Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 11, November, 2025

The Role of Recycled Plastic Bottles in Enhancing Asphalt Longevity

Husham Al-Tuwayyij [1*], Noorance Al-Mukaram [1], Atheer M. Ali [1]

[1] *Civil Engineering Department, College of Engineering, Al-Muthanna University, Samawah, Iraq.*

Received 17 June 2025; Revised 18 September 2025; Accepted 03 October 2025; Published 01 November 2025

Abstract

Producing "green" pavement is important in decreasing the negative effects of plastic on the environment and ensuring sustainable resource management. Because many worldwide strategies are aimed at reducing the use of plastic, this work studies a recycled polymer concrete modified by a defined amount of recycled plastic waste in asphalt. The specimens were prepared with a maximum optimal asphalt content using ±0.5% of the optimum level. The logic indicated that 11% plastic waste can be used as an alternative to the coarse aggregate. Experimental tests were carried out to examine moisture damage, short- and long-term aging, and compressive strength (rutting resistance). The measured properties were ITS, resilient modulus, and permanent deformation of the first load cycle and after 1200 load cycles using the PRLS device. In aging experiments, the resilient modulus was found to increase by 118% during the first cycle and by 40% after 1200 cycles. The decrease in permanent deformation was 40% and 48.5% after the first load cycle and after 1200 cycles, respectively. The results obtained in the moisture susceptibility test were within the required limit. Finally, the compressive strength of samples with asphalt content of 4.0%, 4.5%, and 5% was found to be 3660, 4120, and 2900 kPa, respectively. This achievement indicates the advantages of utilizing plastic waste in road construction to develop sustainable asphalt concrete with improved mechanical properties and reduced environmental impact, especially in hot climates such as Iraq, where it would be beneficial for rutting-sensitive roads.

Keywords: Sustainable Asphalt Concrete; Plastic Waste; Aging; Resilient Modulus; Pavement Performance.

1. Introduction

The study dealt with the use of plastic waste in flexible pavement construction. The method is under investigation because, in addition to improving the road pavement performance, it contributes to solving environmental problems related to plastic dumps. This review integrates the conclusions obtained from different previously mentioned works to provide a comprehensive overview of recycled plastic in flexible asphalt mixtures. It's also inspired by the circular economy; re-using rather than throwing away. One of the most significant environmental challenges is represented by single-use plastics due to their non-biodegradability; however, once used for roads, these create a sustainable solution because they reduce dependency on conventional raw materials [1].

Kumar & Kumar [2] emphasized that remarkable enhancements were made on the resistance and strength of asphalt concrete with waste plastic included. The research undertakes an investigation into the ability of soft computing models to predict the Marshall stability of plastic waste containing AC. The prediction of input parameters, such as the bitumen grade, bitumen content, plastic size, and plastic content, was performed using Random Tree (RT), Bagging RT, Random Forest (RF), Bagging RF, and artificial neural networks (ANN) models. The performance of these models was checked based on three statistical indexes- mean absolute error (MAE), coefficient of correlation, and root mean square error (RMSE). The RF-based model was outperformed by correlation coefficients of below 1, and the testing was 94.2% &

* Corresponding author: husham.mohammed@mu.edu.iq

http://dx.doi.org/10.28991/CEJ-2025-011-11-09

89.57%, respectively. Obtained mean absolute errors were 1.0591 (training) and 1.4736 (testing). RMSE values were also 1.5121 (training) and 2.2225 (testing). The sensitivity analysis showed that the plastic size was one of the most descriptive parameters to predict a moisture damage susceptibility in an asphalt mix.

Another study was done by Sahoo et al. [3] homed in on how the plastic waste was mixed into asphalt. This used process is more durable and has a longer life than regular asphalt pavement. The application of plastic waste, like polyethylene and polystyrene, also tackled the environmental issues of having a sustainable model. In addition, an investigation was carried out concerning the effect of plastic waste level on the performance of the asphalt concrete. They learned that an optimal content of 7.43% by weight would enhance the stability and durability of the mixture as well as remarkably minimize fatigue cracking and rutting [4].

In addition, a number of studies by Hınıslıoglu [5] have investigated the incorporation of different forms/plastics (HDPE) for enhancing asphalt binders. Costa et al. [6] performed experimental analysis to investigate the effect of polymer on properties of bitumen. The results revealed that the presence of 4% wt recycled HDPE can substantially improve the physical and rheological properties of the modified binder. Moreover, different combination parameters, including mixing temperatures, mixing time, and HDPE contents, were taken into account to assess the performance of the mixtures through Marshall properties (stability, emenleh47/entezarey). The best modification was to incur 4% HDPE into PHA at the blending temperature of 165 degrees C over 30 minutes. These positive tendencies became more pronounced if water was added; the Marshall quotient rose by 50% relative to the index value of control HMA. Further, the modified bituminous mix exhibited significantly higher resistance to distresses like serious damage and rutting, which may promote better pavement performance and durability [5].

Al-Hadidy & Yi-qiu [7] investigated the prospect of recycling waste low-density polyethylene (LDPE) for modified asphalt mixture to enhance the engineering performance. Their research also indicated that the softening point of such binders—modified either with LDPE or in combination with lignin—showed a great increase, whereas the ductility value did not fall below the minimum limit (100+ cm). It was also found that this modification decreased the amount of weight loss from exposure to heat and air as well as strongly improved the durability of the conventional (the original Stone Mastic Asphalt (SMA)) mixture. Moreover, results indicate that LDPE and SMA modified blends would be ideal pavements for wearing surfaces and coatings, especially under variable temperature changes, excessive rainfall, humidity, etc. Mashaan [8] demonstrated that waste polymer addition could improve the rheological and engineering properties of asphalt mixtures. While the advantages of polymers are acknowledged in literature, few examples are known regarding long-lasting durability and aging behavior. Furthermore, Aschuri et al. [9] studied the durability of AC by using HDPE plastic additives at varying percentages. Their findings indicated significant enhancements of resistance to moisture, rutting, and disintegration.

Awad et al. [10] studied the optimal binder content for modified and unmodified asphalt mixes. For this, the pavement specimens were produced under different polyethylene and waste plastic contents (2%, 3%, 4%, 5%, and 6%), and the physical characteristics were determined by the Marshall test—stability, flow, specific gravity, and void rate. The optimum asphalt content (OAC) for pure asphalts was 7%. With the addition of polyethylene and waste plastic, OAC was reduced to 4.1% and 4.6%, respectively. The changes also led to a marked improvement in Marshall properties, which would have possible savings in building out costs.

Al-Tuwayyij [11] also studied the impact of using a waste plastic bottle instead of an aggregate in AC mixtures. Plastic contents of 5, 7, 9, and 11% were considered with dry mix to study Marshall properties and variation in volumetric properties. It was found that the reuse of plastic, in addition to reduction in aggregate consumption, could also be accompanied by a decrease in optimum asphalt cement content (OAC), enhanced volumetric properties, and an increase in MR value of AC base. The use of plastics in asphalt mixtures is an environmentally friendly process and leads to cost savings and material reduction. The modified mixture was found to give the best performance when containing 11% plastic. Molayem et al. [12] showed that the introduction of 4% and 6% nano-calcium carbonate (NCC) might enhance crack resistance and augment ductility, especially in the dissipated creep stress energy-creep bond at different temperatures. The bond strength of these additives increased at 0, 10, and 20°C; however, fracture energy only increased at the highest temperature tested (20°C), while it decreased at lower temperatures. The feasibility of NCC and its promotion mechanism on the mechanical properties of asphalt were further demonstrated by the cohesion zone modeling (CZM) based on finite element modeling considering the temperature effect.

In addition, Nazhif et al. [13] was conducted to determine the flow properties of plastic-waste paving blocks separated for various inclines (0% to 15%) with a laboratory rainfall simulator. It was found that these pavements had a lesser runoff coefficient than the standard asphalt and concrete pavements. Meanwhile, the runoff coefficient was greater due to the effect of slope. Applying plastic waste paving blocks at Bandung City utilization by SWMM showed, in addition to the significant reduction of runoff, that they could also function effectively as rain drainage within the city. Another group of failures that asphalt concrete (AC) could have is high-performance asphalt concrete (HPAC). Performance-based asphalt thickness AC was developed by Saleh et al. [14], which had 12% of re-stabilized petroleum pitch-asphaltene modified binder and 0.15% PET fibers. Thicker layers of these failures are qualified as HPAC. Their findings showed considerable enhancements in thermal properties (63% increase of stiffness of bitumen at 15°C) and resistance against low-temperature cracking (27% enhancement noticed in fracture energy at -10°C). The modification of the asphaltene caused binder performance reduction at low temperatures; however, this effect is compensated for by the significant improvement in high-temperature stiffness and better field bitumen durability with PET fibers. The research arrived at the fact that the admixture of asphaltenes with PET fibers could improve the durability of asphalt without any loss of compaction and air voids characteristics.

Also, Maharaj et al. [15] was performed to investigate the recycling effect of PET and waste crumb rubber (CR) on both VMA and VFA values using Trinidad Lake and Trinidad Petroleum Bitumen in the design of HMA mixtures. The addition of 6% CR and PET enhanced the response of pavement materials, such as the Marshall stiffness that improved by 21–22% and minimized a bit of the percentage of bulk specific gravity (0.2%). This result brought attention to the positive influence of waste materials on improving mechanical performance, which might be useful in reusing waste materials for road construction.

Zhao et al. [16] showed that asphalt modified with 8% polyether-polyurethane could improve the mechanical properties and thermal stability of asphalt remarkably and reach traditional SBS-modified asphalt in high temperature resistance. It also demonstrated a significant increase in the fatigue life at intermediate temperatures. FTIR microscopy additionally confirmed the creation of new urethane bonds to improve material structure and age resistance. The performance tests showed that these mixtures satisfy the construction requirement and exhibit better resistance to base asphalt under different thermal conditions, and their moisture stability properties are slightly inferior compared to SBS mixtures. These findings offer both a scientific and an engineering basis to apply polyurethane-modified asphalt in road construction, particularly under severe climatic conditions. A different work indicated that the addition of 2-4% of multi-layer plastic to asphalt mixes provides great improvement in resistance to thermal deformations and long-life pavement performance while reducing moisture susceptibility while maintaining mechanical properties. Extensive tests, including the dynamic modulus of elasticity and Hamburg test, proved that MPP-modified mixes have better resistance to heavy traffic loading and extreme climate than conventional mixes. These results provide an environmentally friendly solution for the recycling of plastics and improvement in asphalt pavement quality in hot, humid regions [17].

Conversely, Al-Fatlawi et al. [18] performed an experimental and numerical study to address the advantages of using plastic and rubber waste as additives for asphaltic mixtures. The research validated lower permanent deformation, resulting in increased life of the road. Furthermore, prior research by Musa et al. [19] exhibited remarkable improvements in the penetration and softening point of 60/70 asphalt grade after adding 20% crumb rubber obtained from waste tires at certain conditions: temperature = 170°C; mixing time = 20 minutes. Lee & Le [20] studied the joint influence of epoxy resin, plastic aggregate, and magnesium additives. They found improved deformation and dynamic stability as well as resistance to rutting, which suggested promising sustainable asphalt materials. The use of plastic waste in an asphalt pavement to improve the durability and environmental resistance of a pavement is very successful. It provides a means for promising management of plastic waste as well. There is still a need for continuous research in order to find out the optimum ratio and approach for beneficial service life impact on pavement structure. With respect to the application of the plastic-reinforced asphalt in harsh environmental Iraqi weather, research activities are restricted to investigating these mixtures under the severe weather of Iraq, especially when intense temperatures are higher than 50°C for long periods, and their reflections on permanent deformation (rutting) and resilient modulus without enough attention given to the fact that there is a widespread of fatigue cracks as well as permanent distortion due to these extreme climates. A summary of the mentioned studies and their findings is given in Table 1.

Table 1. Summary of the above-mentioned studies and their findings

Study Reference	Year	Plastic Type/Additive Used	Methodology	Key Findings	Notable Improvements
Al-Hadidy & Yi-qiu [7]	2009	LDPE	SMA modification	Higher softening point, reduced weight loss	Improved weather resistance
Maharaj et al. [15]	2018	PET + CR	Bitumen modification	21-22% higher stiffness	Improved mechanical properties
Awad et al. [10]	2019	Polyethylene/ plastic waste	Marshall tests	Reduced optimal asphalt content	Cost reduction, better stability
Costa et al. [6]	2019	Recycled HDPE	Bitumen modification	Enhanced physical/rheological properties	50% increase in Marshall quotient
Sahoo et al. [3]	2022	Polyethylene, Polystyrene	Laboratory mixing	Increased road durability and lifespan	Better fatigue cracking resistance
Al-Tuwayyij et al. [11]	2023	Plastic bottles	Dry method	Increased resilient modulus	Reduced aggregate use
Kumar et al. [2]	2023	Mixed plastics	AI models (RF, ANN)	RF model showed highest accuracy (94.2% training)	Improved Marshall stability prediction
Saleh et al. [14]	2024	PET fibers + asphaltene	HPAC design	63% stiffness increase at 15°C	Better thermal performance
Molayem et al. [12]	2025	Nano $CaCO_3$	CZM modeling	Improved crack resistance (at 20°C)	Temperature-dependent results
Qabur et al. [17]	2025	Multi-layer Plastic	Hamburg test	Better deformation resistance	Good for hot/humid climates
Zhao et al. [16]	2025	Polyurethane	FTIR analysis	Comparable to SBS asphalt	Excellent heat resistance

This paper fills this void with an accelerated test program to reproduce Iraqi long-term environments. Hence, this study provides a new set of data by examining some relatively unexplored practical aspects under real Iraqi conditions, with the aim of promoting the sustainable performance of asphalt pavement. The objective of this study on utilizing plastic bottles in hot-mix asphalt concrete is to provide sustainable alternative solutions for improving pavement durability, as well as eliminating environmental problems related to plastic disposal. The primary aim of this study is to investigate whether replacing fine aggregates with plastic waste can be a beneficial solution in terms of mechanical properties and long-term durability, thereby contributing to more sustainable infrastructure and less environmentally harmful construction materials.

The research is structured into six chapters: Chapter One covers the introduction to the subject, literature review, and summary of results, durability, and resilient modulus; followed by materials and methods, including test procedures, in Chapter Two; Chapter Three describes the test methods and sample preparation; Chapter Four presents and discusses the results, comparing them with recent literature; Chapter Five provides the conclusion; and Chapter Six contains the statements.

1.1. Durability and Resilient Modulus

The elastic and strength properties of asphalt concrete pavement are important behavioral characteristics that influence pavement life and performance. The design of pavement structures with high resistance and long service life can be simplified through direct knowledge of these interactions. Durability is defined as the capability of asphalt concrete pavement to resist weathering, traffic loads, and other environmental factors, as well as aging, without undergoing serious deterioration. It is affected by the nature of the materials and by good quality control in proportioning, mixing, and laying the pavement.

The resilient modulus (MR) is an indication of the elastic behavior of asphalt concrete under deformation. It measures the material's resistance to deformation or its ability to return to its original shape after being subjected to traffic loading. In simple terms, the higher the resilient modulus, the stiffer and more elastic the pavement material will be. The elastic modulus of asphalt concrete pavements is a critical parameter that describes the material's elasticity under repeated loading. It can be represented by empirical and mechanistic equations depending on the conditions and properties considered, as follows:

- ***AASHTO Model***

This experimental model is widely adopted in the AASHTO Mechanistic-Empirical Pavement Design Guide, as noted by Uzan et al. [21]. It describes the relationship between the resilient modulus, bulk stress, and octahedral shear stress. The mathematical form can be expressed as follows:

$$M_R = k_1\, p_{atm} \left[\frac{\theta}{p_{atm}}\right]^{k_2} \left[\frac{\tau_o}{p_{atm}} + 1\right]^{k_3} \tag{1}$$

where; p_{atm} is Atmospheric pressure, θ is Bulk stress (sum of principal stresses), τ_o is Octahedral shear stress, and k_1, k_2, k_3 are Empirical coefficients determined through regression.

- ***Witczak Model***

This empirical model was developed by Witcza et al. [22]. It used to predict M_R considering key mixture properties and loading conditions. It is helpful to analyze fatigue performance. The equation can be written as follows:

$$fivene \log(M_R) = A_1 + A_2 \log(f) + A_2 \log(AV) + A_4 \log(\varepsilon) + \frac{A_5}{T} \tag{2}$$

where; f is Loading frequency (Hz), AV is Air void content, ε is Strain rate, T is Temperature (°C), and A_1 *to* A_5 are Empirical coefficients.

- ***Artificial Neural Network (ANN) Model***

According to Bahia [23]. This model utilizes artificial neural networks to predict M_R based on mixture composition and environmental conditions. Unlike regression-based models, the ANN model can be expected from data patterns. The mathematical expression can be represented as follows:

$$M_R = ANN(f, AV, T, AC, \dots) \tag{3}$$

where; f is Loading frequency, AV is Air voids (%), T is Temperature (°C), and AC is Asphalt content (%).

- ***General Sigmoidal Model***

This model captures the non-linear behavior of M_R regarding temperature and stress, using a sigmoidal form as follows [24]:

$$M_R = M_{R,min} + \frac{M_{R,max} - M_{R,min}}{1 + \exp(a + b\theta + cT)} \quad (4)$$

where; $M_{R,max}$ and $M_{R,min}$ are Upper and lower limits of resilient modulus, θ is Bulk stress, T is Temperature (°C), and a, b and c are Regression coefficients.

1.2. Pneumatic Repeated Load System

A Pneumatic Repeated Load System (PRLS) is a special test device used to evaluate asphalt concrete pavements. This system mimics the traffic loads (exerted by moving vehicles) after applying cyclic loads to asphalt concrete specimens. Then, the response of the material under repeated loading conditions will be recorded.

- ***Key Functions and Uses***

Simulation of Traffic Loads: The PRLS applies repeated or cyclic loads to asphalt specimens to mimic the forces exerted by moving vehicles.

- ***Measurement of Resilient Modulus***

It helps in determining the resilient modulus (stiffness) of the asphalt pavement, a key parameter for designing flexible pavements.

Resilient Modulus Equation: $M_R = \frac{\sigma_d}{\epsilon_r}$ (5)

where; σ_d is the deviator stress, and ϵ_r is the recoverable strain.

In this study, the dry mixing method was employed to investigate the effect of replacing a specific proportion of fine aggregate with plastic container particles of the same size. The purpose is to determine the durability of asphalt concrete. The repeated load method was employed under different stresses and at a temperature of 25°C to calculate the resilient modulus by using PRLS.

2. Materials and Methods

2.1. Dry and Wet Mixing Methods

There are two methods for incorporating plastics into asphalt mixtures: wet and dry processes. In the wet method, small plastic fragments are added gradually in a certain percentage to hot bitumen to form a homogeneous and characterized bitumen, which is later mixed with aggregates. Alternatively, in the dry method, plastic materials are shredded into fine particles, sieved, and mixed with aggregates at high temperatures (usually close to the plastic's softening point) to provide an effective coating of the aggregates. This approach of wrapping aggregates with fine plastic prevents moisture damage to the asphalt mixture and extends the service life of asphalt concrete, according to Khan et al. [25]. The dry method results in higher Marshall stability and stripping values compared to the wet method. In the current research, the dry method was chosen. Figure 1 illustrates the study's methodology, with detailed descriptions of the materials used and the experimental procedures provided in the subsequent sections.

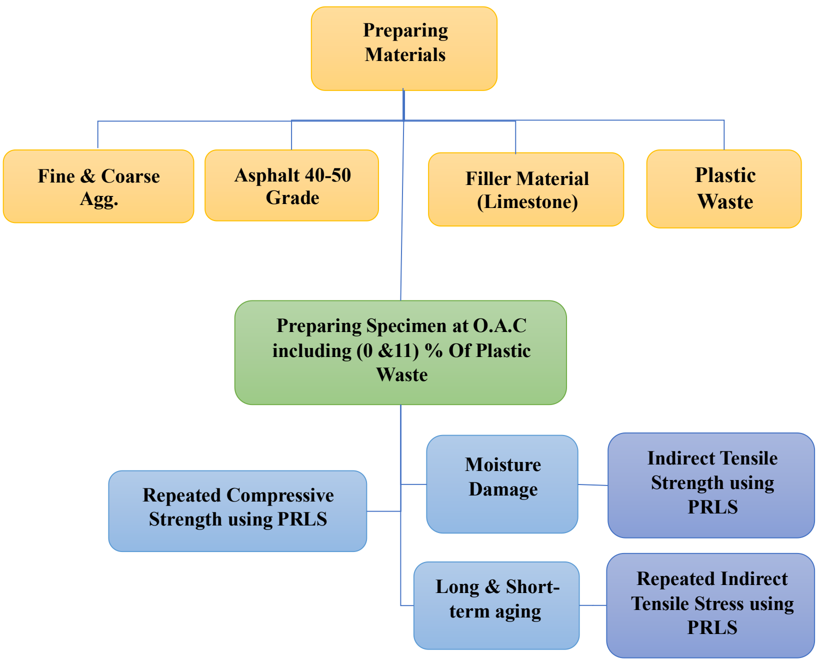

Figure 1. Research methodology flowchart

2.2. Materials

2.2.1. Asphalt Cement

In this study, a grade of (40-50) asphalt binder was produced in the Al-Nasiriyah refinery and applied. Notable results from the physical investigations are presented in Table 2. The tests were conducted according to ASTM standards [26], and the results complied with the Iraqi specifications of roads and bridges SORB/R9 [27].

Table 2. Physical properties of asphalt cement (40-50)

Property	Test Condition	ASTM [26]	Test result	SORB/R9 [27]
Penetration	25ºC, 100 gm, 5 sec	D5-06	43	40-50
Softening Point	-	D36-95	49	-
Ductility	25ºc, 5 cm/min	D113-99	146	>100
Specific Gravity	25˚C	D70	1.03	-
Flash Point	Cleave open the land cup	D92-05/ After Thin Film Oven Test D1754-97	301	>232
Retained Penetration of Residue (%)	25ºC, 100 gm, 5 sec	D5-06	79	>55
Ductility of Residue	25ºC, 5 cm/min	D113-99	-	>25

2.2.2. Aggregate Composition

Coarse and fine aggregates, as well as limestone dust, were collected from the quarries of Assur Company. ASTM standards performed various tests [26]. The obtained results are presented in Tables 3 to 5.

Table 3. Properties of coarse aggregates

Property	ASTM [26]	Test results
The bulk specific gravity of coarse aggregate	C127-88	2.62
The apparent specific gravity of coarse aggregate	C127-88	2.687
Absorption in percent of coarse aggregate	C127-88	1%
Percentage of fractured particles in coarse aggregate	D5821-13	94%
Resistance to abrasion (Los Angeles)	C131/C131M-2014	23%

Table 4. Properties of fine aggregates

Property	ASTM [26]	Test results
The bulk specific gravity of fine aggregate	C128-01	2.629
The apparent specific gravity of fine aggregate	C128-01	2.694
Absorption in percent of fine aggregate	C128-01	1.1%

Table 5. Properties of mineral filler (Limestone dust)

Property	Test results
Percentage passing sieve No. 200	95%
Specific surface area (m^2/kg)	389
Specific gravity	2.85

2.2.3. Plastic Waste

In this study, samples of plastic drink bottles were prepared via the dry method by cutting them into small pieces. These particles were then passed through a sieve with openings of 4.75 mm and retained on a 2.36 mm sieve. Plastic particles from waste bottles were incorporated in varying amounts to substitute fine aggregates of equivalent size. Approximately 11% of the fine aggregates were replaced by plastic pieces, as previously concluded [11].

2.2.4. Combined Aggregated Gradation

The asphalt mixture assigned for the wearing course type (III-B) was prepared by the gradation limits specified by the SORB/R9 [27], as detailed in Table 6.

Table 6. Limitations of mixed aggregate gradation based on SORB/R9 [27]

Sieve size (mm)	Wearing course Type III-B
12.5	100%
9.5	90-100%
4.75	55-85%
2.36	32-67%
0.3	7-23%
0.075	4-10%

2.2.5. Preparation of Asphalt Concrete Specimens

As a first step, the aggregates were dried at 110°C in an oven to reach a constant weight, then sieved into different sizes and stored separately. Fine and coarse aggregates, in addition to limestone dust, were thoroughly mixed to ensure that the composition met the grade requirements for an asphalt concrete wearing course type III-B, as specified by the SORB/R9 [27]. Following that, the combined aggregate mixture was heated to 150ºC before adding heated asphalt. The controlled mixture was prepared with 0% content of plastic waste. The optimum asphalt content was found to be at 5.2%. In the other mixtures, plastic waste was introduced as a partial replacement of fine aggregate in a proportion of 11%, and three asphalt binder contents of 4%, 4.5%, and 5% were tested. The asphalt cement was also heated to 150ºC and then mixed with the heated aggregate to reach the desired quantity. This combination was thoroughly mixed with a mechanical mixer for 120 seconds to ensure all aggregate particles were well coated with a thin film of asphalt. The optimum content of asphalt was achieved at 4.5%, which yielded the highest stability value and resilient modulus, as concluded by Al-Tuwayyij [11]. Two sets of asphalt concrete specimens were prepared. The first set consisted of traditional Marshall specimens with a diameter of 10.2 cm and a height of 6.35 cm, prepared according to the ASTM standards [26] using 75 blows of the Marshall hammer on the top and bottom of the specimen bases. The second set of specimens had a diameter of 10.2 cm and a height of 10.2 cm, prepared using static compaction to achieve a target density of 2.41 g/cm³.

3. Testing Programs

3.1. Repeated Indirect Tensile Stresses Test

The Pneumatic Repeated Load System (PRLS) was used to apply repeated indirect tensile stresses by ASTM standards. This test was conducted on Marshall samples measuring 10.2 cm in diameter and 63.5 cm in height. The repetitive load was applied to the diametral side of the specimen, while the vertical strain was observed and recorded thoroughly. A constant loading frequency of 60 cycles/minute was used, with a stress level of 0.138 MPa. Each cycle consisted of 0.1 seconds of loading and 0.9 seconds of rest. The testing temperature was consistently maintained at 25ºC. The asphalt concrete specimens underwent 1200 repetitions of indirect tensile stresses. Figure 2 illustrates the sequence of repeated tensile or compressive stress loading, while Figure 3 shows the test chamber for repeated tensile and compressive strength.

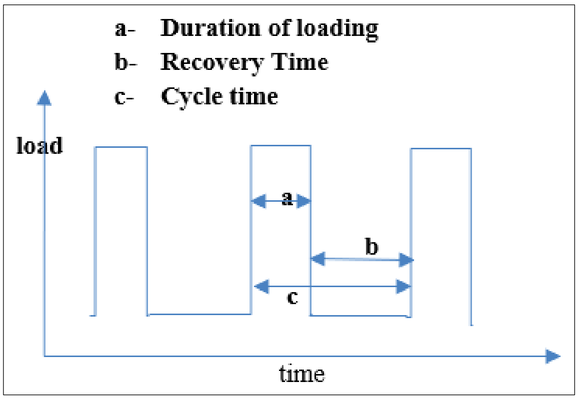

Figure 2. Repeated stress loading sequence

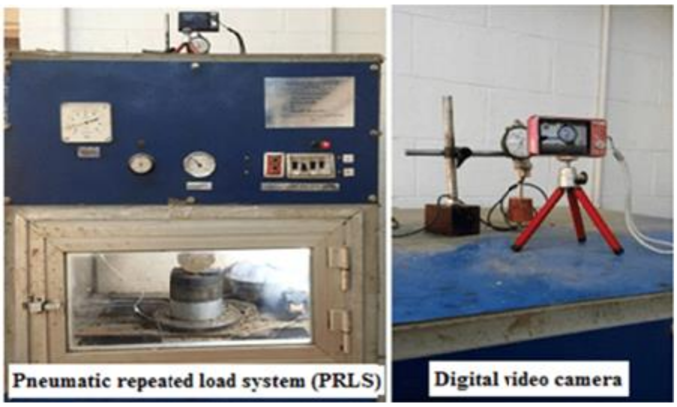

Figure 3. Pneumatic repeated load system PRLS

3.2. Repeated Resistance Compressive Stress (Rutting)

Rutting, a type of permanent deformation, is one of the most common and serious types of pavement distress and is mainly caused by repeated deformation under traffic loads and due to temperature variations. And it is one of the essential indicators of durability. A total of 10.2 cm diameter and 10.2 cm height asphalt concrete samples were prepared along with samples with asphalt content that are 0.5% above and below the optimum for comparison. Specimens were subjected to repeated cycles of compressive stress loading, and vertical strain was monitored during loading cycles. The constant stress level of these load cycles (i.e., 0.138 MPa) was maintained by applying a loading frequency of 60 cycles per minute. One loading lasted 0.1 seconds and was followed by 0.9 seconds of rest, and so on. Tests were performed at 25°C, and the permanent deformation and resilient modulus of these specimens were tested at 25°C at different stresses (0.069, 0.138, and 0.207 MPa) with 1200 load repetitions. The test was performed in accordance with relevant ASTM procedures [26].

3.3. Short- and Long-Term Aging Processes

The aging of asphalt concrete is a basic problem that directly affects the durability of asphalt pavement performance at service life. Over time, the asphalt binder ages, becomes increasingly complex and more brittle, and is more susceptible to fracture under thermal and fatigue stresses. Under normal conditions, oxidation of the asphalt and volatilization of light maltenes from the binder, otherwise known as aging, are accounted for as fundamental aspects of durability. The second key parameter of durability, therefore. Carl Zappala: The engineer who conducted the test was by AASHTO standards [28]. The test specimens were prepared with an OAC of 4.5% and 11% plastic waste content in asphalt concrete mixtures. These mixtures were aged for a short-term aging (STA) process, where the loose mixtures were compiled in an oven at a temperature of 135°C for a period of 5 h prior to compaction. The mixtures were compacted into Marshall specimens and subjected to a 5-day long-term aging (LTA) process in an oven at 85°C. Based on the aging, the characteristics of asphalt concrete specimens were indirect tensile strength (ITS) at 25°C, resilient modulus, and irreversible strain using repeated indirect tensile stress at the same temperature. A controlled mix testing specimen was then used as a standard to compare the results of the tests. This device was made up of a Photoelastic Reflection Lens System (PRLS) that determined deformation due to aging. Monitoring of the aging temperature section in the long-term aging process is shown in Figure 4.

Figure 4. Long-term aging

3.4. Resistance to Moisture Damage

Moisture susceptibility is one of the main issues affecting asphalt concrete pavements. Consequently, this characteristic has been examined as the third key aspect of durability for asphalt concrete samples. Marshall samples were created with 7% air voids and three different asphalt content levels (optimum ± 0.5%). These samples were prepared using 35, 55, and 75 blows of the Marshall hammer on each side of the specimens. The samples were then split into two groups. The first group was subjected to an indirect tensile strength (ITS) test at 25°C, referred to as unconditioned samples. At the same time, the second group was placed in a vacuum container filled with water for saturating using a suction pressure of 15 kPa for 10 minutes. Then, these samples were sealed in tight plastic bags and stored in a deep freezer at -18°C for 16 hours. Subsequently, they were placed in a 60°C water bath for 24 hours. Next, the samples were transferred to a 25°C water bath for two hours before being tested for ITS according to ASTM standards and were referred to as conditioned samples. The tensile strength ratio (TSR) was calculated according to ASTM guidelines as a measure of durability.

4. Results and Discussion

4.1. Assessing the Durability in Terms of Moisture Damage

Asphalt concrete samples were produced by incorporating 11% plastic waste and an optimal asphalt content of 4.5% [10]. The test was conducted by ASTM D4867/D4867M-09. Accordingly, the air voids for this test should be 7% [25]**.** Thus, specimens were prepared and compacted using varying numbers of blows per specimen: 35, 55, and 75 blows on each face. The air voids for each specimen were then calculated, and the relationship between air voids and the number of blows was plotted. It was determined that 49 blows were necessary to maintain 7% air voids. Figure 5 illustrates the relationship between the number of hammer blows and the specimens' air voids.

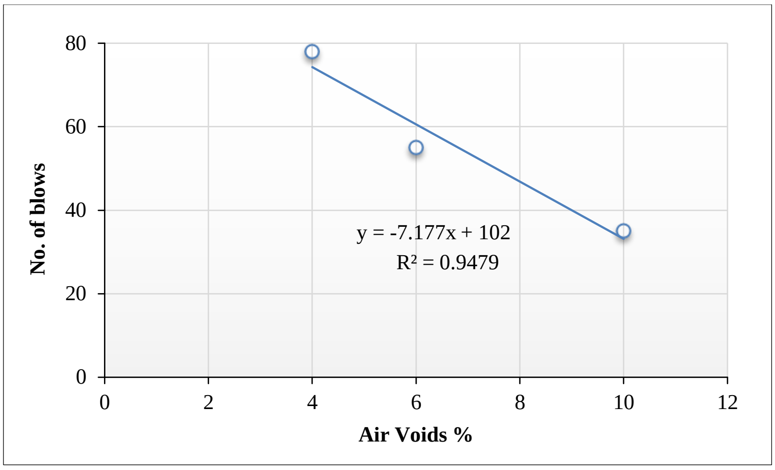

Figure 5. Air voids

Upon completion of the prescribed test protocol, the tensile strengths of both moisture-conditioned and dry-conditioned specimens were measured, and the corresponding TSR was determined. The results are summarized in Table 7.

Table 7. Results of Indirect Tensile Strength and Tensile Strength Ratio

Specimen type	Indirect Tensile Strength, kPa		TSR%	Min. TSR%
	Unconditioned	Conditioned		
Controlled mix (5.2% OAC)	2425	1950	80.4	80
11% waste plastic + 4% asphalt content	2220	1757	79	
11% waste plastic + 4.5% asphalt content	2545	2076	81	
11% waste plastic + 5% asphalt content	2655	2213	83.3	

It was observed that the value of TSR for prepared specimens with an asphalt content exceeding the optimum by more than 0.5% increased by over 3.6% relative to the controlled specimen (without plastics), representing the highest improvement among all tested samples. This aligns with Al-Hadidy & Yi-qiu [7], who noted that excess asphalt compensates for plastic's hydrophobic limitations by improving binder-aggregate adhesion.

Plastic does not absorb water. Most of the plastics used in packaging; especially polyethylene and polypropylene; are themselves naturally hydrophobic, repelling water rather than absorbing it. This water-resistant property, when applied in an asphalt mixture, inhibits moisture from penetrating the pavement. Plastic particles, dosed usually from 5 to 10% by weight, fill voids in aggregate particles but most importantly seal microscopic pores in the asphalt matrix. This pore-blocking operation prevents water from seeping in during the rainy season and ultimately destroying the lower levels of the pavement structure. Additionally, a thin layer of plastic fragments is always surrounding each grain of aggregate, so the water is not in direct contact with the bitumen binder. By providing this barrier effect, stripping (i.e., the loss of adhesion between aggregates and binder) can be mitigated, which is one of the major mechanisms of moisture-induced pavement deterioration.

4.2. Assessing the Durability in Terms of Aging

Short-term conditioning was applied to replicate the aging that occurs during construction (from mixing through compaction) as a part of the mix design procedure. In contrast, long-term aging simulates oxidative hardening over the pavement's service life [16]. The loose asphalt blends first experienced short-term aging at 135°C for five hours. Once this initial aging was complete, Marshall specimens were prepared by compacting the aged blends by the standard Marshall methodology (ASTM D6927). Following compaction, the samples were subjected to long-term aging for 120 hours at 85°C in an electric oven. After aging, a Pneumatic Repeated Load System (PRLS) was applied, inducing repeated indirect tensile stresses at 25°C and a stress level of 0.1379 MPa. Finally, the resulting permanent deformation and resilient modulus were measured and compared with those of a control mixture, which contained the optimum asphalt content with 11% plastic waste and exhibited no short- or long-term aging.

Figure 6 explains the relationship between observed permanent strain and the number of loading cycles for both controlled and aged specimens. The aged specimens exhibited a lower permanent strain and a gentler slope, indicating superior resistance to deformation. Table 8 presents the permanent deformation results for the controlled specimens and those specimens subjected to aging (Aging Index).

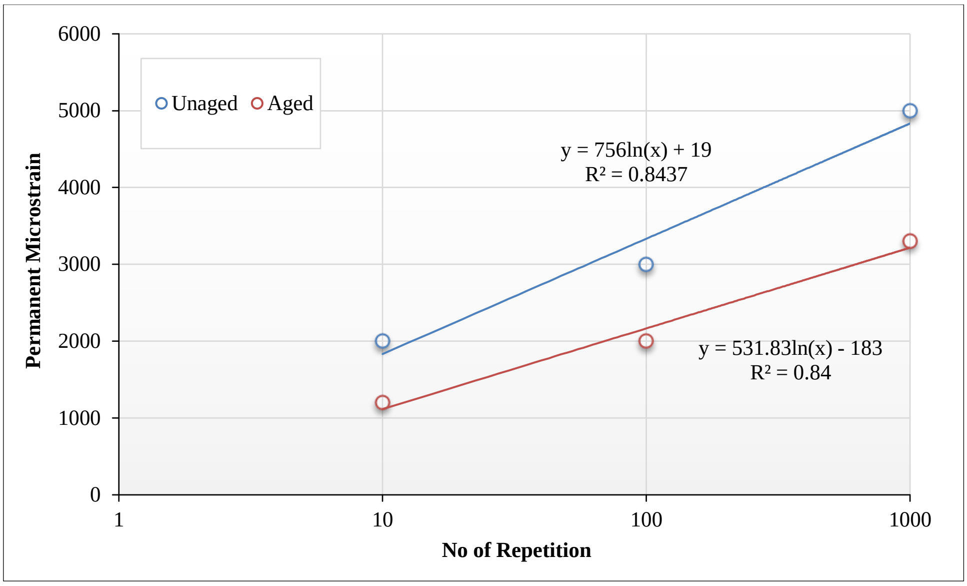

Figure 6. Impact of aging on permanent deformation (microstrain)

Table 8. Values of permanent deformation (microstrain)

Specimen	Permanent Deformation (Micro strain)		Reduction in Micro strain After Aging %	
	At First Repetition	At 1200 Repetitions	At First Repetition	At 1200 Repetitions
Before Aging	2500	7000	40%	48.5%
After Aging	1500	3600		

The permanent deformation test results of the specimen with replacement of 11% of fine aggregate with waste plastic bottles presented an improvement under aging when compared to the reference specimen unaged. Consequently, the data do show that the aged specimen demonstrated substantially lower values for permanent deformation at every stage of loading, thus suggesting that the mixture is more resistant to deformations caused by repeated traffic loads post-rejuvenation. This aligns with Saboo & Kumar [29]. Quantified 30–40% improvements for polymer-modified mixes (PS: our higher reduction is due to greater stress relaxing from the plastic void-filling even effect). Additionally, a better degree of determination indicated a more consistent logarithmic relationship between the number of cycling loads and the permanent deformation values of the aged specimen. For the unaged specimen. This increased R^2 shows a more consistent mechanical performance and stability of the aged sample. Moreover, the smaller slope and interception of the regression equation of the aged specimen suggest that the growth of deformation with the number of load cycles becomes slower, which is encouraging because it indicates that the durability of the concrete improves.

The relevant data on resilient modulus (MR) of the tested specimens is summarized in Table 9. The enhanced elastic stiffness of the modified mixtures as compared to the controlled specimen, as evidenced by the higher MR values of the modified mixtures after exposure to the aging process relative to the unaged, controlled specimen, can be attributed to the presence of the plastic material.

Table 9. Influence of aging on resilient modulus

Specimen	Resilient Modulus MPa		Change in Resilient Modulus After Aging %	
	At First Repetition	At 1200 Repetitions	At First Repetition	At 1200 Repetitions
Before Aging	2400	4550	118%	40%
After Aging	5220	6330		

Among the obligatory mechanical behaviors of this material, the MR test for asphalt mixtures containing 11% recycled plastic waste demonstrated that aging exerts the highest impact on MR. For MR at the first load repetition, it increased from 2400 MPa in the unaged specimens to 5220 MPa in the aged specimens, an improvement of 118%. That is explained by the stiffening of the asphalt binder resulting from thermal aging, which increases the resistance of the mix to short-time deformation. Following 1200 load repetitions, the aged specimens remained superior, exhibiting an MR of 6330 MPa vs. 4550 MPa in the unaged specimens, or an approximate improvement of 40%. Such observations imply that the mechanical properties of the aged bound mixtures are more stable upon repeated load application and that the structural integrity improves with time.

In general, the resilient modulus was not compromised by the introduction of recycled plastic waste. It resulted in comparable performance with ideal aging, indicating potential for enhanced durability in asphalt mixtures to produce a more sustainable pavement. This could be due to plastic helping to facilitate the redistribution of internal stresses in the asphalt mixture. Plastic enhances the dissipation of loads and, therefore, decreases the flow of key stress reaching the asphalt binder, which translates into a reduced rate of permanent deformation build-up. Further, the water absorption is low, so the disintegration of the mixture does not affect the structural stability, and under severe environmental conditions, long-term conditions, and heating and wet conditions, the hot mixture does not lose stability. These results challenge some fears that plastics could make asphalt brittle in the long run. In contrast, the thermoplastic nature of PE seems to prevent age-hardening because the MR slope is constant (Figure 6). This is in accordance with the theory of Airey [30], who mentioned that polymers have the ability to slow oxidative aging in bitumen.

Consequently, using recycled plastic as a modifier in asphalt mixes was proved to both help environmental sustainability and improve its construction functional performance in both the short and long term (as monitored from laboratory test results).

4.3. Rutting Resistance: Assessing the Durability

The repeated compressive loading test PRLS (Permanent Deformation & Rutting Resistance of Asphalt Concrete) was used to characterize the rutting resistance of recycled plastic-waste-modified asphalt concrete at three stress levels (0.0689, 0.1379, and 0.2068 MPa) and a test temperature of 25 °C for up to 1200 load repetitions, with 11% (by weight of fine aggregate) replacement of plastic waste combined with three asphalt binder contents (optimum ± 0.5%). As shown in Table 10, three specimens were prepared for each asphalt content and tested. The mechanical response was measured in terms of permanent deformation and MR. Permanent deformation versus number of load repetitions at different applied stress levels is shown in Figures 7 to 9.

Table 10. Total permanent deformation after 1200 load repetitions

Asphalt content %	Permanent Deformation Parameters After 1200 Load Repetitions ε_p		
	0.0689 MPa	0.1379 MPa	0.2068 MPa
4%	6000	11500	17250
4.5%	4200	8000	12000
5%	3600	7200	10800

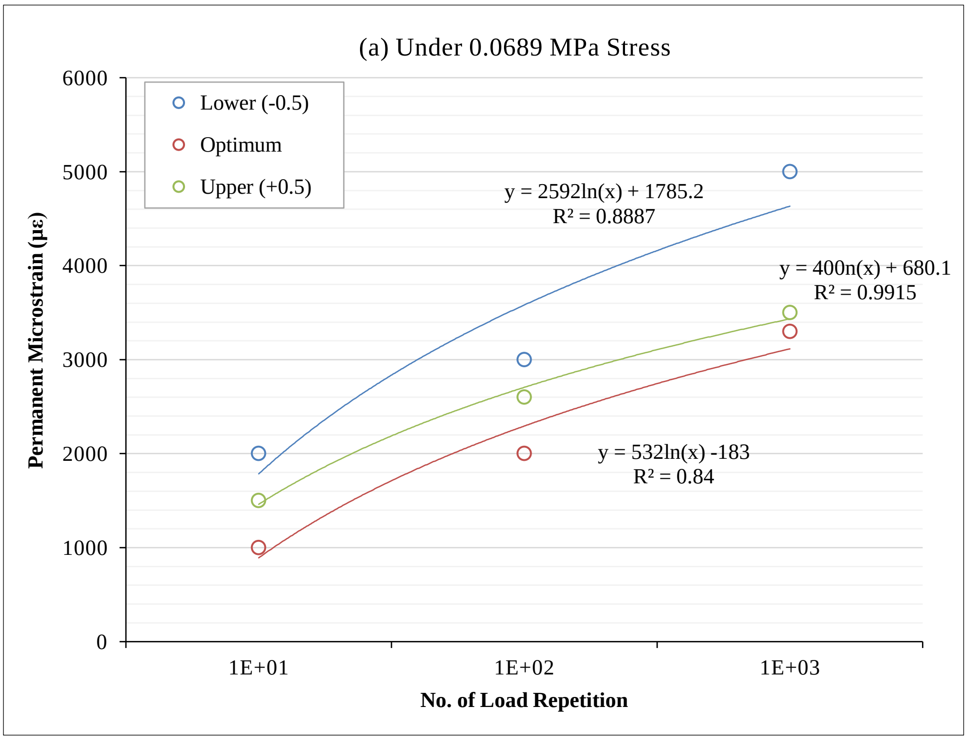

Figure 7. Permanent deformation under 0.0689 MPa stress levels

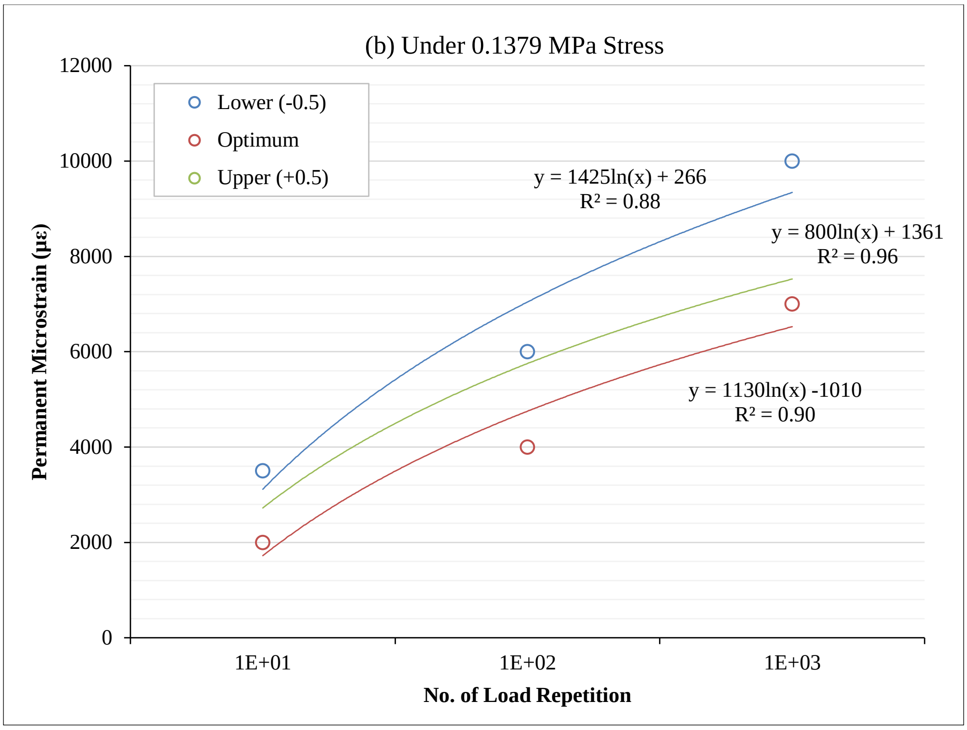

Figure 8. Permanent deformation under 0.1379 MPa stress levels

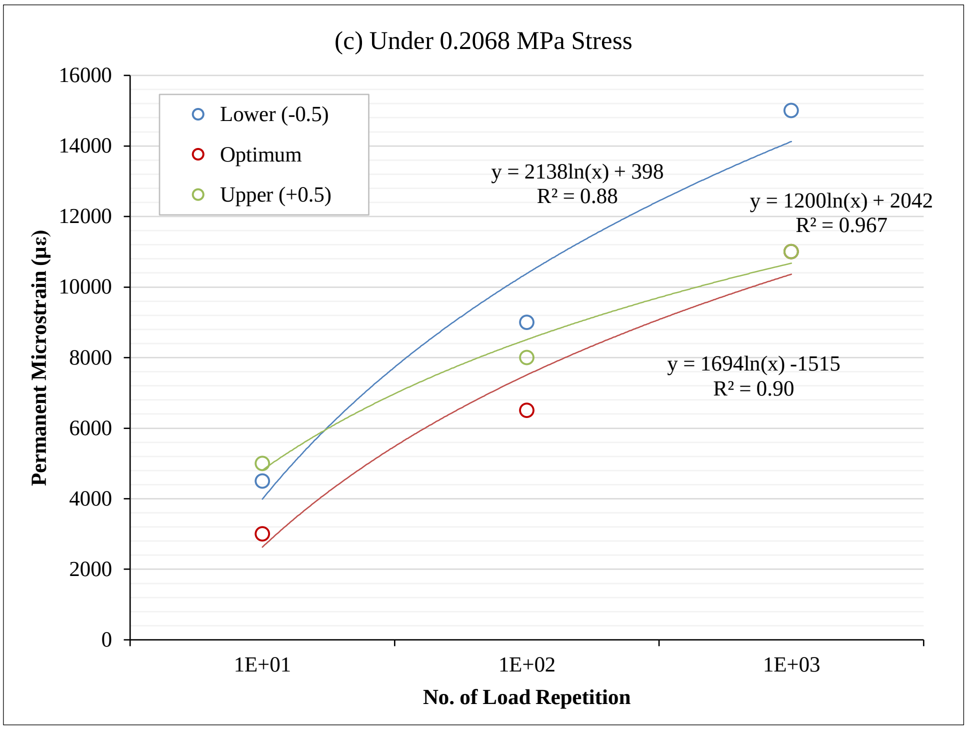

Figure 9. Permanent deformation under 0.2068 MPa stress levels

Regardless of asphalt binder content, the permanent micro-strain increased with higher stress levels. Nevertheless, specimens with the OAC consistently produced the lowest permanent micro-strain. The difference in slope of the mixtures was small, suggesting the rate of deformation development was similar. Table 11 shows the cumulative permanent deformation at 1200 loading repetitions, which demonstrated the same trend as the first loading cycle (intercept). This indicated increased resistance to permanent deformation of the optimal binder contents of plastic-modified mixtures under conditions of repeated loading. It is significant that mixtures containing 11% recycled plastic waste and the OAC exhibited the best performance, keeping the lowest micro strain values between all stress levels compared to mixtures with ±0.5% variation in asphalt content. This is in contrast to Bastidas-Martínez & Rondon-Quintana [31]. Immediately, this contradicts the findings of OAC unconditionally optimal by Dalhat et al. [32]. This observation aligns with the notion that polymers can change optimality by increasing shear resistance. Lastly, Figure 10 shows the compressive strength of asphalt concrete samples before and after cyclic compressive stresses. The peak compressive strength was obtained from samples containing OAC and 11% plastic waste. Optimum binder +0.5% rapid decrease (drastic decrease in value of compressive strength) This sharp decrease can be inferred to result from the restrictive absorptive ability of the aggregate-plastic residue framework, with the coarse plastic fragments permitting small pore spaces for absorbing binder.

Table 11. Resilient modulus after 1200 load repetitions

Asphalt Content %	Resilient Modulus After 1200 Load Repetitions, MPa		
	0.0689 MPa	**0.1379 MPa**	**0.2068 MPa**
4%	7335	5430	3225
4.5%	8755	6540	4200
5%	5700	4360	2230

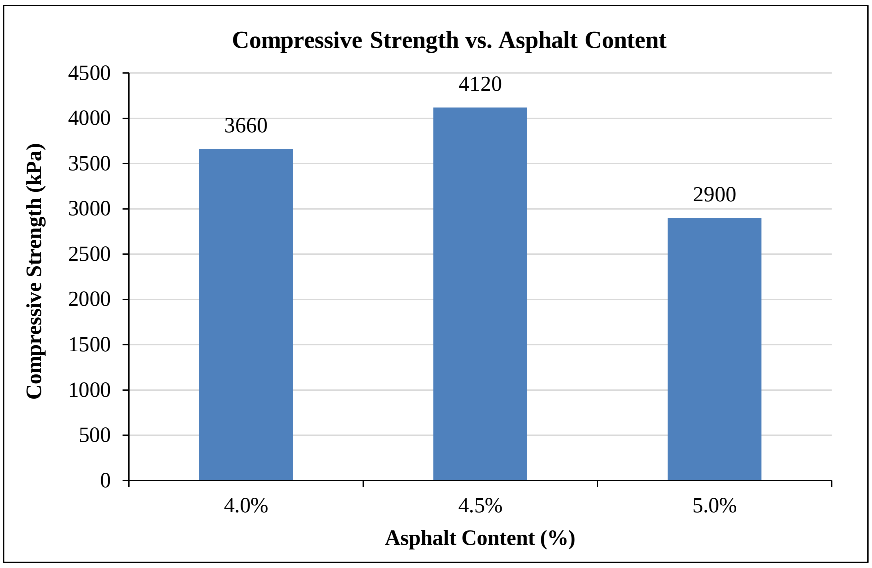

Figure 10. Compressive strength of specimens

5. Conclusion and Recommendations

The benefits of replacing 11% of fine aggregates by plastic bottle waste in asphalt concrete (using a dry process) can be described as follows:

- Improvement of stiffness and load-bearing capacity: this means enhancing resistance to cracking and permanent deformation. The examined samples showed an increase in resilient modulus values up to 118% due to the post-aging process.
- Improvement of moisture resistance: this is due to hydrophobic of plastic. The modified specimens achieved a tensile strength ratio (TSR) of 83.3% compared to conventional mixtures. As a result, water absorption will decrease, which prevents stripping failure.
- Improvement of rutting resistance: samples with 11% plastic and OAC = 4.5% showed lower permanent deformation under repeated compressive loads. This might indicate superior rutting resistance. Furthermore, higher plastic content was found in correlation with rutting reduction. This also confirms its role in enhancing pavement stability.
- Aging effects: long-term aged samples (85°C lasts for 5 days) showed better mechanical properties compared to unaged samples. This includes lower permanent strain and higher resilient modulus. This finding indicated that plastic-modified mixtures can maintain their performance over time and resist oxidative hardening as well as brittleness.
- Environmental sustainability: applying plastic waste in asphalt mixtures considers an eco-friendly alternative to plastic dumps to keep natural fine aggregate resources. This method also minimizes construction costs in addition to the environmental impact of plastic pollution.

These key points demonstrate that adding plastic waste as a replacement for fine aggregates is not only an effective solution for plastic pollution but also enhances deformation resistance and environmental sustainability. Future studies are essential to carry out to show optimization of mix designs and recycling applications in road construction. It is worth recommending further research regarding the evaluation of the long-term performance of plastic-modified asphalt mixture under adverse climatic and traffic conditions. Also, investigating other types of plastic replacement ratios might optimize the durability of asphalt mixtures.

6. Declarations

6.1. Author Contributions

Conceptualization: H.A.; methodology, H.A., N.A., and A.M.; validation, H.A., N.A., and A.M.; investigation, H.A., N.A., and A.M.; resources, H.A.; data curation, H.A.; writing—original draft preparation, H.A.; writing—review and editing, N.A., H.A., and A.M.; supervision, H.A.; project administration, H.A. All authors have read and approved the final version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), 1700782. doi:10.1126/sciadv.1700782.

[2] Kumar, B., & Kumar, N. (2023). Assessment of Marshall Stability of asphalt concrete with plastic waste using soft computing techniques. Multiscale and Multidisciplinary Modeling, Experiments and Design, 6(4), 733–745. doi:10.1007/s41939-023-00180-x.

[3] Sahoo, N. K., Tarai, B., Mohanta, K. A., Kumar, D., Tarasankar, P., Hota, S., & Mangaraj, A. (2022). Project on Preparation of Plastic Road Using Single Used Waste Plastic. International Journal for Research in Applied Science and Engineering Technology, 10(5), 1429–1436. doi:10.22214/ijraset.2022.42556.

[4] Zghair Chfat, A. H., Yaacob, H., Mohd Kamaruddin, N. H., Al-Saffar, Z. H., & Jaya, R. P. (2024). Performance of Asphalt Mixtures Modified with Nano-Eggshell Powder. Civil Engineering Journal, 10(11), 3699-3720. doi:10.28991/CEJ-2024-010-11-016.

[5] Hınıslıoglu, S. (2004). Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix. Materials Letters, 58(3–4), 267–271. doi:10.1016/s0167-577x(03)00458-0.

[6] Costa, L. M. B., Silva, H. M. R. D., Peralta, J., & Oliveira, J. R. M. (2019). Using waste polymers as a reliable alternative for asphalt binder modification – Performance and morphological assessment. Construction and Building Materials, 198, 237–244. doi:10.1016/j.conbuildmat.2018.11.279.

[7] Al-Hadidy, A. I., & Yi-qiu, T. (2009). Effect of polyethylene on life of flexible pavements. Construction and Building Materials, 23(3), 1456–1464. doi:10.1016/j.conbuildmat.2008.07.004.

[8] Mashaan, N. (2022). Engineering Characterisation of Wearing Course Materials Modified with Waste Plastic. Recycling, 7(4), 61. doi:10.3390/recycling7040061.

[9] Aschuri, I., Woodward, D., & Woodside, A. (2008). The Improvement of Durability of Asphalt Concrete Using Modified Waste Plastic-Bitumen. Proceedings of the 6th ICPT, 20-23 July, 2008, Sapporo, Japan.

[10] Awad, A, Al-Manasir, K., Al-Adday, F., & Shadid, O. (2019). Utilizing of polyethylene and plastic wastes for paving asphalt modification in Jordan. International Journal of Current Research, 11(10). doi:10.24941/ijcr.34027.01.2019.

[11] Al-Tuwayyij, H., Al-Mukaram, N., & Musa, S. S. (2023). Impact of Plastic Waste on the Volumetric Characteristics and Resilient Modulus of Asphalt Concrete. Civil Engineering Journal (Iran), 9(4), 915–926. doi:10.28991/CEJ-2023-09-04-012.

[12] Molayem, M., Ameri, M., Aliha, M. R. M., Dehghanbanadaki, A., & Mahmoodinia, N. (2025). Evaluating Fracture Behavior of Nano-CaCO3–Modified Asphalt Concrete Mixtures at Intermediate Temperatures. Journal of Materials in Civil Engineering, 37(8), 04025227. doi:10.1061/jmcee7.mteng-19873.

[13] Nazhif, A. A., Nugroho, E. O., Rusdy, N. F. P., Kardhana, H., Nuraeni, S., Pradoto, R. G. K., Kuntoro, A. A., Mohammed, B. S., Dharmowijoyo, D. B. E., Nurkhaerani, F., Wijaya, A. R., Fauzi, M. F., & Rayya, R. (2024). The effect of paving block from plastic waste material in the urban drainage: Study case in residential areas. E3S Web of Conferences, 479, 3002. doi:10.1051/e3sconf/202447903002.

[14] Saleh, M., Ahmed, N., Penetrante, R., Moghaddam, T. B., & Hashemian, L. (2024). Development of a High-Performance Asphalt Concrete with Enhanced Low-Temperature Performance. Cold Regions Engineering 2024, 518–529. doi:10.1061/9780784485460.048.

[15] Maharaj, R., Maharaj, C., & Hosein, A. (2018). Performance of waste polymer modified road paving materials. Progress in Rubber, Plastics and Recycling Technology, 34(1), 19–33. doi:10.1177/147776061803400102.

[16] Zhao, S., Ouyang, J., & Zhou, L. (2025). Rheological Properties of Polyurethane-Modified Asphalt and Its Effect on the Performance of Porous Asphalt Mixes. Journal of Materials in Civil Engineering, 37(10), 04025327. doi:10.1061/jmcee7.mteng-20750.

[17] Qabur, A., Baaj, H., & El-Hakim, M. (2025). A Laboratory Study on Enhancing Asphalt Mixture Properties through Dry Mixing with High-Dose Multilayer Plastic Packaging Pellet Additives. Journal of Materials in Civil Engineering, 37(4). doi:10.1061/jmcee7.mteng-19101.

[18] Al-Fatlawi, S. A., Al-Jumaili, M. A., Eltwati, A., & Enieb, M. (2023). Experimental-numerical model of permanent deformation in asphalt paving mixtures modified with waste plastic and rubber. Oil and Gas Engineering, 2784, 060015. doi:10.1063/5.0140884.

[19] Musa, S. S., Al-Mukaram, N., & Dakhil, I. H. (2024). Asphalt binder modified with recycled tyre rubber. Open Engineering, 14(1), 20220495. doi:10.1515/eng-2022-0495.

[20] Lee, S. Y., & Le, T. H. M. (2023). Feasibility of Sustainable Asphalt Concrete Materials Utilizing Waste Plastic Aggregate, Epoxy Resin, and Magnesium-Based Additive. Polymers, 15(15), 3293. doi:10.3390/polym15153293.

[21] Uzan, J., Witczak, M. W., Scullion, T., & Lytton, R. L. (1992). Development and validation of realistic pavement response models. International Conference on Asphalt Pavements, 7th, 1992, Nottingham, United Kingdom.

[22] Witczak, M. W., Qi, X., & Mirza, M. W. (1995). Use of nonlinear subgrade modulus in AASHTO design procedure. Journal of transportation engineering, 121(3), 273-282. doi:10.1061/(ASCE)0733-947X(1995)121:3(273).

[23] Bahia, H. U. M. (1991). Low-temperature isothermal physical hardening of asphalt cements. The Pennsylvania State University, Pennsylvania, United States.

[24] Wang, X. Y. (2014). Properties prediction of ultra-high performance concrete using blended cement hydration model. Construction and Building Materials, 64, 1–10. doi:10.1016/j.conbuildmat.2014.04.084.

[25] Khan, M. I., Sutanto, M. H., Khan, K., Iqbal, M., Napiah, M. Bin, Zoorob, S. E., Klemeš, J. J., Bokhari, A., & Rafiq, W. (2022). Effective use of recycled waste PET in cementitious grouts for developing sustainable semi-flexible pavement surfacing using artificial neural network (ANN). Journal of Cleaner Production, 340, 130840. doi:10.1016/j.jclepro.2022.130840.

[26] ASTM Volume 04.03. (2013). Road and Paving Materials; Vehicle-pavement Systems. ASTM International, Pennsylvania, United States.

[27] Jabor, Z. & Azawi, E. (2014). Hot Mix Asphalt Concrete Pavement. Specifications of Roads and Bridges (SORB/R9), Part One: Road Works, vol. 1, Ministry of Construction and Housing, Baghdad, Iraq.

[28] AASHTO. (2013). Standard Specification for Transportation Materials and Methods of Sampling and Testing (14th Ed.). American Association of State Highway and Transportation Officials (AASHTO), Washington, United States.

[29] Saboo, N., & Kumar, P. (2016). Performance characterization of polymer modified asphalt binders and mixes. Advances in civil engineering, 2016(1), 5938270. doi:10.1155/2016/5938270.

[30] Airey, G. D. (2002). Rheological evaluation of ethylene vinyl acetate polymer modified bitumens. Construction and Building Materials, 16(8), 473–487. doi:10.1016/S0950-0618(02)00103-4.

[31] Bastidas-Martínez, J. G., & Rondon-Quintana, H. A. (2024). Assessment of asphalt binder content, temperature and loading rate in indirect tensile strength and resilient modulus tests of a hot-mix asphalt–Comparison with Marshall design method. Construction and Building Materials, 426, 136158. doi:10.1016/j.conbuildmat.2024.136158.

[32] Dalhat, M. A., Al-Abdul Wahhab, H. I., & Al-Adham, K. (2019). Recycled Plastic Waste Asphalt Concrete via Mineral Aggregate Substitution and Binder Modification. Journal of Materials in Civil Engineering, 31(8), 04019134. doi:10.1061/(asce)mt.1943-5533.0002744.