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Enhancing Marshall Properties Through the Integration of Waste Plastic Water Bottles in Dry Process Asphalt Production

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ABSTRACT

Climatic conditions, escalating traffic loads, and inadequate maintenance have been identified as significant contributors to the degradation of road quality, resulting in suboptimal performance of paved roads. One of the critical forms of deterioration is the premature hardening of asphalt, which leads to early onset of cracks and, consequently, the premature failure of pavement surfaces. In response to these challenges, this study explores an innovative approach to improve the properties of asphalt mixes by integrating plastic waste, thus prolonging pavement service life, reducing construction and maintenance costs, and mitigating environmental pollution. Specifically, waste Polyethylene Terephthalate (PET), derived from plastic water bottles, was incorporated as a polymer additive in asphalt mixtures. Asphalt specimens, both modified and unmodified, were produced by integrating plastic waste in proportions of 0, 3, 6, 9, and 12 percent by the weight of asphalt. The specimens were evaluated for their Marshall Stability, flow, and volumetric properties using digital Marshall testing equipment on a selected size range (2.36-1.18 mm) employing a dry process. All test results conformed to Iraqi standard specifications, highlighting an enhancement in the mix properties compared to the conventional mixture. The augmentation of plastic waste was consistent with previous findings and demonstrated improved engineering features of the mixtures. The ideal proportion of waste plastic water bottle integration was found to be 7.77%, resulting in an increase in stiffness and stability by 70.45% and 42.10%, respectively, compared to a conventional mix.

1. INTRODUCTION

Since 2003, Iraq has seen a surge in both vehicle numbers and their respective weights, leading to a marked degradation in asphalt road surfaces, particularly at traffic intersections and parking areas. Consequently, enhancing the performance of asphalt roads through regular maintenance, operational improvements, or the deployment of superior asphalt mixtures has become imperative to mitigate or prevent asphalt road surface deformation. A significant source of environmental pollution worldwide, waste plastic water bottles present a viable solution to improve the properties of asphalt mixtures when added as small particles or powder.

The inclusion of waste plastic has been found to contribute to increased stiffness and rut-resistance in asphalt [1]. Significant improvements in the Marshall flow, Marshal stability, and MQ of Marshall tests have been noted when PET, derived from waste plastic water bottles, was integrated into modified SMA and AC mixes [1]. The innovative technique of utilizing waste plastic water bottles as an additive in asphalt mixtures to surface roads and pavements has been recognized as a means to improve road construction, extend the lifespan of road surfaces, and combat environmental pollution caused by improper disposal of such materials [2].

The use of waste plastics in modified bituminous mixes for flexible paving has shown considerable potential in prolonging their useful life or reducing the surface wear layer's thickness [3, 4]. The addition of plastic waste to hot asphalt mixtures has been seen to enhance the characteristics of bitumen, reduce road construction costs, and decrease noise pollution from heavy traffic [5, 6].

The improvement of bitumen by adding plastic waste has been likened to the enhancement of bitumen through polymer usage [7]. It has been suggested that the properties of asphalt concrete may be improved by employing plastic waste as an additive [7]. Further, it was observed that ductile pavements could be constructed by modifying bitumen with polymers [7].

The incorporation of PET in the form of fibers (length: 4-6 mm, diameter: 0.5 mm) at different percentages of the total weight of asphalt, using the wet method, has been shown to improve the properties of bitumen and asphalt mixtures [8]. It was revealed that the inclusion of 30% PET led to optimal stability (31.82 kg) and acceptable flow (16.76) [8].

Inclusion of PET in bitumen at 0-17% by weight has been found to increase viscosity, softening point, specific gravity, flash, and fire points, but reduce ductility and penetration [9]. The mechanical properties of the asphalt binder showed less improvement than classification properties with the use of PET [9]. The process of plastic application, whether dry or wet, did not show significant differences in the improvement of asphalt characteristics and binder [10].

The modified mixture with plastic waste demonstrated lower fatigue, enhanced resistance to permanent deformations, and extended lifespan [11, 12]. Given the environmental challenges posed by non-degradable plastic waste, the necessity to explore its application in improving asphalt mixture properties, due to its polymer content, has been stressed [13]. Experiments have revealed that the optimal percentage of waste is 9% of the optimal percentage of asphalt 5.1, leading to a 24% increase in stability compared to the traditional mixture [13].

The use of thicker, longer PET fibers with a rough surface has been seen to improve the hardness of asphalt mixes at various temperatures [14]. Utilizing the findings of the dynamic shear rheometer, the performance of modified asphalt paving was modeled by adding PET using AASHTO Ware Pavement ME Design software [15]. The inclusion of 2% PET was found to extend the service life of the paving by a year, and 4% PET by 8 years [15].

PET has been found to significantly alter the rheological behavior and stiffness of the binder under high temperatures [16]. Under testing temperatures of both 5 and 25℃, PET improved fatigue behavior and reduced the stiffness of the mix [17]. DSR findings demonstrated that PET treated samples were superior in minimizing rutting deformation and the asphalt's sensitivity to deformation and cracking at high temperatures [18].

The combination of aggregate with waste plastic and the addition of recommended asphalt content showed a significant effect on the effectiveness of the resultant mix. The outcomes demonstrated improvements in tensile strength, moisture damage, and permanent deformation [18].

The inclusion of waste plastic has been observed to contribute to increased stiffness and rut-resistance in asphalt. By integrating Polyethylene Terephthalate (PET), derived from waste plastic water bottles, into modified Stone Matrix Asphalt (SMA) and Asphalt Concrete (AC) mixes, notable enhancements in Marshall flow, Marshall stability, and MQ of Marshall tests were observed [1]. This innovative application of waste plastic bottles presents a groundbreaking technique for improving road construction, extending the lifespan of road surfaces, and combating environmental pollution caused by improper disposal of such materials [2].

The integration of waste plastics into modified bituminous mixes for flexible paving has demonstrated promising potential for extending the lifespan of pavements or reducing the thickness of the surface wear layer [3, 4]. The addition of plastic waste to hot asphalt mixtures has shown to enhance the properties of bitumen, reduce road construction costs, and mitigate noise pollution from heavy traffic [5, 6].

The enhancement of bitumen by adding plastic waste has been likened to the improvement achieved through polymer usage [7]. Studies have suggested that asphalt concrete properties can be improved by using plastic waste as an additive [7]. Moreover, it was noted that ductile pavements could be constructed by modifying bitumen with polymers [7].

Incorporating PET in the form of fibers (with lengths of 4-6 mm and a diameter of 0.5 mm) at varying proportions of the total weight of asphalt, using the wet process, has been seen to enhance the properties of both bitumen and asphalt mixtures [8]. Optimal stability (31.82 kg) and acceptable flow (16.76) were achieved with the inclusion of 30% PET [8].

The addition of PET to bitumen at 0-17% by weight has been found to increase viscosity, softening point, specific gravity, flash, and fire points, while reducing ductility and penetration [9]. PET was found to be more beneficial in enhancing the classification properties than the mechanical properties of the asphalt binder [9]. The method of plastic application, whether dry or wet, did not significantly alter the improvement in asphalt characteristics and binder [10].

Modified mixtures with plastic waste exhibited lower fatigue, enhanced resistance to permanent deformations, and a longer lifespan [11, 12]. Given the significant environmental challenges posed by non-degradable plastic waste, it's crucial to explore its potential in enhancing asphalt mixture properties due to its polymer content [13]. The optimal waste percentage was discovered to be 9% of the optimal asphalt percentage of 5.1, resulting in a 24% increase in stability compared to traditional mixtures [13].

The use of thicker, longer PET fibers with a rough surface has been seen to enhance the hardness of asphalt mixes at various temperatures [14]. The dynamic shear rheometer (DSR) findings were used to model the performance of modified asphalt paving by adding PET, using AASHTO Ware Pavement ME Design software [15]. The inclusion of 2% PET was found to extend the service life of the paving by a year, while 4% PET increased it by 8 years [15].

PET significantly affects the rheological behavior and stiffness of the binder under high temperatures [16]. Under testing temperatures of both 5 and 25℃, PET improved fatigue behavior and decreased the stiffness of the mix [17]. DSR findings showed that PET treated samples excelled in minimizing rutting deformation and mitigating the asphalt's sensitivity to deformation and cracking at high temperatures [18].

The combination of aggregate with waste plastic and the addition of recommended asphalt content significantly impacted the effectiveness of the resultant mix, demonstrating improvements in tensile strength, resistance to moisture damage, and permanent deformation [18]. Asphalt mixes modified using waste plastic bottles demonstrated greater stability than standard mixtures at lower percentages, though this difference diminished as the plastic content increased [19].

When plastic waste was added to the asphalt binder, viscosity was enhanced, hence it is projected that the stiffness will increase, improving its resistance to rutting at operational temperatures [20].

Previous studies have shown that adding plastic waste to the asphalt mixture of various types has multiple benefits, including:

1. Increasing the bonding strength between the components of the mixture.
2. Strengthening fatigue resistance resulting from high strains applied to the asphalt mixture.
3. Stiffening mix and binders at high temperatures to minimize rutting.
4. Reducing the cost of maintenance work.
5. Ridding the environment of pollutants.
6. Strengthening the durability of asphalt paving roads.
7. Reducing thermal cracks.

In this study, waste plastic water bottles, specifically Polyethylene Terephthalate (PET), were used as an additive to enhance the engineering properties of asphalt mixtures (surface asphalt layer). The waste plastic was shredded into small fragments (between 2.36 and 1.18 mm) and added to the mixture in varying weight ratios to the bitumen. The goal of this research was not only to explore the potential for improving the engineering properties of asphalt mixtures, but also to offer a cost-effective means of waste disposal and recycling. Ultimately, this study aims to provide valuable insights to those involved in construction industries, particularly asphalt production plants, with the overarching objective of enhancing road performance in an economical and sustainable manner.

2. METHODOLOGY

The work was divided into two sections for this investigation. After a series of laboratory tests on samples created in accordance with the Iraqi standard standards for the surface layer of roads and bridges, the ideal proportion of asphalt was first determined [21]. In the second stage, samples of the modified asphalt mixture were created using varying amounts of used plastic water bottles, and these samples were then put through a Marshall test to see how these residues affected the mixture's engineering capabilities. Figure 1 depicts the different phases of the work.

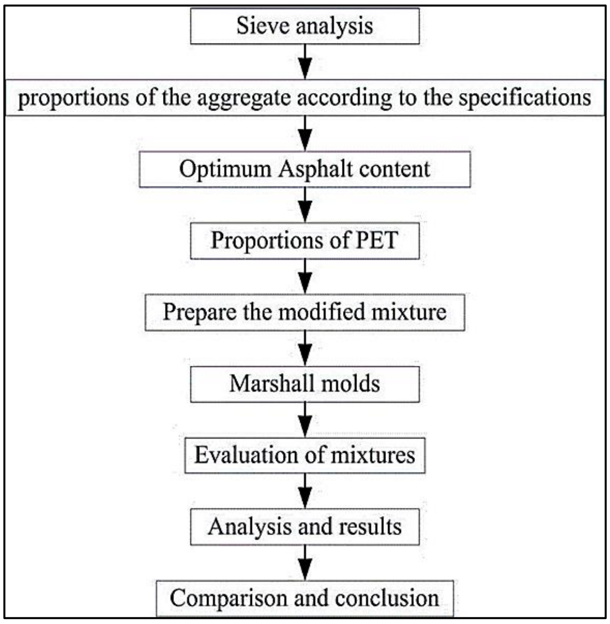

Figure 1. Flowchart diagram of work stages

3. MATERIALS

Durability is defined as the ability of the asphalt mixture to withstand environmental influences represented by water, air, and traffic erosion. To achieve this, the aggregates in the asphalt mixture must be covered with a sufficient amount of asphalt cement to ensure adhesion and cohesion between the aggregates. To enhance the durability, waste plastic water bottles were utilized, and their impact on the properties of the asphalt mixture was investigated.

The outcomes of laboratory tests showed that adding the plastic greatly improved the mixture's effectiveness and workability [11]. For the success design of the asphalt mixture, the materials that it is composed of must be investigated for their physical properties and compared to the standard specifications. All of the materials used were found locally and are widely available. Below is a detailed explanation of these materials.

3.1 Asphalt binder

Binder asphalt is a resinous substance that binds the components of the aggregate to each other. It is a heavy and thick residue that results from the refining of crude oil. The physical properties of asphalt change significantly with temperature variations. For example, the asphalt is brittle at a temperature below zero, whereas it behaves more like a soft rubber at room temperature. At higher temperatures, it has the form of a low fluid consistency [13]. In this study, asphalt with a gradient of (40–50) was chosen, it is the most commonly used in Iraq and is suitable for climatic conditions of high temperatures, which is obtained from the crude oil refinery in Al-Daurah, south-west of Baghdad. Tests based on the Iraqi standards SCRB, R/9 [21] and ASTM criteria were used to determine the asphalt's physical characteristics, as stated in Table 1.

Table 1. The physical properties of asphalt cement

Properties	Stander Test	Results	SCRB. Requirements
Penetration (1/10) mm	(ASTM-D5, 2015) [22]	46	40-50
Flash Point, °C	(ASTM-D92, 2015) [23]	254	>232
Softening Point, °C	(ASTM-D36, 2015) [24]	52	---------
Ductility, cm	(ASTM-D113, 2015) [25]	120	>100
Specific Gravity -----	(ASTM-D70, 2015) [26]	1.02	1.01-1.05

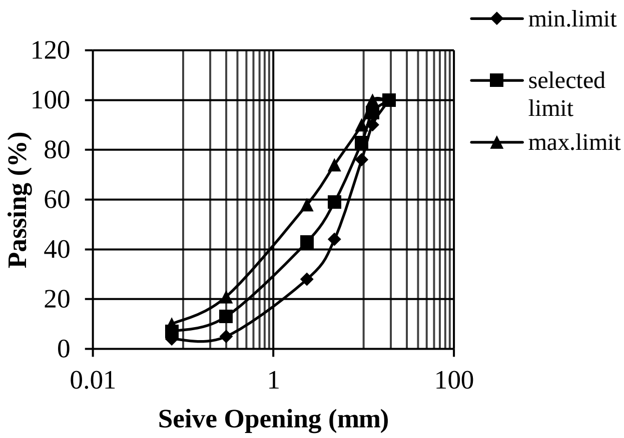

Figure 2. Gradation of the aggregate

Table 2. Physical properties of the aggregate

Type of Aggregate	Properties	Results	ASTM
Coarse	Apparent Specific Gravity	2.64	ASTM-C127
	% Water Absorption	1.39	ASTM-C127
	% Wear (Los-Angeles Abrasion)	23	ASTM-C131
Fine	Apparent Specific Gravity	2.65	ASTM-C128
	% Water Absorption	2.6	ASTM-C128
Filler	% Passing Sieve No. 200	95	ASTM-C117
	Specific Gravity	3.02	ASTM-C188

3.2 Aggregate

Aggregate are stone grains of different sizes ranging between 50 mm and 0.075 mm, and it constitutes approximately 95% of the total weight of a dense graded asphalt mixture. In this study, coarse crushed aggregate brought from Al-Nabai quarry, north of Baghdad, was used, while sand from Al-Ukhaidir quarry in Karbala was used as a fine aggregate. For the filler, ordinary Portland cement was used. The gradation of the aggregate was chosen according to the requirements of the Iraqi standard specifications for roads and bridges for the surface layer, as shown in Figure 2. Table 2 displays each of the aggregate's physical characteristics

3.3 Polyethylene Terephthalate (PET)

PET is a thermoplastic polymer used in the manufacture of bottles for water, liquids, and food containers. It exists in the form of a non-crystalline (transparent) and semi-crystalline material. 60% of the global production of Polyethylene Terephthalate is used in the manufacture of synthetic fibers known as polyester, while 30% is used to make bottles. It has a density of 1.38 gm/cm^3, a melting point of greater than 250℃, and a boiling point of greater than 350℃. It is possible to recycle it. In study, waste of plastic was chosen over other materials for several reasons:

- It is a thermoplastic polymeric material that improves the flexibility of the asphalt mixture.
- A method to achieve sustainability, as it is one of the widely spread environmental pollutants.
- Economical works to reduce road maintenance costs by improving performance of asphalt roads.

4. SPECIMEN PREPARATION

The first step is to determine the optimum percentage of asphalt using a Marshall mix design in accordance with ASTM-D1559 [27]. To achieve this, different percentages of asphalt (4–6) were used with an increment period of 0.5. By using a prior gradation of the aggregate based on the Iraqi standard specifications SCRB/R9 for the surface layer, three samples were prepared for each percentage of the asphalt ratios used. The results show that the optimum percentage of asphalt used to prepare the unmodified asphalt mixture is 4.8, as shown in the Table 3.

Table 3. Iraqi standard specifications for preparation of asphalt mixture

Sieve Size		Selected Limits	Accumulative Retained	Retained	Specification Limits	Weight
Inch	mm	Passing %	%	%	Passing %	gm
¾	19	100	0	0	100	0
½	12.5	95	5	5	90-100	57.12
3/8	9.5	83	17	12	76-90	137.10
No.4	4.75	59	41	24	44-74	274.18
No.8	2.36	43	57	16	28-58	182.78
N0.50	0.30	13	87	30	5-21	342.72
No.200	0.075	7	93	6	4-10	68.54
Asphalt content 4-6 % by total weight of mix. Used optimum asphalt content=4.8%.						

The second stage consists of making samples of the modified asphalt mixture by adding different percentages of ground PET residues 0%, 3%, 6, 9% and 12% of one size (2.36-1.18) mm as a partial replacement of the fine aggregate using the dry process, these ratios were chosen to achieve a wide range than previous studies. Ben Zair et al. [28] have demonstrated that the melting point of PET is very high, up to 250℃ but that, when mixed with asphalt using the wet method, it does not maintain its homogeneity in the asphalt mixture. Thus, when adding PET to the asphalt mixture, the majority of applied studies advise using the dry approach. In order to incorporate the PET residues, the aggregate mixture was heated to between 140℃ and 170℃. Before to adding hot asphalt and mixing until all of the aggregates are coated with asphalt, the heated aggregate is first covered with plastic trash to strengthen the binding. To meet the criteria of the standard specification, a Marshall impact compactor was utilized to crush the material with an effort of 75 hits per face at a temperature of (110–125℃), which was meant to depict significant traffic flow. The samples were then evaluated for volumetric and Marshall Stability using a computerized Marshall testing apparatus.

5. MARSHALL CHARACTERISTICS FOR MODIFIED AND CONVENTIONAL MIXTURES

With regard to its importance in performance, the optimum asphalt content must be determined with regard to its importance in performance. This optimum level affects the paving's durability, hardness, and strength, and it has a role in the emergence of distresses, such as cracks, fatigue, and permanent deformations. To achieve this, the Marshall method was used to produce the asphalt mixture in accordance with ASTM D-1559. In order to determine the average value of Marshall stability, flow, stiffness, air void, and bulk density, fifteen cylindrical Marshall samples—three samples for each asphalt content level—were constructed. It was discovered that 4.80% was the optimal asphalt content (OAC) for the typical asphalt mix. Trash water bottles made of plastic were gathered from nearby homes and marketplaces, cleaned, and broken into small pieces before being ground up and sieved through (2.36-1.18) mm. 15 cylindrical Marshall samples were created with varied PET percentages, including 0%, 3%, 6%, 9%, and 12% by weight of OAC, at 4.80% OAC. Table 4 lists every attribute of the samples analyzed for the modified and conventional mixes [4].

Table 4. Characteristics of Marshall samples

PET (%)	Stability (KN)	Flow (mm)	Bulk Density (Gm/mm)	Air Void (%)	Stiffness (KN/mm)
0	9.50	3.6	2.361	4.7	2.64
3	11.00	3.4	2.358	4.21	3.24
6	12.70	3.1	2.352	3.53	4.10
9	13.80	2.9	2.347	3.7	4.76
12	11.32	3.0	2.334	4.4	3.77

6. IMPACT OF PET ON MARSHALL PROPERTIES AND DISCUSSION

The resistance of asphalt materials to deformation, retardation, displacement, and shear stresses has a significant relationship with Marshall Stability. The stability results mainly from internal friction and cohesion. Internal friction is the interlocking resistance of aggregates, while cohesion is the binding force of the bonding material. Because asphalt surfacing and paving are subject to heavy traffic loads as well as climatic influences, it is necessary to adopt an asphalt material with good stability and flow ability. For this reason, this study was developed to improve the Marshall characteristics by adding waste plastic water bottles, and the following is a narrative to discuss and analyse what was achieved.

Figure 3 demonstrates that the Marshall stability of the modified mixture rises as the amount of PET increases up to 9%, reaching a maximum stability value of about 13.8 KN, before it starts to decline at a larger percentage of waste water plastic bottle material at 12%. A value of (R2) demonstrates that for all percentages, the rise in stability is in excellent accord with the rise in PET content. This implies that there is an improvement in the bonding and adhesion between the aggregate particles and the asphalt binder, which indicates an improvement in the asphalt mixture's strength and, consequently, the stability of the asphalt surface when it is actually used.

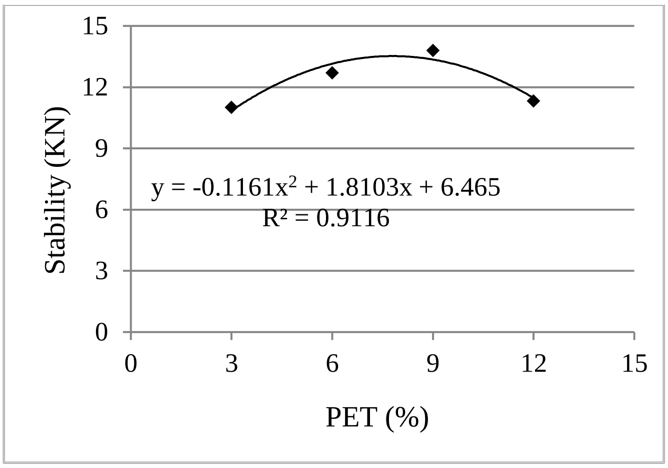

Figure 3. PET Percentage vs. stability

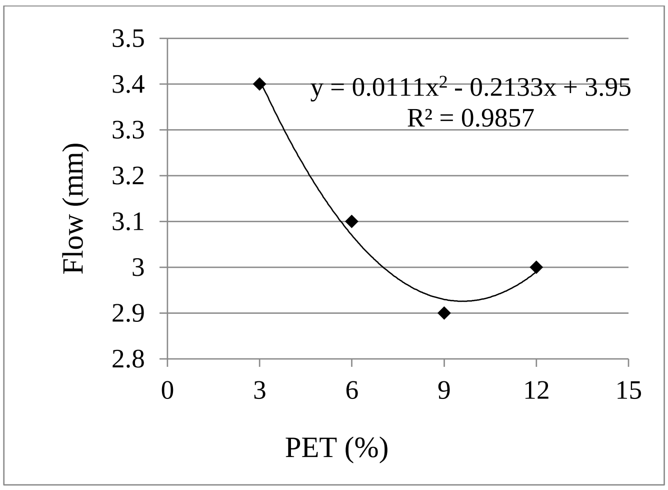

Figure 4. PET Percentage vs. flow

Figure 4 demonstrates that for all percentages of PET, the flow in the modified asphalt mixture was less than that in the standard asphalt mixture. Also, Figure 5 demonstrates that the bulk density of the modified asphalt mixture falls as the PET concentration rises, which translates to a loss in bulk density of almost 1.14% when compared to a standard asphalt mixture.

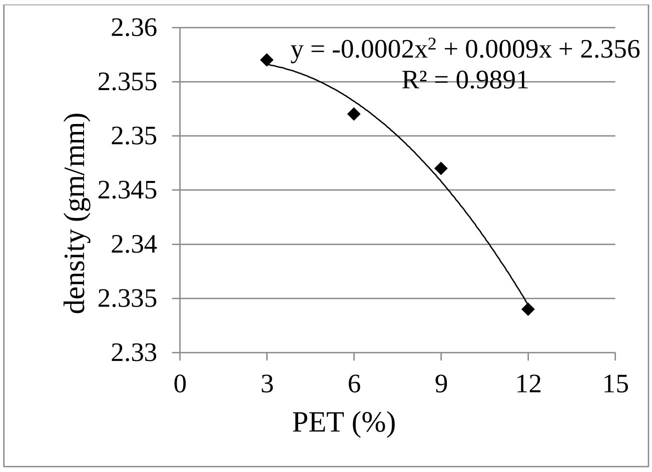

Figure 5. PET Percentage vs. density

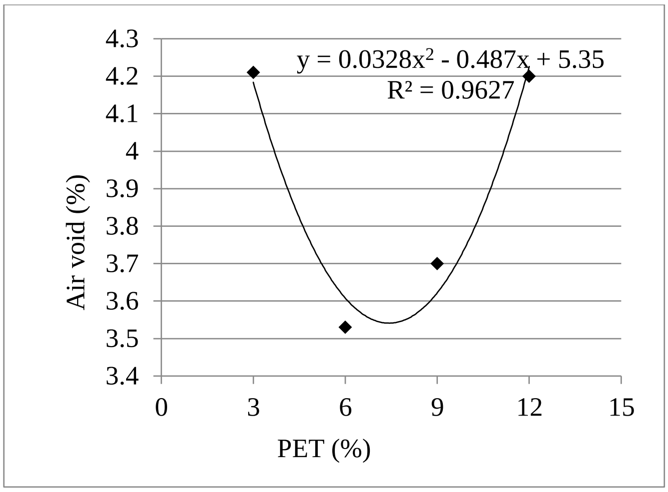

Figure 6. PET Percentage vs. air void

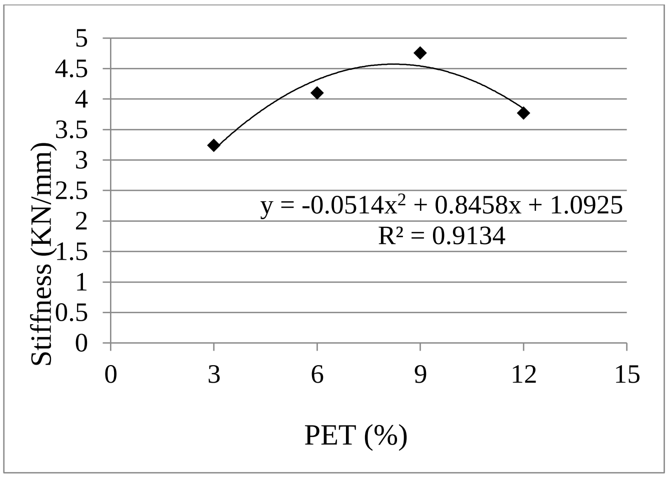

Figure 7. PET Percentage vs. stiffness

Figure 6 demonstrates that the amended asphalt mixture had a lower percentage of air spaces than the standard asphalt mixture. Also, as the PET content rises to 9%, then rises to 12% PET content, the proportion of air void reduces. All air void percentages were within the Iraqi standard specifications for roads and bridges. In Figure 7, the stiffness increases as the PET level rises, reaching a high of 4.76 at 9% before declining again at 12%. Every time, the stiffness values of the modified mixture are greater than those of the standard mixture, demonstrating an increase in the asphalt mixture's qualities that makes it more stable and able to withstand stresses brought on by traffic loads and environmental factors.

7. COMPARISON OF RESULTS OF THE MODIFIED AND CONVENTIONAL ASPHALT MIXTURES

A comparison was made between the conventional and modified asphalt mixtures with the optimum content of PET. the optimum content of PET can be calculated based on a set of controls represented by the maximum stiffness level and percentage of air void within the scope of the standard specifications and the maximum stability level. From Figures 3, 6, and 7, it is possible to deduce the value of the optimal content of PET by taking the average of three ratios as being equal to 7.77% which meets the requirements of improving the properties of asphalt mixture with applicable specifications for surface layer as shown in equation below.

$$Optimum\ PET\ Content = \frac{8+7.5+7.8}{3} = 7.77 \quad (1)$$

where, the maximum stiffness at 8% PET, air void at (7.5%) PET, and maximum stability is found at (7.8% PET). Through the review of previous studies, the results showed that the ideal content of waste plastic is 6-8% [4], it was noted that it is closed to this study. A comparison between the results of the modified mixture with an optimal content of PET and the conventional asphalt mixture is tabulated in Table 5.

Table 5. Comparison of results for (7.77 %) PET & conventional mix

Properties	Con. Mix	Mod. Mix	SCRB/R9	Change %
Stability (KN)	9.5	13.5	min, 8	+42.10
Flow (mm)	3.6	2.95	2-4	-18.05
Air Void (%)	4.7	3.57	3-5	-24.04
Bulk Density (gm/cm^3)	2.361	2.349	-------	-0.50
Stiffness (KN/mm)	2.64	4.5	-------	+70.45

8. CONCLUSIONS

Drawing upon previous studies, tests, and laboratory results of asphalt mixtures modified with the addition of waste plastic water bottles in varying proportions, the following conclusions can be made:

The optimal content of Polyethylene Terephthalate (PET) for the modified mix is found to be 7.77%. This percentage is identified as a critical factor in enhancing the properties of the asphalt mixture for the surface layer, based on the proportions and components of the mixture. The use of this optimal PET content results in a 42.10% increase in stability compared to the conventional mixture, indicating an improvement in the bonding strength among the components of the mix. Furthermore, an overall enhancement in stability over the conventional mixture was observed for all amounts of PET added to the modified mixture.

The increase in stiffness for the modified mixture at the optimal PET ratio reached 70.45%, which suggests enhanced resistance to deformations in the asphalt mixture during its service life. In addition to these improvements, there was a decrease in bulk density by 0.5%, a reduction in flow by 18.05%, and a decrease in air voids by 24.04%.

These findings strongly support the assertion that the addition of waste plastic water bottles to the asphalt mixture can improve stability values and reduce flow. The study offers theoretical insights on how to leverage plastic waste in an economical and sustainable manner within asphalt mixtures and invites future research on the inclusion of other materials.

In this investigation, the determinants of the Marshall test, the type of asphalt, the size of the improver, and the method of its addition were considered. It is recommended that future studies explore advancing asphalt pavement performance by conducting tests for rutting and resistance to permanent deformation.

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