Mechanical Properties of Polyethylene Terephthalate-Modified Pavement Mixture

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Abstract. Utilization of by-product or waste materials in paving structure may provide environmental and economic advantages. Accordingly, in this experimental study, the waste polyethylene terephthalate (PET) polymers, shredded water bottles, was used in hot mix asphalt (HMA) preparation. The HMA’s mechanical properties were inspected by means of Marshall Stability, volumetric characteristics, Indirect Tensile Strength Test, and Tensile Strength Ratio. The laboratory test results revealed a significant enhancement in mechanical performance, especially in moisture damage resistance results.

1. Introduction
The development of technology alongside the modern lifestyle encourage plastic materials production. Unfortunately, most of the plastics are non-biodegradable materials which means they will stuff in dump places for hundreds or thousands of years [1]. The presence of non-disposable materials alongside population growth has led to the global environmental crisis. A kind of plastic is Polyethylene Terephthalate or 'PET'. It is a polyester type made from ethylene glycol and terephthalic acid’s composition [2]. PET production evolves as a significant innovation at the end of the 19th century. Its usage is widespread in the packaging industry as well as the citizen-consumers demand, due to its high stability, non-reactivity with substances, high-pressure tolerance, and gas trapping ability to preserve gaseous beverages [3]. To dispose of such materials, burial, incineration, or recycling methods may be used to diminish the waste problem. However, these materials slowly decompose and may produce poisonous gasses during combustion. Thereby, recycling is an environmentally compatible and economically beneficial solution [4].

Recycling waste PET bottles as pavement modifiers have received much attention from researchers in the last decade. For instance, Moghaddam et al., 2013 [5] investigated adding different dosages of waste PET as a partial replacement of aggregate with different asphalt content. While, Mosa, 2017 [6] partially replaced fine aggregate, passing from sieve 2.36mm, with waste PET. Moreover, Rassol, 2017 [7] utilized PET in the pavement as a crushed powder to behave like a filler, and Awaeed et al., 2015 [8] used it as additive. In addition to Jegatheesan and Rengarasu, 2018 [9] who used PET in the wet process as partial replacement of asphalt binder. They stated, after their visual observation, that a layer of the added PET floats over the asphalt binder due to lack of homogeneity. Other researchers followed optimization techniques to evaluate and optimize asphalt mixture components with PET, in terms of Marshall stability [10], stiffness modulus [11], fatigue [12], and rutting [13]. Basically, most of the aforementioned researchers have preferred using PET in the dry process (adding PET to aggregate)
rather than the wet process, considering its high melting point. Researchers who used PET as partial replacement of fine aggregate get negative results. In contrast, partial replacement of asphalt binder with PET can improve flexible pavement characteristics to a specific amount. Then, extra-addition of PET may worsen the pavement condition.

2. Research Objective
This research aims to assess the mechanical and physical properties of asphalt concrete pavement modified by waste polyethylene terephthalate (PET). For this purpose, a series of tests have been conducted for the control and the modified specimens with different percentages. These tests are Marshall Stability and flow, volumetric properties, Indirect Tensile Strength, and Moisture Damage.

3. Materials and Tests

3.1. Materials
Laboratory tests were conducted for five different mixture types, by adding five different dosages of PET. The materials used in this study were tested with traditional laboratory tests. The results were acted in accordance with the Iraqi`s standards, which implemented by the State Commission of Roads and Bridges (SCRB-R9) [14].

3.1.1. Aggregates. A crushed quartz aggregate, brought from Al-Nibaee quarry which is mostly used for Iraqi`s paving structure, was utilized in this work. The physical properties of the selected aggregate besides the designated aggregate gradation for wearing layer IIIA [14] are displayed in Tables 1 and Fig.1 respectively.

| Property                           | ASTM Designation | Coarse Aggregate | Fine Aggregate |
|------------------------------------|------------------|------------------|----------------|
| Bulk Specific Gravity             | C127, C128       | 2.62             | 2.63           |
| Apparent Specific Gravity         | C127, C128       | 2.69             | 2.68           |
| Percent Water Absorption          | C127, C128       | 0.49             | 0.61           |
| Percent Wear, Los-Angeles Abrasion| C131             | 27.1             | ---            |

Figure 1 Aggregate Gradation for Wearing Layer IIIA

3.1.2. Asphalt Binder. The most common type of asphalt binder used for highways construction in Iraq is 40–50 penetration grade. This type of asphalt, brought from Al-Durah Refinery, was used for this
research. Table 2 presents the physical properties of this asphalt cement which complies with the Iraqi’s specifications (SCRB/R9) [14].

Table 2. Physical properties of asphalt binder

| Property               | Test Conditions       | ASTM Designation | Test results | Specification |
|------------------------|-----------------------|------------------|--------------|---------------|
| Penetration (0.1 mm)   | 25°C, 100gm, 5sec.    | D5               | 44.5         | 40-50         |
| softening point (°C)   | Ring and Ball         | D36              | 50.5         | 50-60         |
| Ductility (cm)         | 25°C, 5cm/min.        | D113             | 100          | >100          |
| Specific gravity       | 25°C                  | D70              | 1.013        | ---           |
| Flash point (°C)       | Cleveland Open Cup    | D 92             | 309          | >232          |

3.1.3. Mineral Filler. An ordinary Portland Cement, having a specific gravity of 3.01 and 96% passing from sieve No.200, were used for this investigation.

3.1.4. Polyethylene Terephthalate. Polyethylene terephthalate (PET), which is the most common type of waste plastic that is found almost everywhere, is a quasi-crystalline thermoplastic polymer. It is a polyester material with a smooth surface that is recognized as a clear, light translucent, safe, chemical resistant, effortlessly formation and cost-effective material [2]. PET properties are presented in Table 3. In this research, waste PET has been acquired from PET plastic water bottles that were cut into small slices, passing through a 2.36 mm sieve. Five various dosages of shredded PET were utilized in this research, are: 0%, 2.5%, 5%, 7.5% and 10% by weight of asphalt. It is decided to select the additive as a partial replacement of asphalt cement as recommended by [5], [8], [9], [15] Since the addition of waste plastic, in general, reduce the amount of optimum asphalt content. This may be due to its lower absorption tendency as compared to aggregate.

Table 3. Properties of Polyethylene terephthalate (PET) [10]

| Properties                | Description                                      |
|---------------------------|--------------------------------------------------|
| Chemical Compounds        | Terephthalic acid, and Ethylene glycol           |
| Chemical formula          | \((C_{10}H_{8}O_4)_n\)                          |
| Density                   | 1.38 gm/cm³                                      |
| Melting point             | >250 °C                                          |
| Boiling point             | >350 °C                                          |
| Thermal Conductivity      | 0.15-0.24 W m⁻¹ K⁻¹                              |

3.2. Testing Program

The asphalt paving mixtures were basically prepared according to the ASTM Designation D 6926-16 [16]. The prepared aggregate and mineral filler in addition to the specified portions of shredded PET have been heated inside a thermostatic oven at 170 °C, whereas the asphalt binder has been heated at 150°C. Then, they all mixed together at 160±5°C for 5 minutes. All samples have been compacted by an automatic compactor for the standard 75-blows/side.

A number of testing procedures were directed to assess the mechanical and volumetric characteristics. These properties have been assessed by Marshall Stability and flow, Indirect Tensile Strength (ITS), and Tensile Strength Ratio (TSR).

Three specimens for each combination were prepared and tested. The average results have been reported.

3.2.1. Marshall Stability and flow. In order to indicate Marshal Stability (MS) and flow on PET modified asphalt mixture, a procedure described in ASTM D6927-15 [17] and AASHTO T-245 [18] was followed. These specifications are designed to assess the plastic flow resistance of cylinder-shaped Marshall samples of 63.5 mm height and diameter of 101.6 mm. for the asphaltic concrete mixture. The
specimen, at a temperature of 60 °C, is loaded, at a steady rate of 2 in. /min (50.8 mm/min), on its lateral surface by Marshall apparatus until the maximum load is reached. The maximum resisted load with the concurrent deformation records is reported as Marshall Stability and flow respectively.

3.2.2. Volumetric properties. The bulk density for PET modified pavement mixtures was tested according to ASTM D2726-19 [19], while, Air Voids, Voids in Mineral Aggregate, and Voids Filled with Asphalt were calculated according to ASTM D3203-17 [20], AASHTO T-269 [21], and AASHTO T-166 [22].

3.2.3. Indirect tensile strength. The Indirect Tensile Strength, ASTM D 6931-17 [24], is a performance test. It is usually conducted to assess the splitting tensile strength of a cylinder-shaped specimen. This test is conducted by loading the specimen diametrically with a steady rate of 2 in. / min (50.8 mm/min) to generate a tension force along its loaded diameter. The maximum indirect tensile strength (ITS) is expressed by Eq(1):

\[ ITS = \frac{2000 \times P_{\text{max}}}{\pi H D} \]  

Where: \( P_{\text{max}} \) represents the maximum applied load, KN, \( H \) is the specimen’s height, mm and \( D \) is the specimen diameter, mm.

3.2.4 Moisture damage. Moisture damage in asphalt mixture refers to the loss of pavement serviceability due to water ingress. ITS test is usually used for the moisture susceptibility evaluation. Tensile Strength Ratio (TSR) is a measure of moisture sensitivity which depicts the loss of adhesion and/or cohesion that occurs due to water intrusion. It is a numerical index of reduced tensile strength. It can be achieved by comparing the indirect tensile strength value of newly cast with duplicate specimens that have been submerged in water for 24h at 60°C. It can be expressed as in Eq (2):

\[ TSR, \% = \frac{ITS_{\text{dry}}}{ITS_{\text{wet}}} \]  

Where: \( ITS_{\text{dry}} \) is the indirect tensile strength of the dry samples, KPa, \( ITS_{\text{wet}} \) is the indirect tensile strength of wet samples, KPa.

A duplicate set of Marshall specimens, modified with PET additives (0, 2.5, 5, 7.5, and 10) % by weight of asphalt, were prepared and allocated into two separated groups. The first ones of modified specimens were submerged inside a thermostatically-controlled water bath at 60°C, for 24 hrs’ time period (conditioned specimens). Thereafter, these specimens were picked up from the water bath and preserved with the uncured specimens (unconditioned specimens) at a temperature of 25°C for 2 hours without soaking. Then, these samples have been tested in accordance with ASTM D 6931-17 [24] for the indirect tensile strength test.

4. Results and Discussions

Firstly, the optimum binder contents for the control mix should be determined in accordance with ASTM D6926-16 [16], the Marshall mix design method. Considering the available and the mostly-used Iraqis aggregate and binder, it is found that (4- 6) % of asphalt binder may cover the optimum content. So, triplicate specimens were cast with these asphalt contents, 4 –6%, at 0.5% intervals, by mass of aggregate. The asphalt content that had the most desirable characteristics, that comply with SCRB,2003 [14], was selected as optimum asphalt content (OAC). As a result, 4.8 is considered as OAC.

4.1. Influence of PET on Marshall Stability and Flow

Marshall Stability (MS) of HMA represents the maximum load that Marshall specimens can sustain, before failure. Whereas, Flow is the corresponding deformation when the load begins decreasing. In addition, by dividing the MS over Marshall Flow, Marshall Stiffness can be attained [25]. Referring to the Marshall test results, it is obvious that the inclusion of PET into the control HMA significantly enhances the strength properties for the PET-modified mixtures, as depicted in Figure 2A. This behaviour may be owing to the semi-crystalline nature of PET, or the high rigidity of the modified binder with PET polymers causing more proper adhesion in the mixture, as compared to the conventional
Thereby, the toughness of the modified HMA is efficiently improved. Additionally, Figure 2 also shows that the MS of PET modified mixture increases up to 7.5% of PET content, and then reduces with increasing PET content. Nevertheless, it still complies with the SCRB [14] of more than 8 kN. The percentage increase in stability value at 7.5% of PET modification as compared to the control mixture is around 10% for the modified HMA. Similarly, Fig 2C. depicts the same trend and improvement in Marshall Stiffness.

Figure 2 B. illustrates that Marshall Flow decreases with PET inclusion. Deflection of PET modified HMA reduces when the PET content is increased up to 7.5%. This may be owing to the higher toughness of the PET-modified HMA. Hence, the flow values of the PET-modified paving mixtures fulfills the SCRB specification requirements [14]. About 26% decrement occurred with 7.5% of PET modification which resulted in greater stability and stiffness with respect to the control mix.

![Figure 2 Influence of PET on Marshall Stability, Flow and Stiffness](image)

4.2. Influence of PET on HMA volumetric properties

The volumetric properties of HMA highly affect the mechanical properties; thereby, their in-field performance. These properties were tested in terms of bulk density, air voids, VMA, and VFA. Fig. 3 depicts these parameters for the conventional and modified mixtures.

4.2.1 Bulk Density. Referring to Fig. 3A, it can be inferred that the relative density of the mixture increase with additional dosages of PET. This may be due to the higher density of PET compared to asphalt binder.

4.2.2 Air Voids. In fact, HMA is a composition of aggregates, asphalt and air voids which are partially filled with asphalt and filler. Excessive air voids in the mix would induce cracking. In contrast, little air
voids would result in permanent deformation and asphalt bleeding [26]. Hence, according to the SCRB requirements [14], air voids should be within (3-5) % to avoid pavement distress. The laboratory test results indicate that air voids decrease with the PET addition into the HMA (Fig. 3B). The mixture density correlates with available air voids in the mix. The addition of the PET into the HMA results in less volume. Thereby, the increment in PET dosage resulted in lower air voids, lower volume and higher density as compared to the control mix.

4.2.3 Voids in Mineral Aggregate. Voids in mineral aggregate (VMA) ensures that the film thickness of asphalt is adequate to protect the in-field paving mixture from abrasion due to the effects of tires and water [2]. The inclusion of PET reduces the VMA of the PET-modified mixture with respect to the conventional mix. Though, VMA of PET modified mixtures still complies with the specification requirements (VMA > 14 [14]). Figure 3C. illustrates the VMA variation with the PET dosage rate.

4.2.4 Voids Filled with Asphalt. A gradual increment results in VFA of the PET modified mixtures with increasing of PET content (Figure 3D) and maintain their values within the specified requirements (70-85) % [14]. VFB refers to the effective volume binder content within the mix which is inversely related to the air voids.

4.3. Influence of PET on Indirect Tensile Strength
The tensile strength represents the material ability to resist cracking. Fig. 4 depicts the ITS test results for HMA at various PET content. A PET increment in asphaltic mixtures reveals greater tensile strength as compared to the control mix, almost a 46% improvement in dry condition, and 66.7% in wet-condition for samples having 10% of PET dosage.
4.4 Influence of PET on Moisture Damage

Moisture damage of a paving mixture is generally owing to multitude factors such as the aggregate mineralogy, interaction between mineral aggregates and binder, air void content in the paving mix, in addition to the binder film thickness [15], [27]. Infield, the water ingress through the small pores of the paved mixture is easier as compared to asphalt, thereby, worsening the interaction of aggregate and the asphaltic film. This would increase with the repetition of vehicles loads. That repetitive vehicular-loading reduces the adhesion bond between aggregates and the asphalt, resulting in moisture damage. The resistance of a paving mixture against moisture intrusion is determined by the tensile strength ratio [27]. It should be more than 80% in order to sustain moisture damage in the field [15]. Additionally, the higher TSR value revealed a better resistance to moisture damage. Laboratory test results indicated that increasing percentage of PET to the HMA improved the TSR from 84 to 96% (Figure 5). Blending 10% by weight of PET in the asphalt mixture via the dry process improves TSR by 12.5% approximately. The moisture resistance ability of PET may be attributed to its stiffing effect on asphalt binder. Therefore, PET can be used as an antistripping agent.

5. Conclusion

A sustainable and economical paving mixture can be obtained by incorporating waste plastic in the conventional paving mixture. In addition, the main points can be reported as the research outcomes:
Blending of waste PET with paving mixture via dry process enhances its mechanical properties, tensile strength resistance, and moisture susceptibility.

Replacement 7.5% of asphalt binder with PET increase mixture stability by 10%, reduce flow by about 26%, as compared to the conventional mix.

Utilizing waste PET up to 10%, by weigh of asphalt, increase bulk density and VFA, and reduce VMA and air voids.

Waste PET can be used as an antistripping agent due to its ability to resist moisture damage by increasing the tensile strength ratio.

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