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Research Article

Investigation of asphalt mixtures with river aggregate, waste glass and PET modification for improved strength and moisture resistance in Iraq

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Abstract

Large quantities of waste plastic and glass are generated annually in Iraq, while the continuous extraction of natural aggregates for road construction increases pressure on natural resources. This study investigates the combined use of locally sourced Iraqi river aggregate, waste glass and waste polyethylene terephthalate (WPET) in asphalt mixtures, an approach that has received limited attention in previous studies. River sand was used as the fine aggregate, while waste glass was used as a partial replacement of fine aggregate at replacement levels of 10%, 20% and 30% by weight. WPET was added 8% WPETto the asphalt binder using the wet process at contents of 4%, 8% and 12% by binder weight. Marshall stability, indirect tensile strength and tensile strength ratio tests were conducted to evaluate the mechanical performance and moisture susceptibility of the mix. Results showed that waste glass improved the Marshall stability up to an optimum replacement level of 20%, before declining at higher replacement levels. Similarly, 8% WPET produced the optimum performance by increasing stability, indirect tensile strength and moisture resistance, whereas increasing the content to 12% reduced the mechanical performance of the mixture. Overall, the combined use of 20% waste glass and 8% WPET produced the optimum asphalt mixture, indicating that the proposed mixtures can enhance asphalt mixture performance. This approach offers a practical solution for constructing asphalt pavement in Iraq.

1. Introduction

The construction industry has been a primary driver for urbanization and economic growth in Iraq but this rapid development has come at the cost of natural resource depletion, it has led to environmental degradation [1]. The ancient Mesopotamian cities of (Ur, Nippur and Uruk) developed along the Tigris and Euphrates rivers, where abundant natural resources supported monumental construction and urban expansion [2]. The conventional extraction of natural aggregates from quarries is no longer sustainable, as it causes significant habitat destruction and high carbon emissions, it poses significant environmental concerns [3, 4]. Consequently, adopting a circular economy in pavement engineering has become essential to promote the use of industrial by-products and waste materials in Iraq road construction [5, 6]. Waste glass and river sand are promising sustainable alternatives to conventional crushed fine aggregates [7]. Furthermore, recycled plastics and glass in asphalt pavements reduce carbon emissions, landfill waste and the consumption of virgin aggregates and bitumen [8-10]. Recent studies indicate that the use of aggregates accounts for approximately 1.8% of global greenhouse gas emissions [11]. Approximately 180 million tons of glass are produced annually worldwide, however, less than 20%

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is recycled, indicating that the present recycling rate remains insufficient and environmentally unsustainable [12]. Their use as polymer additives to enhance the engineering performance of asphalt mixtures has attracted considerable attention in pavement engineering [13, 14]. The use of PET as a binder modifier improves viscosity, stiffness and resistance to rutting, cracking and overall performance, supporting PET recycling in asphalt pavements [15, 16]. Ferreira et al. investigated recycled micro-PET in hot mix asphalt (HMA) and reported enhanced moisture resistance, particularly for regions with heavy rainfall without significantly affecting optimum asphalt content [17]. In Iraq, however, studies on waste glass in HMA remain limited with previous research primarily focusing on its use as a filler [18, 19]. Almuhmdi et al. evaluated the utilization of waste glass (WG) without additives in asphalt mixtures to improve mechanical performance as fillers in asphalt pavements [20]. Reducing waste generation through recycling is essential for long-term environmental protection, supporting resource recovery and **conserving** natural resources within sustainable construction strategies [21-24]. The transport of cores aggregates and fine aggregates from quarries, often located far from city centres, contributes to greenhouse gas emissions. Therefore, it is essential to rely on local resources to lower fossil fuel consumption associated with aggregate production and hauling. Despite increasing interest in sustainable asphalt materials, the combined use of river aggregate, WG and modified asphalt binders remains insufficiently and unexplored, particularly in Iraq. Previous studies have largely investigated individual recycled materials or low replacement levels, with limited attention to their combined application under local conditions. This study addresses this gap by evaluating for the first time in Iraq, the moisture resistance and mechanical performance of asphalt mixtures incorporating high volume river aggregates, WG and PET modified binder. The findings provide a sustainable pavement solution that maximizes local waste utilization while meeting modern pavement performance requirements.

2. Materials and Methods

In this experimental work, asphalt binder and aggregates (crushed and river) were verified per Iraqi standard specification for roads and bridge (SCRB) R/9. In terms of waste materials, utilizing waste plastic bottle and glass debris as additives. A comprehensive laboratory testing program was conducted by using Marshall and indirect tensile strength tests on hot mix asphalt specimens.

2.1. Aggregates and Filler

Coarse aggregate retained on the 4.75 mm sieve was crushed aggregate sourced from the Kerbala quarry, widely used in central and southern regions of Iraq. Fine aggregate that passing the (4.75mm) sieve consisted of stone screenings, crushed fine aggregate from Kerbala quarry, and river fine aggregate sourced from the Euphrates River. Both aggregate types were sieved and recombined to comply with the gradation limits of the SCRB- standard surface course [25]. Routine physical property tests were conducted, with results and SCRB limits summarized in Table 1.

Table 1. Physical properties of aggregates (crushed and river) used in this study.

Property	ASTM Designation	Coarse Aggregate	Fine Aggregate Crushed	River
Bulk (Specific Gravity)	C-(127) C-(128)	2.52	2.66	2.63
Apparent (Specific Gravity)	C-(127) C-(128)	2.66	2.69	2.64
Water Absorption (%)	C-(127) C-(128)	0.85	0.71	0.61
Resistance to Degradation of Coarse Aggregate (Los Angeles Test) (Max 30%)	C-(131)	25 %	…	…
Particle Angularity (Min 90%)	D-(5821)	95%	…	…
Content of Clay Lumps and Friable Particles % (Max 3%)	C-(142)	…	0.22	0.33

(a) (b)

Fig. 1. Illustrative types of fine aggregates used in this study (a)Crushed aggregate, (b) River aggregate

The gradation of the aggregate was selected with specification limits are shown in Table 2. Ordinary Portland Cement (Tasluja) Type(I) was used as the mineral filler, presented in Table 3. The types of fine aggregates are used in present study are illustrated in Figure 1.

Table 2. Grading of the aggregates selected with specification SCRB (type IIIA) [25] and glass materials used in this study

Sieve Size		(SCRB) Specification Limits (%)	Passed Percent (%) Aggregates and Filler	Passed Percent (%) - Glass Material
(19 mm)	(3/4 '')	(100)	(100)	-
(12.5 mm)	(1/2 '')	(90)-(100)	(95)	-
(9.5 mm)	(3/8 '')	(76)-(90)	(83)	-
(4.75 mm)	(No.4)	(44)-(74)	(59)	(100)
(2.36 mm)	(No.8)	(25)-(58)	(43)	(62)
(300 μm)	(No.50)	(5)-(21)	(13)	(18)
(75 μm)	(No.200)	(4)-(10)	(7)	(3)

Table 3. Physical properties of filler (Ordinary Portland Cement (Tasluja)used in the present study

Property	Results
Specific Gravity	(3.12)
Percent Passing Sieve 0.075μm (No.200)	(95%)

2.2. Asphalt Binder

One type of binder was used in this laboratory investigation, it classified as a performance grade (PG70-16) equivalent to penetration grade of (40/50) [26], which had been supplied from AL-Daurah Oil Refinery located in the (south-west) of Baghdad the Capital of Iraq. The physical properties of binder were listed in Table 4. The actual properties of the asphalt binder were verified in accordance with ASTM specification.

Table 4. Physical characteristics of binder according to (ASTM and SCRB) standards limitations [25, 27]

Test	ASTM Standard	SCRB Limitations	Results
Penetration Test (100g, 5sec at 250°C), (0.1) mm	ASTMD5	(40/50)	45
Softening Point Test(°C)	ASTMD36-76	----	54
Kinematic Viscosity Test (1350°C)	ASTM2170	(>350)	384
Ductility Test (5cm/min at 250°C)	ASTMD113	(>100)	110
Flash Point Test (°C)	ASTMD92	(>232)	291
Specific Gravity Test at (250°C)	ASTMD70	----	1.04

2.3. Waste Glass and Polyethylene Terephthalate

Glass is a non-metallic inorganic material primarily composed of silicates and other minor oxides. Due to its brittle nature, waste glass can be easily crushed into small particles suitable for mixing. The specific gravity of waste crushed glasses (WG) about (2.5 g/cm3), low water absorption (0.3%–0.4%) by weight, high thermal stability up to (700°C) and high angularity (indices 12–13) that promotes interlocking despite its smooth surface [28, 29]. For asphalt mixture applications, particle sizes of (4.75mm) or smaller were suitable, the sieve analysis results for WG are presented in Table 2. Local waste plastic bottles, particularly polyethylene terephthalate (PET) are widely used as additive in asphalt mixture applications due to their favorable mechanical and physical properties. PET additive is a thermoplastic polymer characterized by (durability, high strength and resistance at Hight temperature). In this study, waste plastic bottle was collected, cleaned, and ground into small particles < (2.36mm) prior to binder incorporation [30]. Polyethylene terephthalate (PET) has a melting point of (260°C) and a specific gravity of (1.56), which are essential for interpreting its thermal behavior and compatibility within the asphalt mix, PET is recognized as one of the most widely recycled plastic wastes materials [31, 32]. The crushed waste glass (WG) and waste polyethylene terephthalate (WPET), were used in this study were illustrated in Figure 2.

(a) (b)

Fig. 2. Illustrative types of waste are used in the study (a): Crushed waste glass (WG) and (b): Waste polyethylene terephthalate (WPET)

2.4. Sample and Mix Preparation

In Iraq, the conventional surface layer for asphalt pavement is commonly constructed using HMA. A systematic experimental program was conducted to prepare and evaluate asphalt mix, Initially, the conventional crushed fine aggregate (CFA) was completely replaced with river fine aggregate (RFA) at (100%), and the Marshall properties were determined to identify the optimum mixture (control mix). The optimum binder content (OBC) was determined as (4.7%) for the RFA mixture and (5%) for the CFA mixture by evaluating the mechanical and volumetric response of the RFA and CFA mixtures. As summarized in Table 5. These empirical results governed by SCRB criteria, provide the quantitative basis for establishing the design asphalt binder content for both fine aggregates types. Based on the selected mix design, WG was incorporated as a partial replacement of the RFA fraction passing the (4.75 mm) sieve at three different percentages (10%, 20% and 30%) by weight of total river fine aggregates. In addition, particles of waste polyethylene terephthalate (WPET) were introduced into the asphalt binder at three dosage levels to assess its modifying effect. Marshall specimens were then prepared using standard dimensions and compaction procedures, consistent with those used in the indirect tensile strength (ITS) test, to evaluate the influence of moisture susceptibility performance of the mixtures. In this research, the asphalt binder was heated to (160°C), after which WPET particles were added at the specified percentages by binder weight. The WPET-modified binder was prepared using the wet process and blended with a high-shear mixer at (1100rpm) for (120min) at (160°C) to ensure complete dispersion and homogeneity [30, 32]. Separately, the river aggregates and WG were oven dried to eliminate moisture before WG was incorporated as a partial replacement for the fine aggregate fraction using the dry process. The aggregate–WG blend was then mixed with the PET-modified binder at (160°C) for at least (3min) or until all particles were uniformly coated and a homogeneous asphalt mixture was obtained [19, 28]. In the indirect tensile strength test and for Marshall test the dimension of samples with a diameter of (102mm), and with a height of (64mm).

Table 5. Marshall design results and OBC determination in the present study

Marshall Properties	CFA- Mixture	RFA- Mixture	SCRB Criteria
Stability- (KN)	10.3	7.2	8 min
Flow - (mm)	3.12	3.78	2 - 4
Air Voids - (%)	4.3	4.0	3 - 5
Binder Content - (%)	5.0	4.7	4-6

2.5. Laboratory Testing Program

The performance of the asphalt mix was evaluated by using standardized laboratory testing methods, included the Marshall test and moisture susceptibility test

2.5.1. Marshall Stability Test

To evaluate characteristics of hot mix asphalt incorporating waste glass, with and without waste Polyethylene terephthalate, Marshall stability test was conducted in accordance to ASTM (D1559). Cylindrical specimens were prepared using a standard compacted hammer and a cylindrical mold. Prior to testing, the samples were conditioned in a water bath at (60°C) for (30minutes) and tested for deformation resistance under a constant loading rate of (50mm/min). This standardized method was employed to determine key performance parameters, thereby providing a reliable assessment of the load-bearing capacity of the asphalt mix [33].

2.5.2. Moisture Susceptibility Test

The present study, moisture susceptibility of the hot asphalt mixtures was investigated by using the tensile strength ratio (TSR) in accordance with (AASHTO: T283) [34]. This method evaluates the resistance of asphalt mixtures to moisture damage by comparing the indirect tensile strength (ITS) before and after a water-conditioning (conditioned specimens (wet case) and unconditioned specimens (dry case)). Cylindrical samples were prepared and compacted to standard dimensions, then divided into two groups unconditioned tested at (25°C) and conditioned were immersed in water bath at (60°C) for (24hours) and subsequently tested at (25°C) to simulate field moisture effects (moisture susceptibility). In this test was performed by applying a compressive load along the specimen diametral plane at a constant deformation rate until its failure, inducing tensile stresses perpendicular to the loading direction by using a digital Marshall testing apparatus presented in Figure 3. The ITS was calculated from the highest stress calculated from the peak load at failure. TSR was determined as the ratio of the average ITS of conditioned samples to that of unconditioned samples. Higher TSR values indicate improved resistance to moisture damage and improved durability of the hot asphalt mix (HMA). The ITS was calculated by using equation1.

$$ITS = \frac{2\,P}{\pi\, t\, D} \tag{1}$$

In this equation, [ITS] represents the indirect tensile strength (kPa), [P] is Peak Load at failure (KN), [t] is the sample thickness (cm) and [D] is the sample diameter (cm). Moisture susceptibility or the stripping potential of HMA, is determined by using equation2 as the ratio of the average indirect tensile strength of conditioned (wet case) specimen to unconditioned (dry case) specimen.

$$TSR = \frac{ITS\ wet}{ITS\ dry} \times\ 100 \tag{2}$$

In this equation, [TSR] represents the tensile strength ratio (%), [ITS_{wet}] represents the mean indirect tensile strength of the wet-conditioned specimen (kPa) and [ITS_{dry}] represents the mean indirect tensile strength of the dry-unconditioned specimen (kPa) [35].

Fig. 3. Illustrative indirect tensile strength test

3. Results and Discussion

3.1 Marshall Stability

The Marshall stabilities result for both hot mix glass asphalt (HMGA) and WPET-modified mixtures are shown in Table 6, while the comparative trends are graphically presented in Figure 4. The experimental data reveal that the incorporation of waste glass (WG) as a partial replacement for river fine aggregates yields a discernible improvement in Marshall stability compared to the conventional asphalt containing zero WG. Stability values of (HMGA) to comply with Iraqi standards specification limits (SCRB/R9) for the surface layer, which determined the minimum allowable limit by (8kN) [25]. This improvement is further augmented by the introduction of WPET through the wet process method, where Marshall stability reached a peak value of (10.6KN) at an optimum WPET content of (8%). Further increases in the WPET and WG contents, the hot mix glass asphalt modified led to a slight reduction stability under compressive stresses. The observed increase in stability is due to both rheological and mechanical improvements. The use of angular WG increases the internal friction angle and enhances aggregate interlocking [36, 37]. On the other hand, WPET modification increased stiffness, viscosity and cohesion of the asphalt binder, resulting in improved resistance to rutting and compressive stresses [30, 38]. Furthermore, polymer-modified binders enhanced elastic recovery and reduced temperature susceptibility, which ensures to better structural integrity of the HMGA [39].

Table 6. Results for hot asphalt mix modified by WG and WPET

Sample	Waste Glass Content (%)	(Stability-KN)	(ITS-Kpa) Dry Condition	(ITS-Kpa) Wet Condition	TSR (%)
Control (Unmodified)	0	7.2	1180	770	65
	10	8.0	1250	800	64
	20	8.3	1320	830	63
	30	8.8	1100	650	59
Modified with (WPET 4%)	0	7.4	1260	880	70
	10	8.1	1300	940	72
	20	8.9	1360	1040	76
	30	9.4	1210	850	70
Modified with (WPET 8%)	0	7.8	1280	950	75
	10	8.4	1320	1060	80
	20	9.5	1390	1140	82
	30	10.6	1260	920	73
Modified with (WPET 12%)	0	7.3	1070	790	74
	10	7.9	1150	890	77
	20	8.7	1190	820	70
	30	9.6	1070	690	64

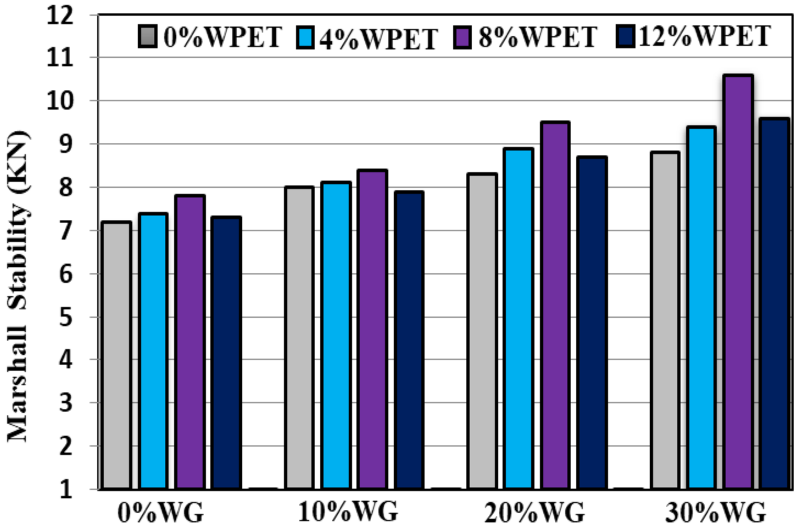

Fig. 4. Effect of WG and WPET on Marshall stability

3.2 Indirect Tensile Strength (ITS)

The results obtained from the indirect tensile strength test in wet and dry conditions are shown in Figures 5 and Figures 6, while the detailed values are summarized in Table 6. Both WG and WPET modification have a significant influence on the moisture resistance and mechanical performance of the asphalt mix. The incorporation of WPET leads to a noticeable improvement in indirect tensile strength (ITS) values compared to the control mixtures (unmodified mixtures) under both dry and wet condition. The experimental results showed that incorporation WPET in HMGA mixtures, caused ITS values to increase about (7%) up to (19%) in dry conditions and about (14%) up to (48%) in wet conditions comparison with non-WPET asphalt mixture samples. As illustrated in the Figures 5 and 6 that the ITS values increase with increasing WG content up to (20%) after which a decrease is observed with (30%) replacement of aggregate. This trend indicates that adding glass content enhances aggregate interlocking, while excessive WG content may weaken the internal structure of mixture due to increased brittleness or reduced cohesion [40].

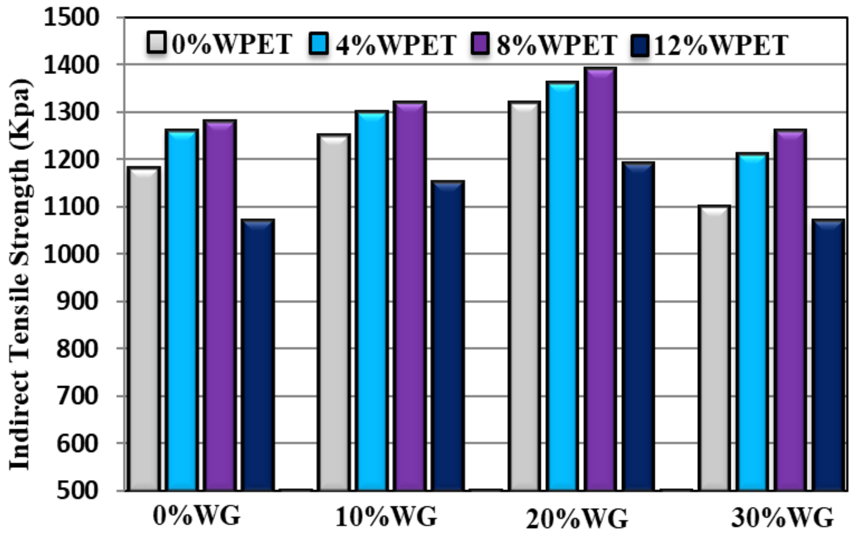

Fig. 5. Effect of WG and WPET on indirect tensile strength (ITS) in the dry condition

A similar behavior is evident under wet conditions, where the resistance to the moisture damage improvement up to (20%) WG and then reduce at higher replacement. Moreover, WPET modification enhances the resistance of mixture to moisture susceptibility (stripping damage), the adding of (8%) WPET showing the best performance of asphalt mixture, particularly at (20%) WG. This indicates that the combination of (8%) WPET and (20%) WG, where the highest ITS values are achieved under both wet and dry conditions and provides the optimum resistance to moisture susceptibility. The improvement can be attributed to enhanced adhesion and cohesion within the mixture; this suggests an optimal interaction between asphalt binder and surface of the aggregates. which limits asphalt binder stripping and improves durability compared to unmodified mixtures. In contrast, mixtures with (12%) WPET show a reduction in performance, likely due to increased stiffness of the asphalt binder [41].

The tensile strength ratio (TSR) results were presented in Figure 7 and summarized in Table 6. It can be observed that the control mixtures exhibit lower TSR values, ranging from (59–65%), indicating limited resistance to moisture damage. In contrast, the incorporation of WPET-modified mixes exhibit improvement in TSR, confirming the positive role of WPET modification on moisture resistance (durability). As shown in Figure 7 and Table 6, TSR increases with addition WG up to (20%), after which a decline at (30%). This behavior is attributed to improved internal structure at moderate glass content, while higher glass content may reduce adhesion due to the smooth surface and impermeable properties of glass particles making glass-containing mixes particularly susceptible to moisture damage and stripping, as the hydrophilic nature of glass surfaces promotes moisture induced debonding at the asphalt binder aggregate interface [42].

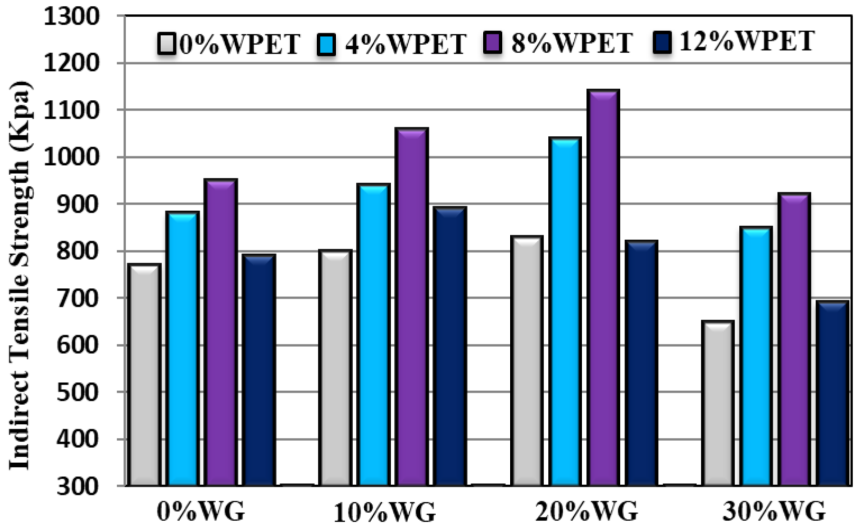

Fig. 6. Effect of WG and WPET on indirect tensile strength (ITS) in the wet condition

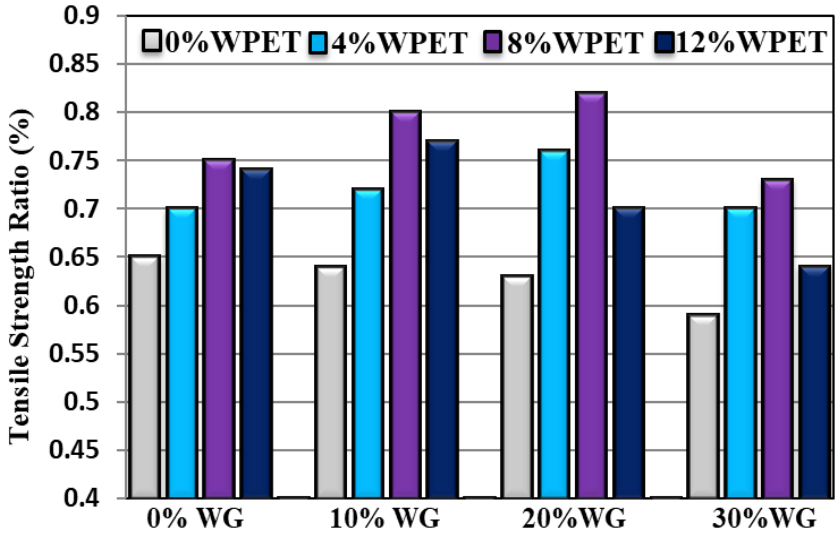

Fig. 7. The tensile strength ratio(TSR) result

Furthermore, the modified mixes, (8%) of WPET exhibit the highest TSR values up to (82%) at (20%) WG, indicating optimal resistance to moisture damage. However, at increasing WPET to (12%) there was reduction in TSR values, which may be to increased asphalt binder stiffness and reduced workability. Overall, the results indicate that combining (20%) WG with (8%) WPET provides the optimal performance, with most modified mixes approaching or exceeding the minimum TSR (80%). Conversely, a TSR value of (60%) or below is generally considered unacceptable, signifying an asphalt mixture that is susceptible to moisture damage according requirement specified by the asphalt institute, while the (80%) threshold is standard, some agencies accept a minimum TSR values of (70%) based on their experience [43]. The ternary mixture achieved a TSR of (82%) exceeding the (80%) specification limit. This improvement demonstrates that the WPET-modified binder effectively enhanced adhesion and moisture resistance despite the use of river aggregates and WG [20, 32]. No general rule for moisture sensitivity performance with the incorporation of the new additives or modification technology. This demonstrates that when a new asphalt mixture is designed it is important engineering consideration to examine its resistance to moisture damage [44].

4. Conclusions

Based on the results obtained from the stability, indirect tensile strength and tensile strength ratio tests, and as illustrated in Figures (4–7) and Table 6, the following conclusions were drawn:

- The use of crushed waste glass (WG) as a partial replacement for fine aggregate is technically feasible, as the resulting mixtures exhibit mechanical properties comparable to conventional hot mix asphalt. The optimum performance was achieved at a (20%) WG replacement level, where both Marshall stability and indirect tensile strength (ITS) increased. However, increasing the WG content to 30% caused both properties to decline because excessive glass reduces adhesion due to its smooth and nonabsorbent surface, leading to a weaker asphalt binder and aggregate interface.
- The asphalt binder modification by using waste polyethylene terephthalate (WPET) improved the mechanical performance and moisture resistance of the asphalt mixtures. The optimal WPET content was identified at (8%), at which the highest ITS values were recorded under both wet and dry conditions. Moreover, the combined incorporation of (8%) WPET and (20%) WG yielded the best overall performance, indicating that this combination is the optimum mixture composition among those evaluated.
- The tensile strength ratio (TSR) results indicate that the combined use of WPET and WG improves the resistance of asphalt mixtures to moisture damage. TSR values increased with WG content up to (20%) particularly in WPET modified mixtures, demonstrating enhanced adhesion and reduced stripping potential. The maximum TSR value (82%) was achieved at (20%) WG with (8%) WPET, indicating optimal moisture damage resistance. However, increasing the WPET content beyond the optimum level (12%) leads to a slight reduction in both ITS and TSR values. This decline is attributed to excessive asphalt binder stiffness and reduced workability.
- The integrated use of locally available river aggregate with waste glass (WG) and waste polyethylene terephthalate (WPET) is technically feasible, providing enhanced mechanical performance and promoting waste recycling. Future life cycle assessment (LCA) and life cycle cost analysis (LCCA) are recommended to quantify the full environmental and economic benefits of this sustainable pavement system.
- Future studies are recommended to investigate the rutting resistance, fatigue cracking, low-temperature cracking and aging performance of modified mixtures to complement the findings of this work.

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