads to a more cohesive polymer phase, which increases consistency and restricts molecular motion, resulting in lower penetration and a higher softening point [37]. The sample containing 6% HDPE waste achieved the best penetration, with an improvement of 29.8% compared to the base bitumen. It is known that lower penetration, within acceptable limits, is preferable for increasing the bond strength between the asphalt binder and the mixture under various traffic loads and conditions.

The softening point test determines the

temperature at which viscosity reaches a certain level during the transformation of bitumen from a solid to a liquid state. The ball-and-ring test results showed a significant increase with the addition of HDPE waste. The same trend was observed when increasing the additive proportions in the asphalt binder for the reasons mentioned above. Adding 6% HDPE waste resulted in an 18.9% improvement, indicating enhanced high-temperature resistance of the modified asphalt binder. Conversely, the ductility test results showed a decrease with increasing proportions of HDPE waste due to the rigid polymer phase, which limits the binder's ability to withstand tensile deformation. Furthermore, the potential for phase separation at high proportions reduces flexibility and increases rigidity [38]. While 6% showed the best performance among the percentages studied, this result should be interpreted within the studied range. Higher waste percentages were not evaluated, and further improvements or different performance trends may occur beyond this percentage. Therefore, the identified optimal percentage is relative, not absolute.

5.2 Effect of the HDPE waste on the mechanical properties of HMA samples

5.2.1 Marshall stability and flow

The strength of all compacted HMA samples, including the control sample and samples modified with varying proportions of HDPE waste, was measured using a Marshall stability and flow test apparatus. All samples underwent load tests, and the maximum load the samples could withstand before failure was measured. Deformation at maximum load was also recorded, and the test results are presented in Figure 3.

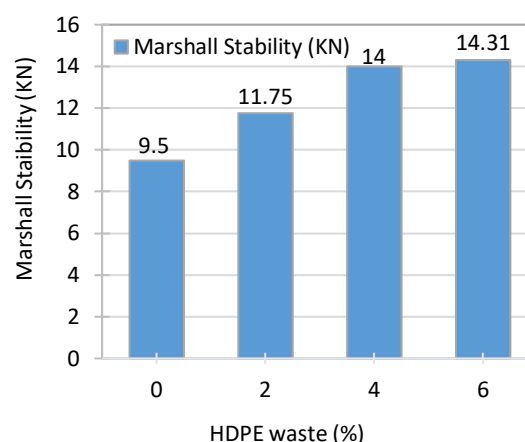


Fig. 3 Variation in Marshall stability test results for control and modified HMA specimens

As shown in Figure 3, Marshall stability tests indicated that asphalt mixtures modified with HDPE waste increased stability by 23.7%, 47.3% and 50.6% when 2%, 4% and 6% of HDPE waste were added, respectively. All asphalt mixes modified with varying amounts of HDPE waste exhibited a significant improvement in Marshall stability compared to the control mix. This improvement is attributed to the homogeneity of the modified asphalt binder and the positive role of HDPE waste in enhancing mixture cohesion and strengthening the bonds between the aggregate particles. This result supports the findings obtained from the physical properties tests of the asphalt binder.

On the other hand, the Marshall flow test results showed a decrease in binder flow within the HMA sample. All modified samples recorded flow values lower than the control sample but remained within the acceptable range of 2–4%, as shown in Figure 4, indicating that the addition of HDPE waste enhanced the strength of the asphalt binder and its ability to bond the components of the HMA. The results showed that adding 2%, 4%, and 6% HDPE waste decreased the Marshall flow test results by 11.3%, 19.4%, and 32.3%, respectively, compared to the control sample.

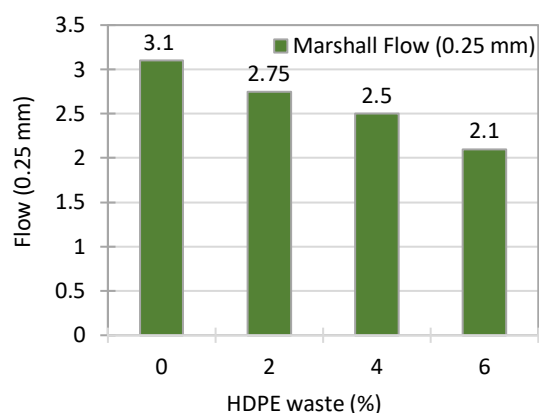


Fig. 4 Marshall flow results for the control and modified HMA

Based on the Marshall stability and flow test results, it can be concluded that the asphalt mix is suitable for light, medium, and heavy traffic conditions due to its load-bearing capacity and resistance to deformation. Samples of the HMA modified with HDPE waste exhibited high stability and low flow, indicating greater stiffness and higher resistance to permanent deformation under traffic loads, thus performing better than the control sample. Furthermore, the results of these two tests suggest that the improvement is related to increasing the proportion of HDPE waste in the hot

mix asphalt sample. The HMA sample containing 6% HDPE waste recorded the best Marshall stability and flow test results, at 14.31 kN and 2.1 mm, respectively.

The MQ is one of the most important parameters used to support Marshall stability and flow test results, and it is a good indicator of mixture stiffness. The MQ can be used to measure the resistance of samples to permanent deformation, supporting the results obtained from the tests, as shown in Figure 5. It can be observed that all samples modified with different selected proportions of HDPE waste, regardless of the proportion used, had a higher MQ value than the control sample mixture, and that 6% of HDPE waste had the best value, indicating that the modifier has a significant effect on the stiffness and resistance of the mixture to deformation under repeated loading.

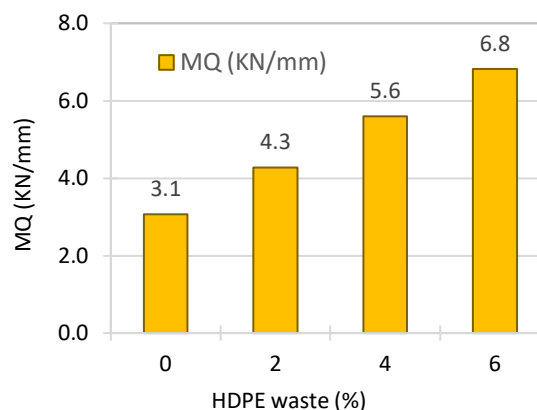


Fig. 5 MQ values for the control and various HDPE waste samples

5.2.2 ITS measurement

This study also investigated the effect of moisture on HMA samples, both the control and those with an added selected proportion of HDPE waste. As mentioned above, two sets of samples were prepared, one conditioned and the other unconditioned. Both sets of cylindrical HMA samples were subjected to load-to-failure testing to calculate ITS. Figure 6 shows that all HMA samples modified with varying proportions of HDPE waste, whether conditioned or not, exhibited higher ITS values than the control sample, which reflects the ability of the modified samples to withstand greater loads. The recorded increase was approximately 5%, 15%, and 19% for 2%, 4%, and 6% HDPE waste, respectively, for the unconditioned samples, and 16%, 29%, and 40% for 2%, 4%, and 6% HDPE waste, respectively, for the conditioned samples. It was also observed that the increase continues with increasing proportions of the asphalt binder additive.

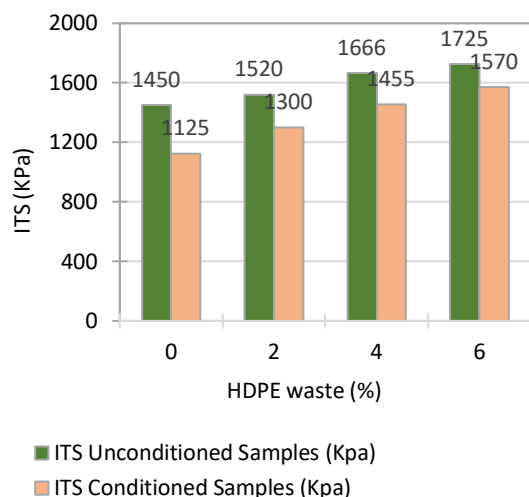


Fig. 6 ITS calculations test results for control samples and samples modified with an HDPE waste mixture

The ITS is a crucial measure for determining the TSR, which provides a good indication of how much the asphalt mixture is affected by moisture. According to ASTM D4867 and Iraqi SCRB requirements, the acceptable value for the TSR is 80% or higher. The rise in TSR results for the modified HMA samples compared to the control sample, presented in Figure 7, notably confirms the improvement in stiffness and moisture susceptibility. Increasing the proportion of HDPE waste in the asphalt binder and blending it homogeneously resulted in a significant increase in the TSR, which improved the cohesion of the modified asphalt mix components. Consequently, its resistance to tensile stress and moisture increased, resulting in a more durable mix. The TSR values increased by 10.2%, 12.5%, and 17.3% when using 2%, 4%, and 6% HDPE waste in the asphalt binder, respectively.

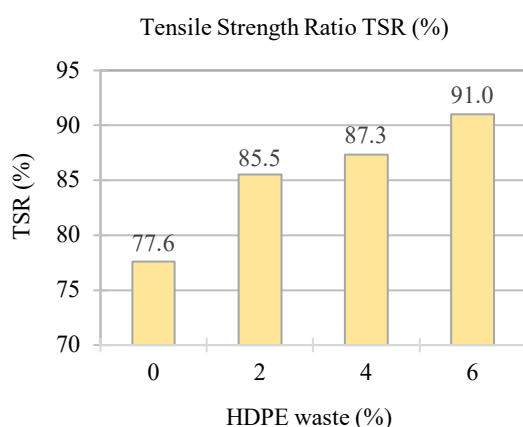


Fig. 7 The variation in TSR values for HMA control and modified HMA samples using HDPE waste

6. CONCLUSIONS

This study investigated the performance of HMA containing an asphalt binder modified with 2, 4, and 6% HDPE waste. Both the base bitumen and the modified binder, as well as HMA samples (including control and modified samples), underwent various tests to determine their physical and mechanical properties, and the results can be concluded as follows:

- The addition of HDPE waste improved the physical properties of the modified asphalt binder by reducing penetration and increasing the softening point values, resulting in increased consistency and reduced temperature susceptibility. Compared to the base bitumen, the asphalt sample made from 6% HDPE waste achieved improvements of 29.8% in penetration and 18.9% in softening point test results.
- All samples of HMA modified with specific proportions of HDPE waste exhibited positive mechanical properties, including increased Marshall stability and a corresponding decrease in flow values. This indicates homogeneity of the additive within the asphalt binder, enhancing the cohesion and bonding of the asphalt mix particles, and thus increasing their stiffness. The 6% HDPE waste HMA sample was found to exhibit 50.6% greater stiffness than the control sample. MQ index values supported these results and confirmed this improvement.
- ITS and TSR calculations indicate a significant improvement in the cohesion and bonding of the modified HMA, enhancing its moisture resistance. The TSR value in the mix sample containing 6% HDPE waste increased by 17.3% compared to the reference samples. Notably, all samples exceeded the 80% TSR value.
- It should be noted that the optimal percentage of HDPE waste determined in this study for both the asphalt binder and the mixture 6%, which is limited to the investigated range. The potential performance of higher waste percentages was not examined and could be considered in future research to determine the true optimal value.

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