Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Evaluation asphalt concrete mixture with plastic waste and crumb rubber as fine aggregate replacement in Iraq

Mohammed Aziz Hameed [*,1,2,a]
[1]*Ministry of Education, Karbala, Iraq*
[2]*College of Engineering, Al-Nahrain University, Baghdad, Iraq*

Article Info

Article History:

Received 29 Oct 2025

Accepted 15 Feb 2026

Keywords:

Asphalt;
Crumb rubber;
Plastic waste;
Marshall test;
Wheel track test

Abstract

The massive accumulation of waste materials crumb rubber (CR) and plastic waste (PW), represents a global environmental concern particularly regions like Iraq. This study investigates of using waste materials as partial replacement for fine-aggregates to production of modified hot mix asphalt. Marshall and wheel track tests were performed on samples were prepared by partially replacing the fine-aggregate with CR and PW at five replacement percentages (1%, 3%, 6%, 9% and 12%) are used by weight of fine-aggregate. The objective was explaining the effect waste additives on asphalt mixture performance. Performance was assessed using the Marshall and wheel truck tests. The laboratory results indicate that partial substitution of fine-aggregate by waste materials showed a difference in Marshall's characteristics and rutting resistance compared to control mix. Based on result, the optimal amount of CR and PW that can add to mixture is 3% and 6%, respectively. The 3% CR mixture exhibited reduction in stability about11.9%, but remained within SCRB specifications. In contrast, the 6% PW mixture showed a 20.8% stability increase. Moreover, rutting resistance at 55°C was significantly enhanced, it has reduced by 32.6% and 14.7% for 3% CR and 6% PW, respectively. Consequently, using waste materials enhance asphalt mixtures performance and promotes sustainable construction.

1. Introduction

In Iraq and other countries around the world, the safe disposal of a solid waste is a significant priority for environmental protection authorities worldwide [1]. The expansion of the rubber tire industry is largely driven by the growth of the automotive sector, according to the European tire and rubber manufacturers association, approximately (65%) of the total production of rubber materials is allocated to this industry [2]. The Energy recovery waste incineration remains a common management technique. However, its sustainability is limited by high costs, emissions and inefficiency in waste volume reduction. In modern paradigms prioritize waste prevention and minimization over treatment. Tire retreading exemplifies this shift by extending product life, that extends the usable life of tires can help them, figure1 shows imported commercial vehicles tires and collected (protected) waste tires in the European union [3].

Plastic is considered a quasi-solid, nonbiodegradable synthetic material and insoluble produced from refined crude oil and petroleum derivatives [4]. Plastics are widely used in various fields owing to their advantages properties including affordability, durability, lightweight structure, straightforward manufacturability and longevity relative to many traditional materials [5-8]. The longstanding dominance of the linear production model characterized by extraction, producing. The result is a global pollution and solid waste management crisis. These impacts cause climate change and threaten ecosystems and public health. The thinking of transition to circular systems remains incomplete, even among developed countries [9]. In this regard global plastic production

*Corresponding author:mohammed.aziz.eng25@nahrainuniv.edu.iq
[a]orcid.org/0009-0000-7008-2556
DOI: http://dx.doi.org/10.17515/resm2026-1307ss1019rs

has increased dramatically from (1.5) million-tones in (1950) to (299) million-tones in (2013) reaching about (335) million- tones by (2016) [10]. Projections indicate that worldwide plastic production may increase to triple in (2050) [11], figure2 depicts the total amount of produced plastic and discarded plastic waste from (1950 to 2015), as well as the amount predicted by (2050). In last years, solid waste management is a critical national issue in Iraq, driven by its potential adverse effects on environmental quality, public health and urban aesthetics [12]. These challenges are exacerbated by rapid population growth, unplanned urban development, and a lack of public-municipal cooperation. Modified asphalt gained popularity in the second half of the twentieth century and are now essential in limiting the deterioration of road networks. Due to increasing traffic volumes in Iraq because of the growing growth of unregulated vehicles and severe weather condition attributable to global climate change many distresses such as permanent deformations (rutting) or fatigue cracking [13]. The modified asphalt mixture has demonstrated reduced fatigue, improved durability (longer life service), and higher resistance to rutting (permanent deformation) [14]. The dry and wet methods are currently the most commonly employed for incorporating plastic waste and tire waste into asphalt concrete mixtures [15,16]. Despite widespread application, the wet process is limited and exhibits notable drawbacks due to incompatible or inadequate polymers [17]. If polymer-modified asphalt produced by using the wet process is stored at elevated temperatures in the absence of continuous agitation may exhibit poor storage stability [18].

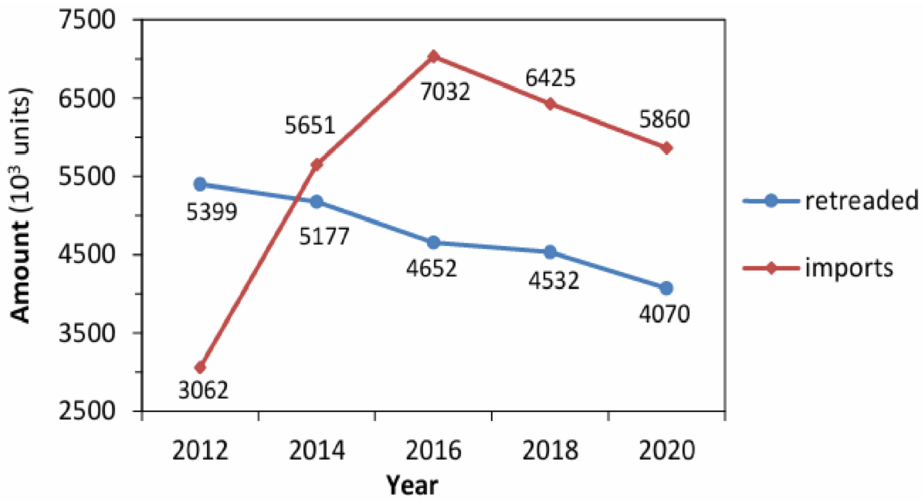


Fig. 1. Imported commercial vehicles tires and collected (protected) waste tires in the European union[3]

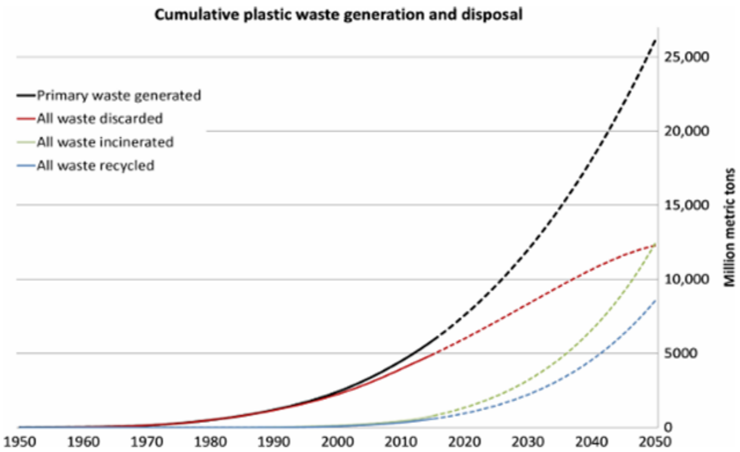


Fig. 2. The total amount of produced plastic and discarded plastic waste from (1950 to 2015) as well as the amount predicted by 2050[19]

While the use of specialized tanks equipped with stabilizing agents can avoid asphalt storage problems, they will have high production costs when manufacturing for asphalt concrete mix [17, 19]. The mixing process should be carried out in a high-temperature and high-speed mixer to produce a uniform, stable, and high-performance modified binder of asphalt. This necessitates a specialized plant, significantly increasing production costs to ensure complete additive digestion and homogeneity [20]. The dry method offers a practical alternative by directly mixing CR or PW with heated aggregates before asphalt binder addition, by using standard equipment. This process coats aggregates particles, improving mixture performance, with efficacy governed by additive characteristics and mixing conditions [21, 22]. Several previous investigations have demonstrated successful enhancements by using polyethylene additives by utilizing this method [23, 24]. Finally, if poor materials are used in the mixture or if the mix is subjected to environmental factors or vehicles loads not accounted for in the mixing design, premature distress such as fatigue, rutting, potholes formation may occur. The extremely high pavement temperatures in Iraq during the summer season and increased heavy axle loading, are the primary causes of pavement deterioration [25, 26]. Hence, it is necessary to promote the design of green and resilient pavement construction. In this research crumb rubber and plastic waste were used as additives to the mix by using the dry method and recycling these wastes for the sustainable infrastructure construction of paved highways and roads will play a significant role in solving environmental challenges due to discarding these wastes in landfills throughout Iraq.

2. Materials and Methods

The materials were used in this study available and currently used in flexible pavement construction in Iraq except for the plastic waste and crumb rubber which is brought from landfill and Najaf tire factory.

2.1. Binder

The asphalt binder used in this study is classified as a penetration-grade asphalt (40-50) equivalent to performance grade PG (70-16) [27]. It was obtained from dourah refinery in Iraq. table1 shown physical properties of asphalt.

Table (1). Physical properties of asphalt according to ASTM and SCRB specifications [28]

Tests Property	Units	ASTM Designation	Test results	SCRB (R9)
Penetration at(25^{0}C), 100 gm, 5sec.	1/10 mm	ASTM(D5)	45	40-50
Kinematic Viscosity at(135^{0}C).	Cst	ASTM (2170)	383	----
Ductility at(25^{0}C), 5cm/min.	Cm	ASTM (D113)	110	> 100
Flash Point(°C).	^{0}C	ASTM (D92)	291	min232
Specific Gravity at(25^{0}C).	---	ASTM (D70)	1.042	1.01-1.05

2.2. Aggregates and Mineral Filler

The coarse aggregate was sourced from Al-Nibaie quarry and the fine aggregate was brought from Karbala quarry. This aggregate is used in the south and middle areas of Iraq. The coarse and fine aggregate were sieved and recombined in the proper proportions to meet the gradations requirements by state corporation of roads and bridges in Iraq (SCRB) specifications [28]. Physical properties of course and fine aggregates limits set by the SCRB were summarized in table2. The gradation of the aggregate was selected with specification limits and illustrated in table3. One type of mineral filler was used, the ordinary Portland cement (Type I), which was brought from factory of Karbala. properties of the filler are presented in table4.

Table2. The physical properties of coarse and fine aggregate

Test Property	ASTM Standard		Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity	C127	C128	2.53	2.65
Apparent Specific Gravity	C127	C128	2.66	2.67
Water Absorption%	C127	C128	0.83	0.63
Los Angeles Abrasion Test	C131		24 % (Max.) 30 %	----
Particle Angularity	D5821		97 %	----

Table 3. Grading of wearing course SCRB (R9) type (IIIA) in Iraq[28]

Sieve size		Specification limits for wearing coarse (A) (SCRB)	(% Passing by weight of total aggregate & filler)
English sieves (in)	Standard sieves (mm)		
3/4''	19	100	100
1/2''	12.5	90-100	95
3/8''	9.5	76-90	83
No.4	4.75	44-74	59
No.8	2.36	25-58	43
No.50	0.3	5-21	13
No.200	0.075	4-10	7

2.3. Additives

Two types of additives plastic waste (PW), and crumb rubber (CR) were used in this study. Incorporating these additives into asphalt using the dry process is a promising approach for sustainable road construction. Dry method addresses environmental concerns by recycling waste materials while aiming to enhance pavement performance. The PW was separated from the municipal solid waste and shredded to a particle size was approximately (0.3mm–4.75mm) see figure3(a), and the CR were used in this study was taken from vehicle tires, and it also shredded mechanically to a particle size was approximately (0.3mm–4.75 mm). see figure3(b).

(a) (b)

Fig. 3. Illustrative additives (a) plastic wastes and (b) crumb rubber

2.4. Mixture and Samples Preparation

Conventional asphalt concrete pavement surface layer is a typical hot mix asphalt (HMA) intended for pavement construction in Iraq. Plastic waste and crumb rubber were added into the asphalt mixtures independently. For each additive, five contents of (1%, 3%, 6%,9% and 12%) were considered, calculated by weight of total fine aggregates. The incremental replacement is a widely accepted to determine the optimal additive content in asphalt mixes, balancing performance enhancement with structural integrity while meeting mixture design requirements [29, 30]. Additives are used in particle sizes between 0.3mm and 4.75mm, this small particle size range was chosen to improve the mixture homogeneity during the blending [31]. The experimental work program consisted of three phases, in the first phase an asphalt concrete control mix was prepared without modification, the second phase involved the preparation of asphalt concrete mix modified with plastic waste (PW) and in the last phase crumb rubber (CR) modified asphalt concrete mix were prepared. Five blends (with 4%, 4.5%, 5%, 5.5% and 6%) asphalt binder contents were used to determine the OAC, "Optimal asphalt content", based on Marshall's mix design method, applied for design each asphalt concrete mix individually; the mixes were prepared with an optimum asphalt content of (5%). In this study modified mixtures were prepared by using dry blending method, where the aggregates were heated at 180°C for two hours before adding the PW and CR particles. Subsequently, asphalt binder preheated to a temperature approximately 160°C. The high aggregate temperature can optimize the process of asphalt digestion and creates a thin layer of asphalt modified on the surface of the aggregate particles [32]. Mechanical mixing ensued for four minutes to ensure that the additives had melted and coated the aggregate. under continuous temperature regulation. Process homogeneity was confirmed via visual inspection for aggregates coating and the absence of modifier agglomerates. In the wheel track test, specimen dimensions with a height of (60mm) and with a diameter of (150mm), and for Marshall test the dimension of specimens, approximately with a height of (63.5mm) and with a diameter of (101.6mm) [33, 34].

Table 4. Physical properties of ordinary Portland cement (Filler)

Test Property	Test results
Specific gravity	3.13
Passing sieve (0.075 mm) No. 200	96%

2.5. Test Methods

The testing methods were used in this study to assess the performance of various asphalt mix: Marshall's test, and wheel track test.

2.5.1 Marshall Test

The testing procedure follows ASTM(D1559) "Standard test method for resistance of asphalt mixtures to plastic flow using the Marshall's method" [35]. Specimens are prepared with the dimensions mentioned above and compacted with 4.5 kg by hammer apparatus (98.4) mm face, (45) cm drop. Before testing specimen are conditioned in a water bath at (60°C) for thirty minutes dried and placed into the Marshall apparatus for immediate loading, see figure4(a) shows photos of the specimens during the Marshall testing.

2.5.2 Wheel Track Test (WTT)

The test is used to evaluate the asphalt mixtures resistance to permanent deformation shape change (rutting) conditions, which simulates that is applied on asphalt pavement surface. This analysis can be conducted on natural asphalt roads pavement from field, and from laboratory specimens' asphalt for both cylinder, and slabs shaped by using WTT in which involve a loaded wheel moving across asphalt samples in a reciprocating motion, digital measurement tool is used to records ruts depths formed by the wheel along the sample path.

(a)

(b)

Fig. 4. Illustrative (a) Marshall machine and (b) wheel track apparatus

A load of (705N ± 5N) about (158Ib ± 1.0Ib) is applied. The procedures for this test are based on according to AASHTO (T324) [33]. The wheel tracking test was performed at (55°C) to simulate a high temperature pavement condition in hot summer climates such as in Iraq accelerating rutting (permanent deformation) evaluation. A total of (5,000-wheel passes) were applied, a standard criterion ensuring the test arrive key performance, this duration is critical to identification the SIP (Stripping Inflection Point) on the deformation. The SIP marks transition from compaction to damage serving as a key sample failure indicator. These parameters (55°C) and (5,000 passes) provide an assessment of permanent deformation [27], Figure 4(b) displays photos of the wheel - track apparatus.

3. Results and Discussions

This section is divided into two parts to present the testing results, the first is addresses Marshall test results, while the second focuses on the wheel tracking test results.

3.1. Marshall Characteristics

The Marshall characteristics include four main parameters: (stability, flow, bulk density and air voids) to evaluate their effect on the performance of hot mix asphalt pavement. The results of this test are shown in Table (5) and Table (6). Marshall characteristics of asphalt binder mixtures with CR and PW reveal specific performance trends, as evidenced in Figures (5-8). Marshall stability of CR modified mix decreased with increasing CR content. Whereas PW modified mix showed improved Marshall stability up to 6% before declining at higher contents. At 1%CR Marshall stability decreases by about 3%, and at 3%CR Marshall stability reduced by approximately 11.9% compared to the conventional mix (control mix without CR). This reduction increases with higher CR content in mixture, with a 18.8% reduction at 6%CR reaching approximately the lower acceptable specification limit of 8KN. Stability reductions about 25.6% and 30.7% occur at 9%CR and 12%CR respectively, dropping below the acceptable limits of the (SCRB) requirements as shown in Figure (5).

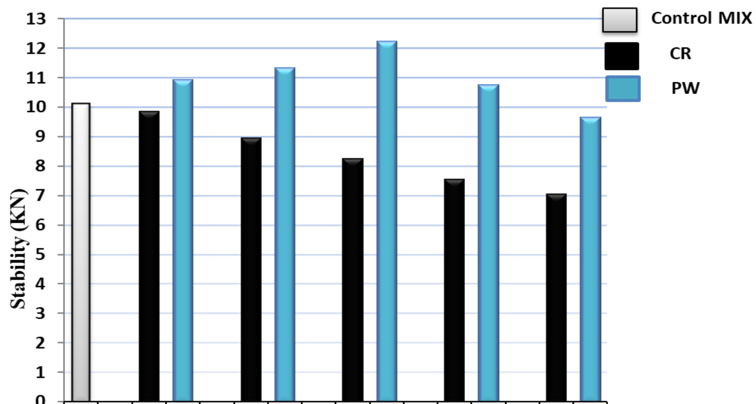
Table 5. Results for asphalt mixes modified by CR

Specimen	Additive (%)	Marshall Stability (kN)	Marshall flow (mm)	The bulk density (gm/cm^3)	Air void (%)	Rut depth at (55°C) after 5000 passes (mm)
Control	0	10.1	3.2	2.342	3.7	9.2
Modified by Crumb Rubber	1	9.8	3.6	2.335	4.1	8.7
	3	8.9	4.0	2.325	4.3	6.2
	6	8.2	4.5	2.305	5	7.1
	9	7.5	4.8	2.290	5.4	8.9
	12	7.0	5.1	2.274	6.0	10.2

Table(6). Results for asphalt mixes modified by PW

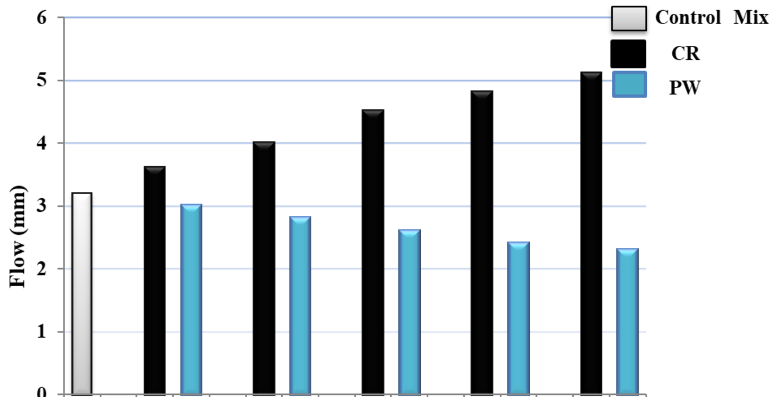
Specimen	Additive (%)	Marshall Stability (KN)	Marshall Flow (mm)	The bulk density (gm/cm^3)	Air void (%)	Rut depth at (55°C) after 5000 passes (mm)
Control	0	10.1	3.2	2.342	3.7	9.2
Modified by Plastic Waste	1	10.9	3.0	2.340	3.9	9.0
	3	11.3	2.8	2.332	4.1	8.3
	6	12.2	2.6	2.323	4.5	7.9
	9	10.7	2.4	2.312	5	9.5
	12	9.6	2.3	2.295	5.6	10.8

At a 1%PW inclusion level stability increases by approximately 7.9% and at a 3%PW stability increases approximately 11.8% compared to the control mix (without PW). This improvement continues with higher PW content, reaching a peak value at 6%PW stability increases by approximately 20.8%. However, beyond this optimal content, mixture stability gradually decreased, potentially remaining approximate to the control mix levels depending on the specific percentage as shown Figure (5). This contras behavior is primarily governed by the nature and interaction of each additive within the aggregate particle's skeleton. In the dry method, the nature of CR particles acts as the elastic inclusions, which reduces the interlock of aggregate and reduces internal friction in the mixture of asphalt as their content increases, results in a reduction in mix stiffness. Conversely, the rigid behavior of PW, which enhances mix stiffness at moderate contents, leading to improved stability. A continued increase beyond the optimum resulted in increased air voids compromising mixture cohesion, causing a reduction in stability. Similar studies have been widely reported in dry method modified asphalt mixtures [29, 36-38]. Marshall Flow values indicative of the mix resistance to deformation increased with CR content, while PW modified mixt exhibited a noticeable reduction in flow as PW content increased as shown in Figure (6).



	0%		1%	1%		3%	3%		6%	6%		9%	9%		12%	12%
Stability (KN)	10		9.8	11		8.9	11		8.2	12		7.5	11		7	9.6

Fig. 5. Effect of CR and PW on stability



	0%		1%	1%		3%	3%		6%	6%		9%	9%		12%	12%
Flow (mm)	3.2		3.6	3		4	2.8		4.5	2.6		4.8	2.4		5.1	2.3

Fig. 6. Effect of CR and PW on flow

At 1%CR content, flow raised by 12.5%, while at 3%CR, it increased by 25% suggesting improved deformation resistance, and at 6% CR, the flow value rises by 40.6%, exceeding the maximum acceptable limit of SCRB (4mm). For 9%CR and 12%CR, flow values increase by 50% and 59.4%, respectively. Whereas, at 1%PW content, flow reduced by 6.2%, while at 3%PW it decreased by 12.5% and at 6%PW, the flow value reduced by 18.7% and continues falling, suggesting reduced deformation resistance. For 9%PW and 12%PW, flow values decreased by 25% and 28.1%, respectively, reaching approximately the minimum acceptable limit of SCRB (2mm). Higher Marshall flow in the CR mix indicates improved flexibility and deformation capacity due to crumb rubber elasticity, while reduced Marshall flow in the PW mix reflects increased resistance to deformation and stiffness, consistent with findings by Agha et al. [39]. Air voids increased and bulk density decreased for both polymers as additive content increased, with a more pronounced effect observed in the CR mix, as shown in Figure (7) and Figure (8). The control mix has an AV of 3.7%. Adding 1%CR increased AV by 10.8%, 3% CR increased it by 16.2%, and 6% CR raised it by 35.1%. Higher contents of crumb rubber 9%CR and 12%CR increases AV by 45.9% and 62.1%, respectively. It exceeded the acceptable limits of SCRB (3%-5%). Whereas, a notification of different behavior when using PW with 1%PW increased AV by 5.4%, 3%PW increased it by 10.8% and 6%PW raised it by 21.6%. Higher plastic waste contents of 9%PW and 12%PW increased AV by 35.1% and 51.3%, respectively, indicating more voids within the mixture. Elevated air void content at higher replacement contents of CR and PW indicates reduced compaction efficiency, which may adversely affect durability. The control mixture has the highest density. With 1%CR, density decreased by 0.3%, with 3%CR decreased by 0.7% and with 6%CR, it was reduced by 1.6%. At 9%CR and 12%CR, density decreases by 2.2% and 2.9%, respectively. And when used PW with 1%PW density decreased by 0.1%, 3%PW decreased by 0.42%, and 6%PW decreased by 0.81%. At 9%PW and 12%PW, density decreases by 1.3% and 2% respectively. This reduction in density is attributed to CR and PW having less density than the fine aggregates, they were replacing as a percentage of CR and PW increases, the density of the modified mix is decreased. Similar volumetric studies have been reported in previous dry process modification researcher [30, 40]. In summary, the addition of PW and CR modifies various Marshall's properties of asphalt concrete mixtures. Stability was decreased with higher CR content and acceptable levels at CR content up to (6%), Flow values were increased. While stability increased with higher PW content and acceptable levels at PW content up to (6%). Flow values are decreased. Density was decreased and AV was increased for both additives, indicating a less dense mixture composition.

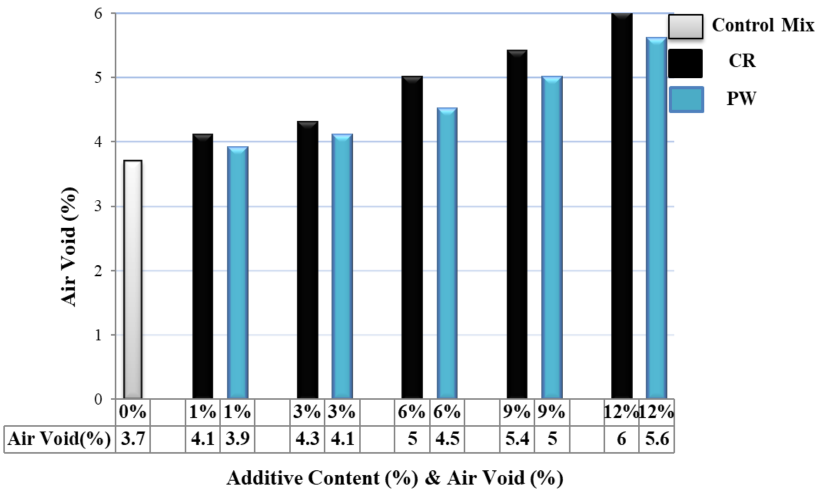


Fig. 7. Effect of CR and PW on air void percentage

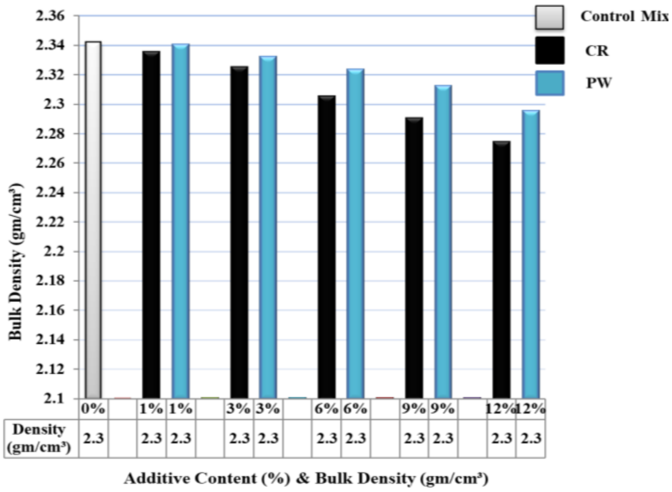


Fig. 8. Effect of CR and PW on bulk density

3.2. Wheel Track Test Results

The permanent deformation (rutting) resistance of asphalt concrete mix incorporating PW and CR were assessed by using a wheel tracking test, its results were presented in Table (1) and Table (2). As Figure (9) shows the rutting depth development over 5000-wheel tracking passages at55°C for the conventional and modified mixtures. The control mixture without PW and CR indicates a consistent increasing rutting depth. While using the addition of PW and CR impacts the performance of rutting. At 1%CR and 1%PW, the rutting depth decreases by approximately 5.4% and 2.2% after 5000 passages, respectively. At 3%CR mix shows significant improvements by 32.6% reduction and with 6% PW by 14.1% reduction after 5000 passages. However, 6% CR and 9% result in a slight increase in rut depth. In summary, the addition of 3%CR and 6%PW shows the best performance of the rutting resistance, exhibiting the lowest rut depth through the test. Conversely, higher percentage contents of CR and PW (9% and 12%) result in increased rutting depths. The improved permanent deformation resistance at optimal PW and CR contents is associated with improved energy dissipation in CR mix due to the elasticity of rubber and increased mixt stiffness in PW modified mix resulting due to the rigidity of the additive structure. However, at higher additive contents, the combined effects of increased air voids, loss of aggregate interlock, and non-uniform binder dispersion reduce resistance to rutting. The superior rutting performance of CR mix compared to PW mix at equivalent replacement contents highlights the greater effectiveness of CR in enhancing high temperature performance. These findings are in agreement with previous studies [39, 41, 42].

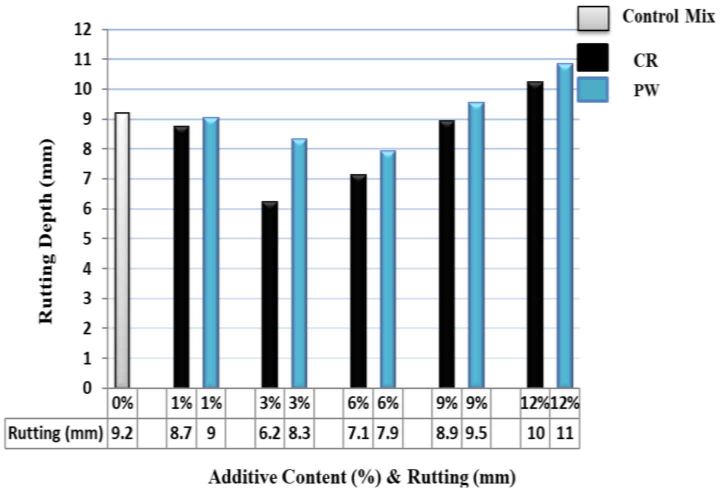


Fig. 9. Effect of CR and PW on rutting depth (5000-wheel passages) at 55 °C

4. Conclusions

The following conclusions have been obtained as a result of this research based on the Marshall tests and wheel track test, and the results were encouraging.

- This study demonstrates the technical feasibility of using plastic waste (pw), and crumb rubber (cr) as partial replacements for fine aggregate in mixtures of asphalt by using the dry mixing technique.
- This study explored the integration of CR and PW as additives into Iraqi HMA, by evaluating multiple compositions with differing CR and PW (1%, 3%, 6%, 9% and 12%), by weight of total fine aggregates.
- The addition of CR and PW impacts the Marshall's properties of asphalt mix, adding CR modified resulted in asphalt mix with exhibited stability that is decreased, and increased flow, indicating enhanced mixture flexibility. Conversely, PW modified mix showed improved Marshall stability and reduced flow, which enhances mix stiffness at moderate contents.
- Based on the experimental work result, performance improvement was strongly dependent on CR and PW content, with optimal permanent deformation (rutting) resistance observed at approximately (3%) CR and (6% PW), higher replacement contents resulted in performance deterioration due to increased air voids and reduced aggregate interlock.
- The comparative evaluation demonstrated that CR is more effective in improving high temperature performance, while PW contributes primarily to mixture stiffness.

- Despite the performance of the control asphalt mix deteriorating in some properties following the addition of additives CR and PW, the results meet the Iraqi requirements of SCRB specifications in Iraq and seem to be applicable for road construction.
- The results directly address the study objective of identifying optimal replacement ranges that balance mechanical performance and volumetric stability
- The observed trends were consistent with findings reported in previous research on dry method waste modified asphalt mix, corroborating the scientific validity of the experimental results.
- From a practical perspective, using CR and PW as replacements for fine aggregate reduces the carbon footprint of asphalt mix by lowering the demand for virgin aggregate materials production. Additionally, incorporating these recycled wastes supports green, flexible pavement construction and alleviates the environmental effects of waste disposal at landfills.
- These innovations offer significant potential to tackle existing challenges and advance future developments in solid waste management in the asphalt concrete industry.
- This study is limited to laboratory evaluation and one type of asphalt binder, future study should investigate long-term aging, fatigue performance, moisture susceptibility and field implementation to assess durability and constructability

References

[1] Sulyman M, Sienkiewicz M, Haponiuk J. Asphalt pavement material improvement: A review. International journal of environmental science and development. 2014;5(5):444. https://doi.org/10.7763/IJESD.2014.V5.525
[2] Zakerzadeh M, Shahbodagh B, Ng J, Khalili N. The use of waste tyre rubber in Stone Mastic Asphalt mixtures: A critical review. Construction and Building Materials. 2024;418. https://doi.org/10.1016/j.conbuildmat.2024.135420
[3] Dabic-Miletic S, Simic V. Smart and sustainable waste tire management: decision-making challenges and future directions. Decision Making Advances. 2023;1(1):10-6. https://doi.org/10.31181/v120232
[4] Ameur AB, Valentin J, Baldo N. A Review on the Use of Plastic Waste as a Modifier of Asphalt Mixtures for Road Constructions. CivilEng. 2025;6(2):17. https://doi.org/10.3390/civileng6020017
[5] Gao G, Zhang Y, Zhang Y, Sun K, Fan Y. Improved storage stability of LDPE/SBS blends modified asphalts. Polymers and Polymer Composites. 2002;10(3):229-36. https://doi.org/10.1177/096739110201000305
[6] Hopewell J, Dvorak R, Kosior E. Plastics recycling: challenges and opportunities. Philosophical Transactions of the Royal Society B: Biological Sciences. 2009;364(1526):2115-26. https://doi.org/10.1098/rstb.2008.0311
[7] Amirkhanian S. Utilization of scrap plastics in asphalt binders. Eco-efficient pavement construction materials: Elsevier; 2020. p. 13-32. https://doi.org/10.1016/B978-0-12-818981-8.00002-3
[8] Pasetto M, Baliello A, Giacomello G, Pasquini E. Towards very high RAP content asphalt mixes: A comprehensive performance-based study of rejuvenated binders. Journal of Traffic and Transportation Engineering (English Edition). 2021;8(6):1022-35. https://doi.org/10.1016/j.jtte.2020.12.007
[9] da Silva CL, Franz NM. The Global Movement of the Transition from Linear Production to the Circular Economy Applied to the Sustainable Development of Cities. Fronteira: Journal of Social, Technological and Environmental Science. 2022;11(2):52-67. https://doi.org/10.21664/2238-8869.2022v11i2.p52-67
[10] Crippa M, De Wilde B, Koopmans R, Leyssens J, Muncke J, Ritschkoff A-C, et al. A circular economy for plastics: Insights from research and innovation to inform policy and funding decisions2019.
[11] Commission E. Green paper on a European strategy on plastic waste in the environment. EU Brussels, Belgium; 2013.
[12] AL-MOHAMMED MA, ULUTAGAY G, ALABDRABA WMS. The reality of solid waste management in Iraq and ways of development. Tikrit Journal of Engineering Sciences. 2021;28(3):1-20. https://doi.org/10.25130/tjes.28.3.01
[13] Mustafa S, Hameed MA, Dulaimi A. Evaluation of thE pRopERtiES of modifiEd local aSphalt bindER by uSing StyREnE butadiEnE RubbER (SbR) oR low-dEnSity polyEthylEnE (ldpE). Scientific Review Engineering and Environmental Studies (SREES). 2022;31(3):190-202. https://doi.org/10.22630/srees.3375
[14] Rossi CO, Spadafora A, Teltayev B, Izmailova G, Amerbayev Y, Bortolotti V. Polymer modified bitumen: Rheological properties and structural characterization. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2015;480:390-7. https://doi.org/10.1016/j.colsurfa.2015.02.048

[15] Khadim HM, Al-Mosawe HM. Crumb rubber modification for enhanced rutting resistance in asphalt mixtures. Open Engineering. 2024;14(1):20220500. https://doi.org/10.1515/eng-2022-0500
[16] Cardoso J, Ferreira A, Almeida A, Santos J. Incorporation of plastic waste into road pavements: A systematic literature review on the fatigue and rutting performances. Construction and Building Materials. 2023;407:133441. https://doi.org/10.1016/j.conbuildmat.2023.133441
[17] Yu R, Fang C, Liu P, Liu X, Li Y. Storage stability and rheological properties of asphalt modified with waste packaging polyethylene and organic montmorillonite. Applied Clay Science. 2015;104:1-7. https://doi.org/10.1016/j.clay.2014.11.033
[18] Brasileiro L, Moreno-Navarro F, Tauste-Martínez R, Matos J, Rubio-Gámez MdC. Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A review. Sustainability. 2019;11(3):646. https://doi.org/10.3390/su11030646
[19] Yin F, Fortunatus M, Moraes R, Elwardany MD, Tran N, Planche J-P. Performance evaluation of asphalt mixtures modified with recycled polyethylene via the wet process. Transportation Research Record. 2021;2675(10):491-502. https://doi.org/10.1177/03611981211011650
[20] Fernandes S, Costa L, Silva H, Oliveira J. Effect of incorporating different waste materials in bitumen. Ciência & Tecnologia dos Materiais. 2017;29(1):e204-e9. https://doi.org/10.1016/j.ctmat.2016.07.003
[21] Ahmadinia E, Zargar M, Karim MR, Abdelaziz M, Ahmadinia E. Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt. Construction and building materials. 2012;36:984-9. https://doi.org/10.1016/j.conbuildmat.2012.06.015
[22] Lastra-González P, Calzada-Pérez MA, Castro-Fresno D, Vega-Zamanillo Á, Indacoechea-Vega I. Comparative analysis of the performance of asphalt concretes modified by dry way with polymeric waste. Construction and Building Materials. 2016;112:1133-40. https://doi.org/10.1016/j.conbuildmat.2016.02.156
[23] Zoorob S, Suparma L. Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). Cement and concrete composites. 2000;22(4):233-42. https://doi.org/10.1016/S0958-9465(00)00026-3
[24] Yin J, Wu W. Utilization of waste nylon wire in stone matrix asphalt mixtures. Waste Management. 2018;78:948-54. https://doi.org/10.1016/j.wasman.2018.06.055
[25] Al Helo KHI, Qasim ZI, Kadhim ZA, editors. Prediction Models for Modified Pavement Mixtures by Reclaimed Asphalt in Terms of Durability Indicators. E3S Web of Conferences; 2023: EDP Sciences. https://doi.org/10.1051/e3sconf/202342703026
[26] Abbas AS. Temperature zoning of Iraq for asphalt mix design. Journal of Engineering and Sustainable Development. 2017;21(5):54-63.
[27] Hameed MA, Mustafa S, Dulaimi A, editors. The effect of Styrene Butadiene Styrene on hot asphalt mixes in Iraq. AIP Conference Proceedings; 2023: AIP Publishing LLC. https://doi.org/10.1063/5.0163550
[28] SCRB/R9. General specification for roads and bridges, Section R/9, Hot-Mix Asphalt Concrete Pavement. Baghdad, Iraq: Ministry of Housing and Construction,2003.
[29] Arabani M, Mirabdolazimi S, Sasani A. The effect of waste tire thread mesh on the dynamic behaviour of asphalt mixtures. Construction and Building Materials. 2010;24(6):1060-8. https://doi.org/10.1016/j.conbuildmat.2009.11.011
[30] Fahmy EA, Youssef AM, Ali EE, Algabry A, Elbagalati O. Evaluation of asphalt mixtures modified with polyethylene terephthalate (PET). Innovative Infrastructure Solutions. 2024;9(11):434. https://doi.org/10.1007/s41062-024-01734-9
[31] Movilla-Quesada D, Raposeiras A, Olavarría J. Effects of recycled polyethylene terephthalate (PET) on stiffness of hot asphalt mixtures. Advances in Civil Engineering. 2019;2019(1):6969826. https://doi.org/10.1155/2019/6969826
[32] Rodriguez-Fernandez I, Baheri FT, Cavalli MC, Poulikakos LD, Bueno M. Microstructure analysis and mechanical performance of crumb rubber modified asphalt concrete using the dry process. Construction and Building Materials. 2020;259:119662. https://doi.org/10.1016/j.conbuildmat.2020.119662
[33] 324-23 ADT. Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures. Washington, D. C., USA2023.
[34] D-6927 A. Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus. USA2006.
[35] Aksoy A, Iskender E, Kahraman HT. Application of the intuitive k-NN Estimator for prediction of the Marshall Test (ASTM D1559) results for asphalt mixtures. Construction and Building Materials. 2012;34:561-9. https://doi.org/10.1016/j.conbuildmat.2012.02.091
[36] Hassan NA, Airey GD, Jaya RP, Mashros N, Aziz MMA. A review of crumb rubber modification in dry mixed rubberised asphalt mixtures. Jurnal Teknologi (Sciences & Engineering). 2014;70(4). https://doi.org/10.11113/jt.v70.3501
[37] Karmakar S, Kumar Roy T. Influence of plastic waste on chemical and mechanical properties of modified bitumen used in the bituminous mix for flexible pavement. Journal of Materials in Civil Engineering. 2021;33(2):04020440. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003545

[38] Mishra B, Gupta MK, editors. Use of plastic waste in bituminous mixes by wet and dry methods. Proceedings of the Institution of Civil Engineers-Municipal Engineer; 2020: Thomas Telford Ltd. https://doi.org/10.1680/jmuen.18.00014

[39] Agha N, Hussain A, Ali AS, Qiu Y. Performance evaluation of hot mix asphalt (HMA) containing polyethylene terephthalate (PET) using wet and dry mixing techniques. Polymers. 2023;15(5):1211. https://doi.org/10.3390/polym15051211

[40] Yildirim Y. Polymer modified asphalt binders. Construction and building materials. 2007;21(1):66-72. https://doi.org/10.1016/j.conbuildmat.2005.07.007

[41] Radeef HR, Abdul Hassan N, Abidin ARZ, Mahmud MZH, Yusoffa NIM, Idham Mohd Satar MK, et al. Enhanced dry process method for modified asphalt containing plastic waste. Frontiers in Materials. 2021;8:700231. https://doi.org/10.3389/fmats.2021.700231

[42] Picado-Santos LG, Capitão SD, Neves JM. Crumb rubber asphalt mixtures: A literature review. Construction and Building Materials. 2020;247:118577. https://doi.org/10.1016/j.conbuildmat.2020.118577