Research on Engineering Structures & Materials
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Research Article

Performance evaluation of asphalt mixtures modified with waste plastic and nitrile rubber

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Article Info

Article History:

Received 25 May 2026

Accepted 26 June 2026

Keywords:

Modified bitumen;
Asphalt mixture;
Plastic waste;
Waste rubber;
Marshall properties

Abstract

The increasing accumulation of plastic and rubber waste in Algeria poses significant environmental challenges, highlighting the need for sustainable recycling solutions in road construction. This study investigates the influence of waste plastic (WP) and waste nitrile rubber (WNR) used as partial bitumen replacement materials on the mechanical and volumetric properties of asphalt mixtures. The bitumen binder was modified by incorporating 1%, 3%, and 5% (by weight of bitumen) of each additive. Asphalt mixtures were then prepared with these binders and evaluated through volumetric properties (bulk density, air voids (Va), Voids in Mineral Aggregate (VMA), and Voids Filled with Bitumen (VFB) and Marshall parameters, including Stability (MS), Flow (FM), and Marshall Quotient (MQ). A conventional 0/14 asphalt mixture prepared with unmodified 35/50 penetration-grade bitumen served as the control mixture. The results indicate that at an additive content of 5%, WP and WNR increased Marshall Stability by 22% and 37%, respectively, and decreased Flow by 15% and 33%, respectively, compared with the control mixture, indicating enhanced resistance to permanent deformation. However, distinct behaviors were observed. WP mainly acts as a stiffening agent, resulting in moderate mechanical improvement and stable volumetric characteristics. In contrast, WNR exhibits a swelling effect that increases the effective binder volume, leading to lower air voids, higher VFB, and improved mixture densification. Consequently, WNR-modified mixtures show higher Stability and MQ values. Despite these advantages, excessive WNR content may result in overly dense mixtures with very low air voids, potentially affecting durability. Generally, WNR provides a more effective improvement through combined densification and viscoelastic behavior, while WP primarily contributes through increased stiffness.

1. Introduction

The majority of the road network in Algeria is formed by the flexible pavements [1, 2]. However, these pavements exhibited remarkable flaws under heavy traffic loading, which induce permanent

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DOI: http://dx.doi.org/10.17515/resm2026-1707ma0525rs

deformations (Rutting) that threaten road safety and discomfort drivers and passengers [3]. The long summer heat waves experienced in the southern regions of Algeria significantly minimize the viscosity and stiffness of the bitumen, which makes bituminous mixtures more susceptible to permanent deformation [4,5]. On the contrary, cold winter temperatures experienced in some regions of Algeria increase the binder's stiffness and brittleness, which restricts the pavement's ability to relax under thermal stress and increases its vulnerability to thermal and low-temperature cracking [6]. The above-mentioned climatic conditions constitute one of the main motivations for improving the performance of asphalt mixtures used in Algeria. Moreover, like most developing countries, the disposal of solid municipal wastes and the like is considered to be one of the major environmental and social problems being confronted in Algeria. Statistics from the Algerian Ministry of Environment and Quality of Life indicate the total household waste was around 13 million tons annually [7], with an expectation of exceeding 20 million tons by 2035 [8]. The waste plastic materials form a huge part of the entire household waste in Algeria, reflecting the high consumption rate of these materials in municipal solid waste streams. Regarding the soles of rubber shoes, the National Waste Management Agency states that they make up merely a fraction (0.87%) of absolute household refuse yet present a unique ecological predicament due to the robustness and persistence against breakdown of synthetic rubber. Plastic and rubber waste can endure in the environment for many years to even centuries because of the sluggish breakdown of polymer substances [9, 10]. These wastes fragment into micro- and nano-plastic particles that disperse widely across soil, rivers, oceans, and air, and can enter food chains, posing ecological and health risks [9, 11-13].

The discovery of better performing pavement materials that can last longer is essential in light of the above problems. Various strategies have been adopted, including the use of polymer-modified binders. The incorporation of polymers has shown a substantial improvement in flexibility, adhesion and structural strength of bitumen, leading to an overall improvement in pavement performance [5, 14, 15]. The polymers used for bitumen modification can be categorized into virgin (synthetic) and recycled (wastes) [16]. A range of virgin polymers, encompassing SBS, SBR, and EVA, have seen utilization in the process of modifying bitumen [17-20]. However, the high expenses tied to these options might dull down the use of virgin polymer in road construction because of this factor. The use of waste polymeric materials in asphalt mixtures has emerged recently as an attractive solution. Among the most important wastes used in modifying bitumen binders are: (plastic waste and rubber waste).

Previous studies have shown that waste plastics and rubber-based materials can significantly improve the performance of asphalt binders through different modification mechanisms. Waste plastics generally increase binder stiffness and viscosity, which enhances rutting resistance and reduces permanent deformation at high service temperatures. In contrast, rubber particles interact with the bitumen by absorbing its lighter fractions and swelling within the binder matrix, resulting in increased elasticity, improved stress relaxation, and enhanced resistance to fatigue and cracking. These modifications can also reduce temperature susceptibility and improve the overall durability of asphalt pavements under varying climatic conditions [21- 24]. Table 1 summarizes a selection of studies published between 2018 and 2025 that investigated the use of plastic waste and crumb rubber as modifiers for bitumen. The literature indicates that research on bitumen modified with waste plastics and rubber materials has become widespread, particularly in Asian countries. Nevertheless, significant challenges remain regarding the development of guidelines, standards, and specifications for large-scale practical implementation. These challenges are mainly related to the determination of the optimal additive type, particle size, dosage, modification method, and characterization procedures [31].

Several parameters strongly influence the performance of modified binders, including mixing temperature, additive content, mixing method, and mixing duration. Moreover, some studies did not clearly report the physical form of the plastic waste (e.g., powder, flakes, granules, or pieces), although this factor can significantly affect the mixing process and the resulting properties of the modified binder [20- 23].

Crumb rubber (CR) derived from end-of-life tires is the most extensively investigated rubber additive. Its content generally ranges from 5% to 25% by weight of bitumen, with most studies focusing on the 10–20% range, which appears to provide the best balance between performance enhancement and workability. Mixing times typically vary from 30 minutes to 2 hours and may extend to 5 hours depending on the process and the desired level of interaction between the rubber particles and the bitumen. Regarding plastic waste, several polymer types have been employed as bitumen modifiers, including low-density polyethylene (LDPE) [25,26], high-density polyethylene (HDPE) [25,27], polyethylene terephthalate (PET) [28,29], and polypropylene (PP) [30]. Plastic contents generally range from 1% to 12%, although most studies have reported optimum performance within an intermediate range of 4–8%, either by weight of aggregate in the dry process or by weight of binder in the wet process. In wet processes involving high-shear mixing, mixing durations generally range from 45 to 90 minutes, whereas in dry processes the polymer is blended directly with the aggregates. Most studies have employed mixing temperatures between 160°C and 190°C, although temperatures approaching 200°C have also been reported.

Table 1. Previous studies (between 2018 and 2025) that used plastic waste or rubber crumb as additives to improve bitumen properties

Author, (Year), Country of the author	Bitumen class	Polymer type	Additive content %	Mixing time(min)and speed (rpm)	Mixing temperature (°C)	Tests performed	Observation
Plastic waste							
Cherdsak Suksiripattana-pong et al. (2022) [27]. Thailand	60/70	HDPE	1, 3, 5 and 7% by aggregate weight	dry method	dry method	Marshall mixes design (stability, flow, air voids, VMA, VFA, density); Indirect tensile strength (ITS);	HDPE increased stability and ITS; flow decreased up to 5% then leveled; maximum MR and fatigue life at 5% HDPE; 7% caused phase separation and surface rupture; pavement age highest at 5%
Muhammad Rafiq Kakar et al (2021) [31], Switzerland	70/100	PE-pellets and PE-shreds	5% by mass of the base binder	60 min/ 3500 rpm	170 °C	DSC, TGA, FTIR, Dynamic Shear Rheometer (DSR)	PE improves rutting resistance while maintaining low-temperature performance. However, poor high-temperature storage stability suggests that mixture preparation methods require careful optimization to ensure binder compatibility.
Nuha Mashaan et al (2022) [24], Australia	C320	LDPE /HDPE/ PET	(0%, 8%).	45 min /2000 rpm	180°C	Penetration; DSR (rutting, fatigue); RTFOT, PAV	2–4% LDPE/HDPE provides ideal performance, but exceeding 6–8% causes permanent deformation. Conversely, PET improves stiffness, aging resistance, and rheological properties up to 8%.
Assel Jexembayeva et al (2024) [29], Kazakhstan	70/100	PET and PE	0%, 2%, 4%, 6%, and 8% by weight of the asphalt	60 min /5000 rpm	185 °C	FTIR, X-ray diffraction (XRD), softening point test , DSR, Tensile strength tests	combining PE and PET waste improves the mechanical and thermal characteristics of asphalt, providing a balance between stiffness and flexibility

Author, (Year), Country of the author	Bitumen class	Polymer type	Additive content %	Mixing time(min)and speed (rpm)	Mixing temperature (°C)	Tests performed	Observation
Plastic waste							
Puja Brohomo et al (2025) [28], Bangladesh	The 60-grade bitumen	PET (6 mm ± 0.1 mm)	2.5%, 5.0%, 7.5%, and 10%	dry method	dry method	Stability, Flow, Air void, VMA%, VFA%	The PET content positively affects the Marshall mix design That PET addition significantly improves rheological properties.
Usman Ghani et al (2022) [25] Pakistan	PG 58-22 and grade 60/70	HDPE and LDPE	2%, 4%, and 6% by weight of bitumen	60 min/ 3000 rpm	163°C	DSR, RTFOT, PAV, XRD, BBR, FTIR	Results have revealed the best rutting resistance for 6% HDPE. Similarly, the addition of 4% LDPE resulted in maximum dynamic viscosity irrespective of the temperatures.
Haibin Li et al (2022) [30], China	80/100 (SK-90)	(Polypropylene (PP) and polyethylene (PE))	PP: 0, 2, 4, 6, 8, 10, 12% PE: 0, 2, 4, 6, 8%	30, 60, 90 min/ 3000, 4000, 5000 rpm	170, 180, 190°C	FTIR, TG-DSC	The asphalt containing PP and PE shows better overall performance at high temperatures. PE-modified asphalt and PP-modified asphalt exhibited optimal properties when prepared at 3000 rpm for 30 min at 170 °C.
Melkamu Birlie Genet et al (2022) [26], Ethiopia	80/100	waste LDPE plastic (2-5mm)	4, 6, 8 and 10% waste LDPE plastic	60, 90 and 120 min	160, 170, and 180 ∘C	penetration point, softening point and ductility, Marshall Test	LDPE enhances key bitumen properties. Optimal mixing at 170 °C for 1.5 hours ensures a homogeneous blend, with an ideal LDPE content of 6.5% by weight of OBC.
Rubber waste							
Ayad Subhy et al (2018) [32], United Kingdom	Bitumen's with 200 dmm and 40 dmm penetration	Recycled waste tire rubber	18%	120 min/ 3000rpm	180 C	TFOT, PAV, DSR,	the rubber addition improves considerably the thermal oxidation aging resistance.
Danning Li et al. (2021) [33], Hong Kong	60–70	waste tires (CRM)	20% by weight of the raw asphalt	60 min/ 4000 rpm	180 °C	TFO chemical and rheological tests.	The addition of CRM could mitigate the oxidation degree of bitumen, while the bitumen fractions absorbed into the gel layer were even less oxidized, indicating the protective function of rubber absorption.

Author, (Year), Country of the author	Bitumen class	Polymer type	Additive content %	Mixing time(min)and speed (rpm)	Mixing temperature (°C)	Tests performed	Observation
			Rubber waste				
Emilio Turbay et al (2022) [34], Colombia	60/70	Crumb rubber (CR)	15, 18, 21%	50-60 min Wet process, time not specified	160-170°C	Penetration, softening point, RV, DSR, MSCR	CR increases binder stiffness, enhancing rutting resistance and softening points while reducing penetration and fatigue life. These effects amplify further as CR content increases.
Anar Akkenzheyeva et al (2023) [35], Kazakhstan	70/100	Crumb rubber obtained from used car tires and SBS	15 to 25%	60–120 min/ 6000–7000 rpm	~200 °C	penetration, softening point, elastic recovery, Fraass DSR,	As temperature increases, shear stress, viscosity and complex shear modulus decrease, while the phase angle increases. Rubber particle size has a significant influence on bitumen properties.
Barbara Gawdzik et al (2020) [36], Poland	50/70	Rubber from recycled car tires and SBS	10%, 15%	120, 240, 480 min	190 °C , 220 °C	penetration, softening point, Fraass Breaking Point, elastic recovery, Storage stability, DSC, RTFOT	for road building purposes, the waste product of recycled rubber can partially replace much more expensive SBS
Israel Rodríguez-Fernández et al (2020) [37], Switzerland	50/70	Crumb Rubber	1% by weight of aggregate	Dry Process	Dry Process	Marshall test, Water sensitivity (EN 12697-12), volumetric properties	the experimental asphalt mixtures were found to be less susceptible to aging than the reference mixture (PmB).
Haopeng Wang et al (2020) [38], Netherlands	70/100	Crumb rubber	5%, 10%, 15% and 22% by weight of base bitumen	30 min /6000 rpm	180 °C	frequency sweep tests, time sweep (TS) tests and linear amplitude sweep (LAS) tests	CRMB binders exhibit superior fatigue performance compared to the neat bitumen.
Muhammad Jamal, Filippo Giustozzi (2022) [39], Australia	C320	Waste rubber	7.5% ,15% ,22.5% of CR	30, 60 and 90 min (700 rpm and 3500 rpm)	177 ± 10 °C	Physio-chemical, thermal, and rheological tests	Shear rate and mixing time are closely linked and strongly influence rheological properties. A 60-minute mixing time is optimal for rubber particle swelling, while excessive mixing damages polymer chains and reduces performance

Author, (Year), Country of the author	Bitumen class	Polymer type	Additive content %	Mixing time(min)and speed (rpm)	Mixing temperature (°C)	Tests performed	Observation
				Rubber waste			
Greg White, Andrew Kidd (2025) [40], Australia	PG 64-22	Crumb rubber	5%, 10%, and 15% (by weight of the bitumen)	300 rpm for 300 min	190°C	stiffness, fatigue resistance, fracture resistance, rutting resistance, and moisture damage resistance. Penetration, Softening Point, Viscosity at 60 ∘ C, Segregation,	10% crumb rubber was optimal, significantly improving deformation and fatigue cracking resistance. However, performance varied with crumb rubber content and digestion time.
Qian Liu et al (2025) [41], China	60/80	rubber powder (RMA)	20%	10, 20, 30 min/ 3000, 4000, 5000 rpm	185°C	UV radiation, RTFO, DSR, BBR, FTIR,	Photo-oxidation impacts carbonyl groups more than sulfoxides due to increased chemical activity. While UV radiation triggers rubber detachment and cracking (especially in thin films (the rubber powder itself acts as a stabilizer by absorbing radiation.
				Combined plastic waste and rubber waste			
Arun Kumar et al (2022) [42] India	VG30 type of bitumen	waste tire rubber (CR), Plastic	8% CR (by weight of bitumen), 8% Waste plastic (by weight of aggregate)	Not clearly specified (standard lab mixing)	Aggregates and binder heated for hot-mix asphalt (exact °C not fully reported)	penetration test, flash/ point test, ductility test, viscosity test, softening point test, specific gravity test and Marshall Test,	Plastic mix asphalt outperforms standard and crumb rubber modified bitumen by providing maximum strength and stability with lower bitumen requirements.
Getnet Mekuria Alemu et al (2023) [43], Ethiopia	80/100	crumb rubber and polyethylene terephthalate plastic (PET)	5%, 10%, 15%, and 20%) of crumb rubber. 2%,4%, and 6% of PET	60 min	160°C	Penetration, ductility, softening point; Marshall stability, flow, stiffness; tensile strength; moisture susceptibility	A 10% crumb rubber and 2% PET blend provides the ideal asphalt mix, significantly enhancing tensile strength. This synergy proves that the additives are more effective when used together than individually.

Although numerous studies have reported improvements in asphalt performance through the incorporation of waste plastics and crumb rubber, the reported benefits vary considerably depending on the type, dosage, physical form, and incorporation method of the additive. In general, increasing the plastic content enhances binder stiffness and rutting resistance; however, excessive dosages may lead to increased brittleness and reduced cracking resistance. Similarly, crumb rubber contents in the range of 10–20% are often reported as optimal, providing a balance between stiffness and elasticity. At lower contents, the improvement in mechanical performance may be limited, whereas excessive rubber contents can significantly increase binder viscosity, complicate mixing and compaction operations, and affect workability. Furthermore, the effectiveness of these waste materials strongly depends on their interaction with the base binder and the production conditions, making direct comparison between studies difficult.

Despite the growing body of research, studies addressing the use of waste plastics and rubber-based materials in asphalt mixtures under Algerian conditions remain scarce. In particular, little attention has been given to the valorization of locally available waste plastic and waste nitrile rubber generated in Algeria and to their effects on the volumetric and mechanical performance of asphalt mixtures produced with local materials. Therefore, the novelty of the present study lies in evaluating the effectiveness of locally sourced waste nitrile rubber (WNR) and polypropylene waste plastic (WP) as partial bitumen replacement additives within the Algerian context. This work contributes to the existing body of knowledge by providing experimental evidence on the behavior of asphalt mixtures modified with materials representative of local resources and waste streams, thereby supporting the development of sustainable pavement technologies adapted to Algerian climatic and operational conditions.

The objective of this study is to evaluate the influence of waste nitrile rubber powder (WNR) and polypropylene waste plastic (WP) on the volumetric and mechanical performance of asphalt mixtures through physical modification of the bitumen binder. The originality of this work lies in the valorization of locally sourced aggregates and industrial waste materials available in Algeria, as well as in the comparative assessment of two different waste-derived modifiers. The findings are expected to contribute to the development of sustainable pavement solutions based on locally available alternative materials.

2. Materials and Methods

2.1. Base Materials

The base bitumen used in this study is a 35/50 penetration grade from Naftal (Algeria). This binder was chosen because it is commonly employed in Algerian pavement construction and provides an appropriate balance between stiffness and flexibility under the prevailing climatic conditions and traffic loading experienced in the region. Its penetration value is 38 ±0.1mm and its softening point 51.8 °C. Plastic waste (WP) used in this study was sourced from food packaging bags. After cleaning and drying, the material was cut into 2–6 mm fragments. The waste consists primarily of polypropylene with a density of 0.9 g/cm^3 and chemical formula C_3H_6 [44].

Table 2. Chemical and physical properties of aggregates

Standard	Test	Sieve (mm)	Results			Specifications
			0/3	3/8	8/15	
NF P18-591	Property	P (%)	-	0,576	0,18	< 2%
EN FN 933-3	flattening test	A (%)	-	7,56	10,71	< 20%
NF P18-572	Micro-Deval Wet	MDE (%)	-	14,68		< 20%
NF P18-573	Los Angeles	LA (%)	-	18,42		< 25%
NF P18-554	Density	G (g/cm^3)	2.57	2.61	2.62	-
NF P15-461	Chemical analysis %	Insoluble (SiO_2+Silicates)	4.9	6.4	5.6	-
		Sulfates	1.67	0.24		-
		Carbonates	76.3	84.38		-
		Gypsum ($CaSO_4$, $2H_2O$)	Traces	Traces	Traces	-
		Chlorides (NaCl)	0.21	0.45		-

Waste Nitrile Rubber (WNR) was obtained from shredded rubber soles provided by SAEL (Company of Application of elastomers, Algeria). The powder exhibited a particle size below 0.8 mm and a density of 1.22 g/cm^3. Aggregates used correspond to standard fractions (0/3, 3/8, 8/15) from the El Hachimia quarry were used, commonly applied in Algeria for surface asphalt layers.

Their chemical and physical properties are presented in Table 2. The aggregates are predominantly calcareous in nature.

2.2. Preparation of Polymer-Modified Bitumen

Polymer-modified binders were produced by incorporating 1%, 3%, and 5% of polymer additive (WP or WNR) by weight of bitumen. These dosage levels were selected based on previous studies [44] and preliminary laboratory observations, which indicated that contents below 1% have a negligible effect on asphalt mixture performance, whereas contents above 5% may significantly increase binder viscosity and compromise mixture homogeneity. Mixing was carried out at 175 ± 5 °C and 650 rpm for 2 h to ensure adequate dispersion and homogenization of the additives within the bitumen.

2.3. Asphalt Mix Design and Specimen Preparation

The asphalt mixture used is a 0/14 bituminous concrete, the most common surface layer in Algeria. The selected aggregate proportions were 35% of 0/3, 30% of 3/8, and 35% of 8/15, with a constant binder content of 5.8% by mass of aggregates. A conventional 0/14 asphalt mixture prepared with unmodified 35/50 penetration-grade bitumen served as the control mixture.

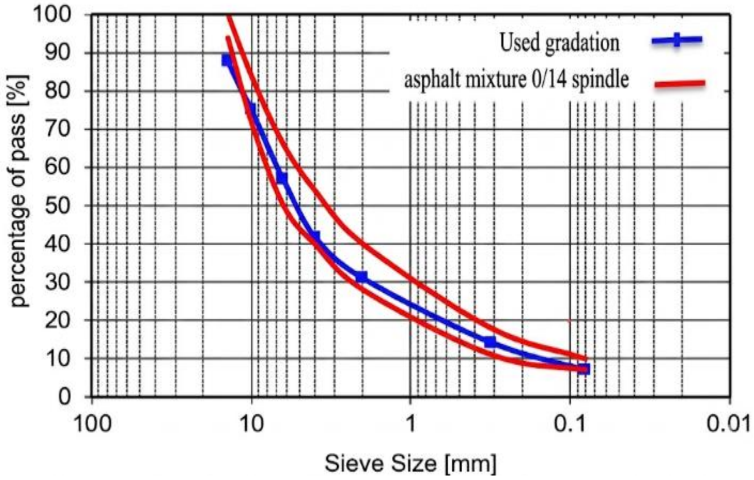

Fig. 1. Particle size distribution curve of the 0/14 mixture

Fig. 2. Marshall testing apparatus and speciment fabrication

Aggregates and binders were preheated at 165 °C and mixed at 165 °C for 3 minutes, according to EN 12697-35. After mixing, Marshall specimens (101 mm of diameter and 63 mm of high) were compacted with 50 blows per face. All specimens were cooled under controlled conditions, then demolded and conditioned for 24 hours before testing. Figure 1 shows the particle size distribution curve for a 0/14 mixture.

2.4. Marshall Test

The Marshall tests (MT) were conducted to examine the asphalt's resistance to cracking and rutting under heavy traffic [24]. Marshall stability (SM), flow (FM), and Marshall quotient (MQ = SM/FM) were measured according to the EN 12697-34. Specimens were immersed at 60 °C for 30 minutes before testing at a loading rate of 0.86 mm/s. Figure 2 illustrates the Marshall specimen fabrication process

2.5 Volumetric Analysis of Compacted Mixes

Volumetric analysis of mixtures is considered one of the most important decisive factors for predicting pavement performance and lifespan.

2.5.1 Bulk Specific Gravity of the Total Aggregate (Gsb)

The bulk specific gravity of the mixture (Gsb) is calculated using the following weighted average formula: [26]

$$G_{sb} = \frac{P_1 + P_2 + \cdots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \cdots + \frac{P_n}{G_n}} \tag{1}$$

Where: P_i: indicates the percentage corresponding to each aggregate, and Gi corresponds individual bulk specific gravity of aggregates.

2.5.2. Effective Specific Gravity of Aggregate

The effective specific gravity (Gse) considers all void spaces present in the granular particles, except the ones that have absorbed bitumen. It establishes the relationship between the bulk and apparent specific gravities and is calculated as: [26] [45]

$$Gse = \frac{100 - Pb}{\frac{100}{Gmm} - \frac{Pb}{Gb}} \tag{2}$$

$$Gmm = \frac{100}{\frac{Ps}{Gsb} + \frac{Pb}{Gb}} \tag{3}$$

Where: Ps = aggregate content (percent by total weight of mixture), Pb= bitumen content, Gb = specific gravity of the bitumen, Gmm = maximum theoretical specific gravity of the loose paving mixture.

2.5.3 Air Voids (VA)

Air voids refer to the total volume of air spaces between the coated aggregate particles in a compacted mixture and are expressed as a percentage of the bulk volume. The air void content is determined by: [26] [45]:

$$VA = 100\frac{(G_{mm} - G_{mb})}{G_{mm}} \tag{4}$$

2.5.4 Void in the Mineral Aggregate (VMA)

VMA corresponds to the intergranular space existing between aggregate particles in a mixture intended for compressed paving. This volume includes the air voids as well as the effective volume of bitumen [36]. It is calculated using Eq (5) [26,45]:

$$VMA = 100 - \frac{Gmb \ X \ Ps}{Gsb} \tag{5}$$

2.5.5 Void filled with bitumen (VFB)

VFB is the percentage of the intergranular void space (VMA) that is occupied by the effective bitumen film. It represents the degree to which the aggregate voids are filled with binder. The VFB is determined by [26] [45]:

$$VFB = 100\,(1-\frac{VA}{VMA}) \quad (6)$$

Figure 3 provides a summary of the overall methodology that was adopted in this study.

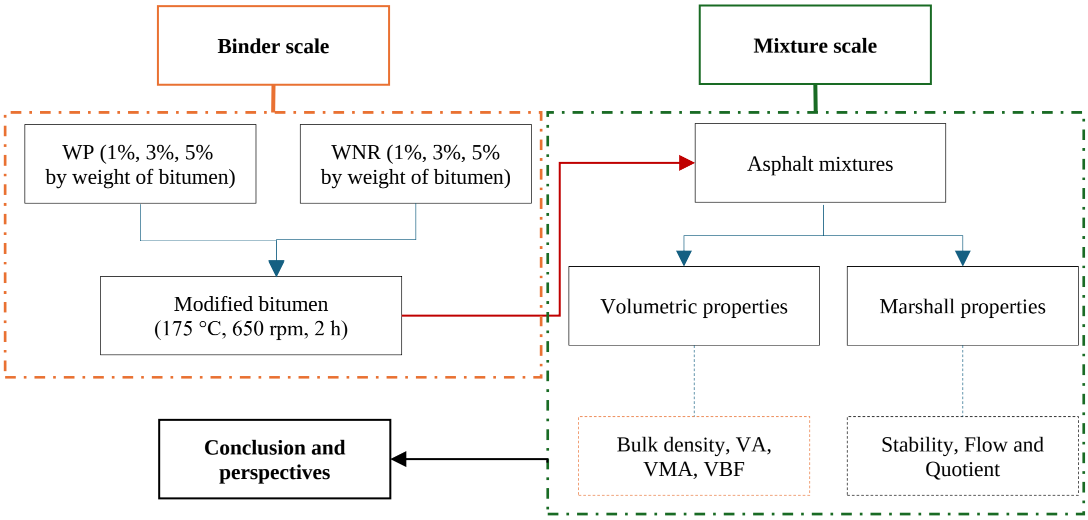

Fig. 3. Overall methodology that was adopted in this study

3. Results and Discussion

3.1. Volumetric Properties of Asphalt Mixtures

3.1.1. Bulk Density

Bulk density represents the actual density of the compacted asphalt mixture and reflects the overall packing efficiency and internal structure of the mix. As shown in Figure 4, the bulk density of both WP- and WNR-modified mixtures increases with increasing additive content, reaching maximum values at 5%. This trend is consistent with the simultaneous reduction in air voids, indicating improved densification of the mixtures. The incorporation of polymeric modifiers enhances aggregate coating and promotes better rearrangement of particles during compaction, leading to a more compact structure.

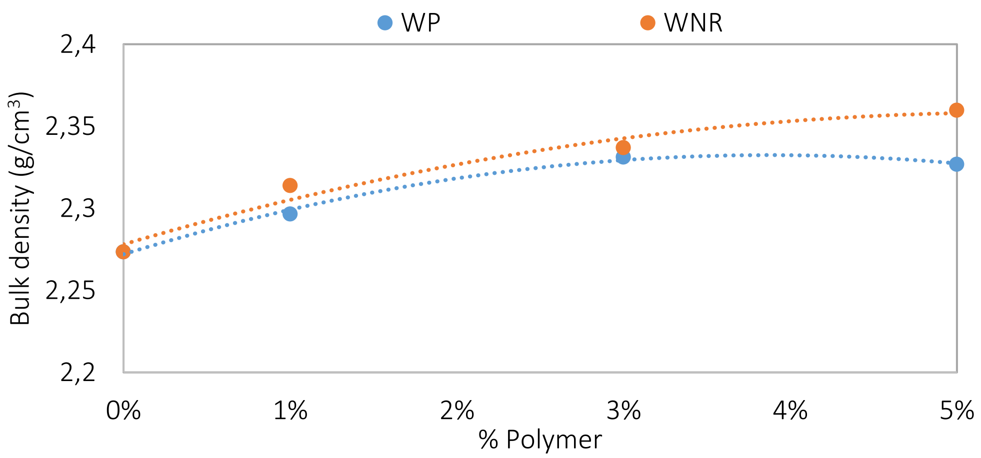

Fig. 4. Bulk density as a function of WP and WNR content

A noticeable difference is observed between the two modifiers, with WNR-modified mixtures exhibiting higher bulk density compared to WP-modified mixtures at equivalent contents. This behavior can be attributed to the swelling capacity of nitrile rubber, which increases the effective binder volume and enhances void filling, thereby improving packing efficiency. In contrast, the higher stiffness of WP-modified binders may reduce workability during compaction, slightly limiting densification despite their higher intrinsic rigidity.

3.1.2. Air Void Content (Va)

Figure 5 shows a progressive decrease in air void content with increasing WP and WNR content, confirming the densification trend observed in bulk density results. These two parameters are intrinsically linked, as an increase in bulk density directly corresponds to a reduction in air voids. The reduction in air voids is mainly attributed to improve binder distribution and enhanced filling of intergranular spaces [21]. From a durability perspective, this is beneficial as it limits the ingress of oxygen, moisture, and UV radiation, thereby reducing oxidative aging and moisture damage [46, 47].

At equivalent dosages, WNR-modified mixtures exhibit lower air void contents than WP-modified mixtures. This difference is explained by the swelling behavior of nitrile rubber, which absorbs light fractions from the bitumen and expands, increasing the effective binder volume. This mechanism significantly improves void filling and packing efficiency. Conversely, WP acts primarily as a stiffening agent with limited volumetric expansion. Its higher viscosity can reduce mixture workability, making compaction less efficient and resulting in relatively higher air void contents. However, an important limitation is observed for WNR at high contents. At 5% WNR, the air void content approaches a very low value (~1.85%), which may lead to durability concerns such as bleeding, rutting, or creep due to excessive binder presence [48, 49]. In contrast, WP-modified mixtures maintain air void levels within the recommended range (typically 3-5%), indicating a more balanced volumetric structure [46, 47].

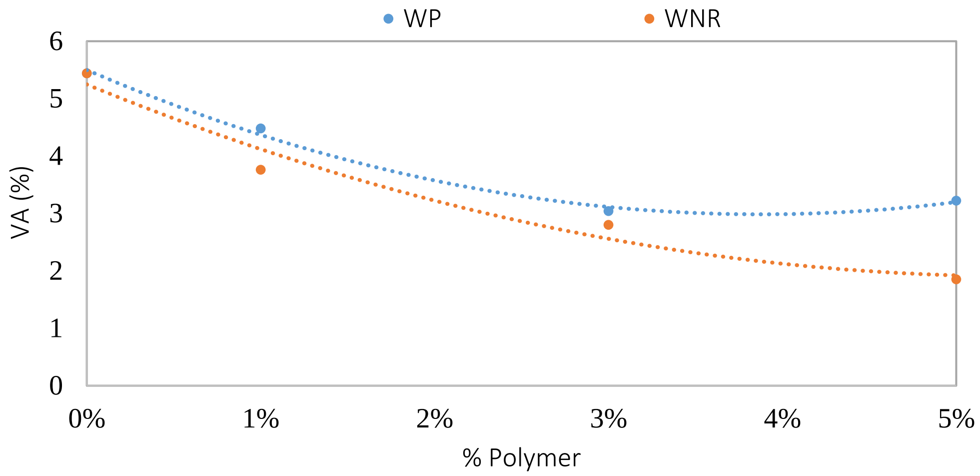

Fig. 5. Air void content as a function of WP and WNR content

3.1.3 Voids in Mineral Aggregate (VMA)

VMA represents the total volume of intergranular void space within the aggregate skeleton and is a key parameter controlling the amount of binder required for adequate coating and durability. As shown in Figure 6, VMA decreases gradually with increasing polymer content for both WP and WNR. This trend is consistent with the reduction in air voids and the increase in bulk density, confirming the progressive densification of the mixtures. The decrease in VMA indicates a more efficient packing of aggregates combined with improved binder distribution [50, 51]. However, excessive reduction in VMA may be detrimental, as it limits the space available for binder, potentially affecting durability. A more pronounced decrease is observed for WNR-modified mixtures, reaching values close to the lower specification limit (~14-14.5%) at 5% additive. This behavior is directly related to the swelling of rubber particles, which occupy part of the intergranular space and reduce the available void volume. Although all mixtures satisfy the minimum VMA requirement for surface courses, the values obtained for high WNR contents suggest a critical condition where further reduction could compromise durability, particularly in terms of binder film thickness and resistance to aging.

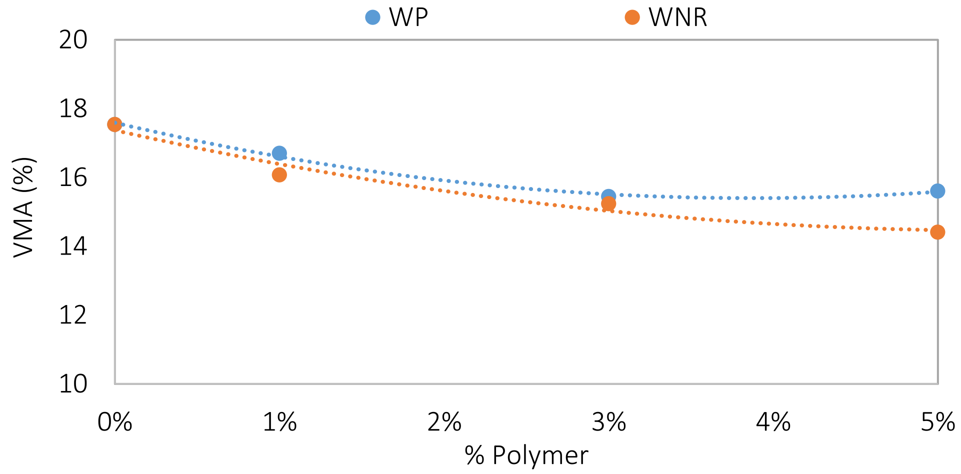

Fig. 6. VMA as a function of WP and WNR content

3.1.4 Voids Filled with Bitumen (VFB)

VFB represents the percentage of VMA filled with binder and is directly influenced by both air voids and VMA. As expected from the previous results, VFB increases with increasing polymer content for both modifiers. This increase is a direct consequence of decreasing air voids and decreasing VMA, which together lead to a higher proportion of void space being occupied by binder. WNR-modified mixtures exhibit significantly higher VFB values, reaching up to ~87% at 5% content, compared to ~79% for WP. This behavior is consistent with the swelling and absorption characteristics of nitrile rubber, which increase the effective binder volume and promote a more continuous binder phase.

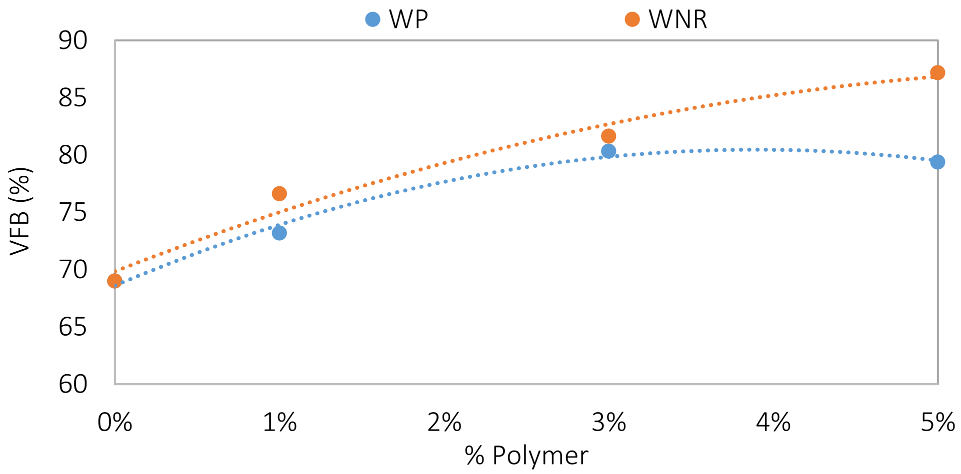

Fig. 7. VFB as a function of WP and WNR content

Additionally, the polar nature of nitrile rubber enhances its interaction with the aromatic and resin fractions of bitumen [52], improving compatibility and facilitating binder diffusion into the rubber particles. This results in a more homogeneous and dense internal structure [44, 45]. In contrast, WP, being nonpolar and more rigid, shows limited interaction with the bitumen matrix. Its contribution is mainly mechanical (stiffening) rather than volumetric, leading to lower VFB values [21,52]. However, excessively high VFB values, as observed in WNR mixtures at high contents, may indicate overfilling of voids, which can increase the risk of bleeding and permanent deformation under loading.

3.2 Marshall Stability

Figure 8 illustrates the variation of Marshall stability (MS) of asphalt mixtures incorporating different contents of waste plastic (WP) and waste nitrile rubber (WNR). A clear increasing trend in Marshall stability is observed with increasing content of both modifiers, indicating an overall enhancement in the load-bearing capacity and resistance to plastic deformation of the mixtures. This improvement can be attributed to the modification of the binder phase, which enhances the cohesion within the mixture and strengthens the aggregate-binder adhesion. The incorporation of polymeric waste leads to a more structured binder, which improves stress distribution under loading and limits permanent deformation. As a result, the mixtures exhibit higher resistance to applied loads, which is a key requirement for pavement performance under traffic conditions.

The superior performance of WNR-modified mixtures can be explained by the elastomeric nature of nitrile rubber. Upon interaction with bitumen, WNR particles swell and form a flexible, three-dimensional network within the binder. This structure enhances the ability of the mixture to absorb and redistribute stresses under loading, thereby delaying the initiation of microcracks and improving resistance to deformation under repeated or sustained loads. In contrast, waste plastic primarily increases binder stiffness through the formation of a rigid structure. While this contributes to higher resistance to deformation at high temperatures, excessive stiffness may reduce the mixture's ability to relax stresses, leading to a more brittle response under loading conditions. Consequently, the load-bearing efficiency at the mixture level may be lower compared to WNR-modified mixtures, despite the higher stiffness of the binder. Overall, these results suggest that WNR provides a better balance between stiffness and elasticity, which is critical for optimizing Marshall stability and improving the mechanical performance of asphalt mixtures.

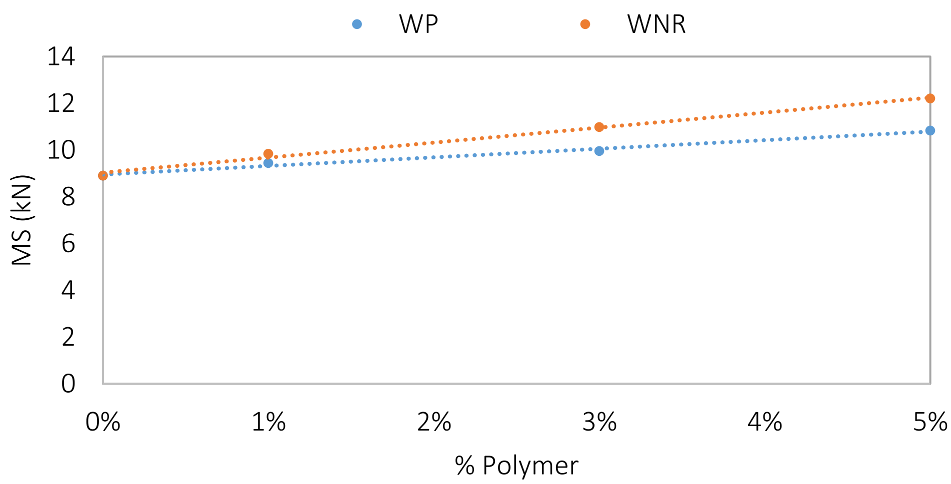

Fig. 8. Marshall Stability as a function of WP and WNR content

3.3 Marshall Flow (FM)

Figure 9 presents the variation of Marshall Flow (FM) for asphalt mixtures modified with waste plastic (WP) and waste nitrile rubber (WNR). Marshall Flow reflects the deformation capacity of the mixture at failure and provides important insight into its flexibility and ability to accommodate stresses without cracking [53]. For WP-modified mixtures, a slight decrease in Marshall Flow is observed with increasing additive content, followed by a stabilization beyond approximately 3%. This behavior indicates an increase in mixture stiffness, which limits deformation under load. This trend is consistent with the binder-level observations [54], where WP significantly reduces penetration and increases the softening point, resulting in a stiffer and less deformable material. However, the stabilization of Flow at higher contents suggests that beyond a certain threshold, additional plastic does not significantly alter the deformation behavior, likely due to reduced workability and limited further modification of the internal structure.

In contrast, WNR-modified mixtures exhibit a continuous and more pronounced reduction in Marshall Flow with increasing additive content. This indicates a progressive limitation of deformation under load, combined with an enhanced ability to control strain. Unlike WP, this behavior is not solely due to increased stiffness, but rather to the development of a viscoelastic network within the binder. The swelling of rubber particles and their interaction with bitumen lead to a flexible three-dimensional structure capable of absorbing and redistributing stresses, thereby limiting excessive deformation while maintaining structural integrity. At equivalent dosages, WNR-modified mixtures consistently show lower Marshall Flow values compared to WP-modified mixtures. This difference can be directly linked to the combined effects of volumetric and rheological modifications. The lower air void content and higher VFB observed in WNR mixtures contribute to a denser and more cohesive internal structure, which restricts deformation. Simultaneously, the elastomeric nature of nitrile rubber enhances stress recovery and reduces permanent strain.

From a coupled interpretation with Marshall Stability, the reduction in Flow together with the increase in Stability suggests an overall improvement in mixture resistance to deformation. However, it is important to note that excessively low Flow values, particularly at high WNR contents, may indicate reduced deformation capacity, which could increase the risk of brittleness or cracking under certain loading or temperature conditions. Overall, while both WP and WNR improve the mechanical performance of asphalt mixtures, they do so through different mechanisms. WP primarily enhances stiffness, leading to reduced deformability, whereas WNR provides a more balanced improvement by combining densification (lower air voids, higher VFB) with viscoelastic stress dissipation. This makes WNR particularly effective in improving resistance to permanent deformation while maintaining adequate flexibility.

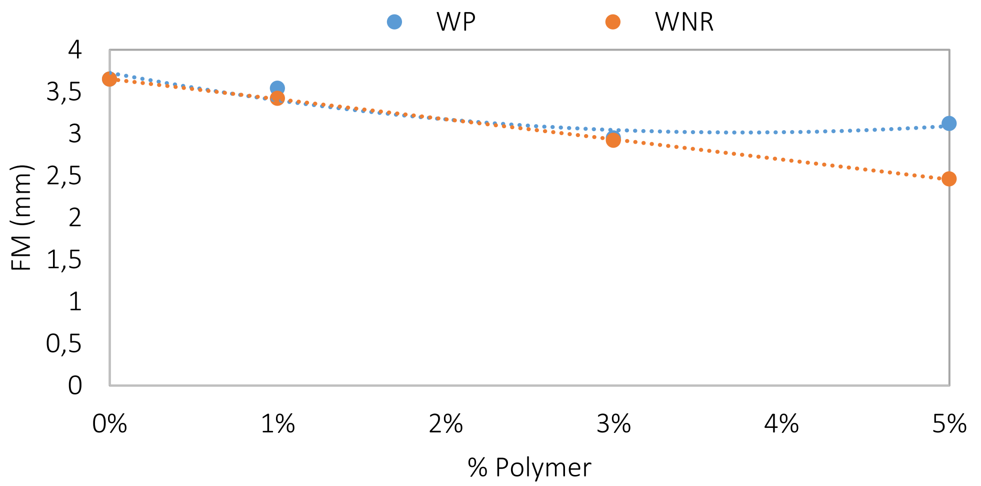

Fig. 9. Marshall Flow as a function of WP and WNR content

3.4 Marshall Quotient (MQ)

Figure 10 illustrates the effect of incorporating waste plastic (WP) and waste nitrile rubber (WNR) on the Marshall Quotient (MQ) of asphalt mixtures. An overall increase in MQ is observed with increasing additive content for both modifiers, indicating an enhancement in the mixture's resistance to deformation under load [24]. Since MQ is defined as the ratio of Marshall Stability to Marshall Flow, its increase reflects the combined effect of higher load-bearing capacity (increase in Stability) and reduced deformation (decrease in Flow) [55]. Therefore, MQ provides a more comprehensive indicator of mixture stiffness and structural integrity than either parameter considered individually. For both WP- and WNR-modified mixtures, MQ tends to stabilize beyond approximately 3% additive content, suggesting that the improvement in mechanical performance reaches a plateau. This behavior is consistent with previous observations on Marshall Flow and volumetric properties, where limited additional densification and structural modification occur at higher dosages.

A clear distinction is observed between the two modifiers, with WNR-modified mixtures exhibiting significantly higher MQ values, exceeding 5 kN/mm, compared to WP-modified mixtures, which remain below 4 kN/mm. This difference can be explained by the combined volumetric and rheological effects induced by WNR. From a volumetric perspective, WNR-modified mixtures exhibit lower air voids and higher VFB, resulting in a denser and more cohesive internal structure. From a rheological standpoint, the swelling of nitrile rubber particles and their interaction with the bitumen lead to the formation of a viscoelastic network capable of efficiently redistributing stresses and limiting permanent deformation [52]. In contrast, WP primarily increases binder stiffness without significantly enhancing stress redistribution mechanisms or volumetric efficiency. As a result, although WP improves MQ, its effect remains less pronounced compared to WNR. It is important to note, however, that excessively high MQ values, particularly at high WNR contents, may indicate an overly stiff mixture with reduced deformation capacity. This observation is consistent with the very low air void content and high VFB values previously reported, which may increase the risk of brittleness, cracking, or bleeding under service conditions. Overall, the results highlight that while both modifiers improve the mechanical performance of asphalt mixtures, WNR provides a more effective enhancement due to its combined densification and viscoelastic mechanisms. Nevertheless, an optimal dosage should be carefully defined to balance stiffness and flexibility and ensure long-term pavement performance.

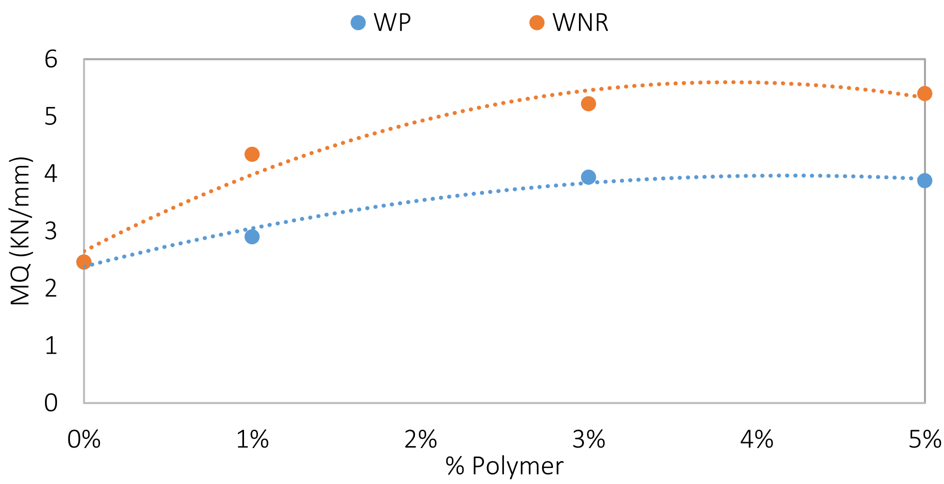

Fig. 10. Marshall Quotient as a function of WP and WNR content

4. Discussion

4.1. Relationship between Volumetric and Mechanical Properties

To better understand the mechanisms governing the performance of the modified asphalt mixtures, correlations were established between the volumetric properties (VA, VMA, and VFB) and the Marshall parameters (MS and FM). As shown in Figures 11-13, strong relationships were obtained, with coefficients of determination exceeding 0.98 in all cases, indicating that the mechanical response of the mixtures is closely controlled by their internal volumetric structure. A clear linear relationship was observed between Marshall Stability and the volumetric parameters. Marshall Stability decreased with increasing air void content (VA) and VMA, while it increased with increasing VFB. These trends indicate that denser mixtures with a larger proportion of voids filled by bitumen are able to withstand higher loads before failure. The negative correlation between MS and VA suggests that excessive air voids reduce aggregate interlock and create stress concentration zones within the mixture. Similarly, higher VMA values indicate a larger volume of unfilled spaces within the aggregate skeleton, resulting in lower structural cohesion and reduced load-bearing capacity.

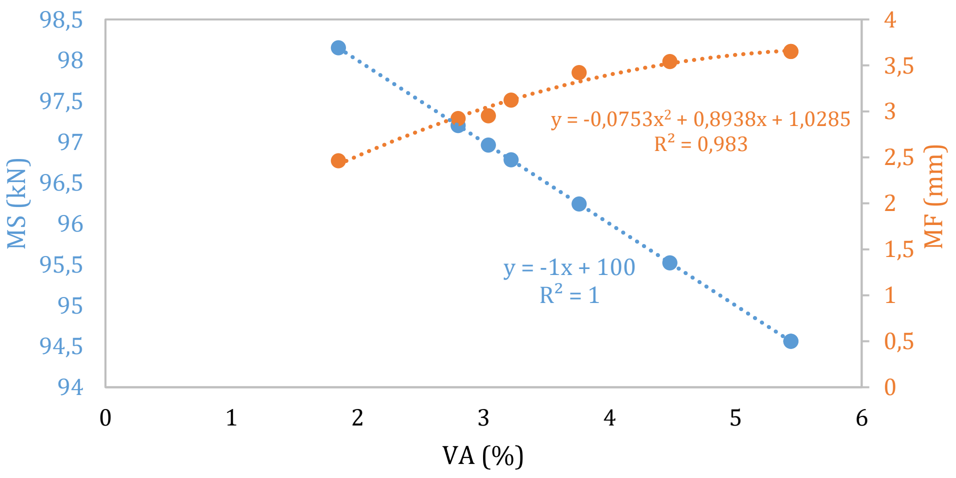

Fig. 11. Correlation between Marshall parameters and air void content (VA)

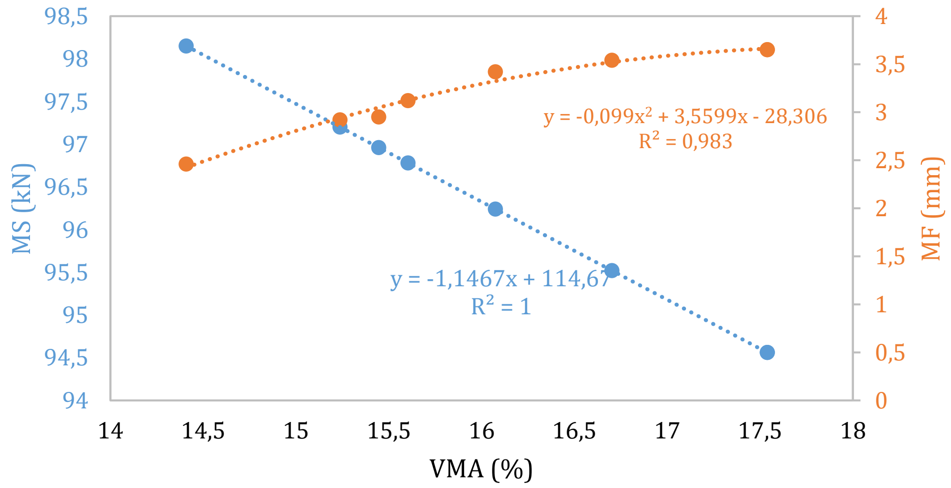

Fig. 12. Correlation between Marshall parameters and voids in mineral aggregate (VMA)

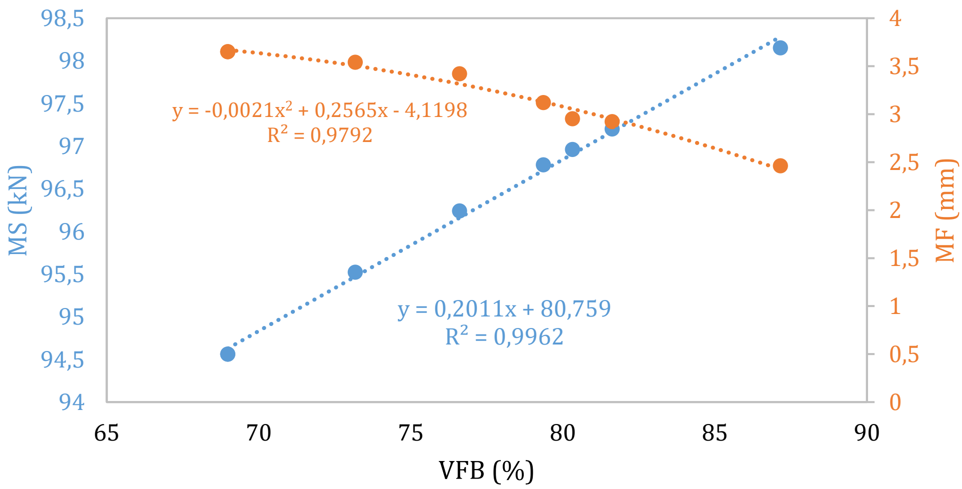

Fig. 13. Correlation between Marshall parameters and voids filled with bitumen (VFB)

Conversely, increasing VFB reflects a more effective filling of the available void structure by the binder, leading to improved aggregate bonding and a more homogeneous stress distribution throughout the mixture. The evolution of Marshall Flow also exhibited strong correlations with the volumetric characteristics. Unlike Stability, the relationship between Flow and the volumetric parameters was best described by second-order polynomial functions. Flow increased with increasing VFB and decreased with increasing VA and VMA. This behavior highlights the dual role of the binder in controlling mixture deformability. As the void structure becomes progressively filled, the continuity of the binder phase increases, allowing greater strain accommodation before failure. However, when the mixture contains higher air void contents or larger VMA values, the discontinuity of the internal structure restricts stress transfer and reduces the deformation capacity. These results demonstrate that the improvements observed in Marshall Stability and Flow are not solely related to the intrinsic properties of the modified binders, but are also strongly influenced by the volumetric evolution of the asphalt mixtures. The addition of WP and WNR reduces air voids and VMA while increasing VFB, resulting in a denser internal structure. This densification enhances aggregate–binder interaction and promotes more efficient stress transfer under loading conditions. The superior performance of WNR-modified mixtures can also be explained through this volumetric-mechanical relationship. The swelling of nitrile rubber particles increases the effective binder volume, leading to lower air void contents and higher VFB values than those obtained with WP. Consequently, WNR mixtures develop a more cohesive internal structure, which contributes to their higher Marshall Stability and Marshall Quotient values. In contrast, WP primarily acts by increasing binder stiffness, with a less pronounced effect on volumetric optimization.

4.2. Relative Improvement in Marshall Properties Compared to the Control Mixture

To quantify the effectiveness of the two waste modifiers, the relative variation of Marshall Stability (MS), Marshall Flow (FM), and Marshall Quotient (MQ) was calculated with respect to the control mixture, as shown in Figures 14 and 15. The incorporation of WP resulted in a progressive increase in Marshall Stability, ranging from approximately 6% at 1% WP to 22% at 5% WP. Simultaneously, Marshall Flow decreased by about 3%, 19%, and 15% for 1%, 3%, and 5% WP, respectively. As a consequence, Marshall Quotient increased substantially, reaching improvements of 18%, 60%, and 58% for 1%, 3%, and 5% WP, respectively. These results indicate that waste plastic primarily acts as a stiffening modifier. This behavior is consistent with the binder characterization, where WP significantly reduced penetration and increased the softening point [54]. The thermoplastic nature of the plastic promotes the formation of a rigid structure within the bitumen, increasing mixture stiffness and reducing its susceptibility to deformation. The incorporation of WNR also resulted in significant improvements in mechanical performance. Marshall Stability increased by approximately 11%, 23%, and 37% for 1%, 3%, and 5% WNR, respectively, while Marshall Flow decreased continuously, reaching a reduction of nearly 33% at 5% WNR. Consequently, Marshall Quotient exhibited the most remarkable improvement, increasing by approximately 76% at 1% WNR and up to 120% at 5% WNR compared with the control mixture. These results demonstrate the superior ability of WNR to enhance the structural integrity of asphalt mixtures.

The different responses of WP and WNR can be explained by their distinct modification mechanisms. Waste plastic mainly improves mixture performance through binder stiffening. The formation of a rigid thermoplastic structure increases resistance to deformation but has a limited influence on the internal stress redistribution mechanisms of the mixture. This explains the moderate increase in Stability and the plateau observed in MQ beyond 3% WP. In contrast, nitrile rubber waste provides a dual reinforcement mechanism. Besides increasing binder consistency, WNR particles absorb light fractions from the bitumen and swell, generating a viscoelastic network within the binder matrix. This network enhances stress distribution and recovery under loading, resulting in higher Stability and lower Flow values. Furthermore, the volumetric analysis revealed lower air void contents, lower VMA values, and higher VFB values in WNR-modified mixtures, indicating a denser and more cohesive internal structure. The combination of volumetric densification and viscoelastic reinforcement explains the substantial increase in Marshall Quotient observed for WNR mixtures.

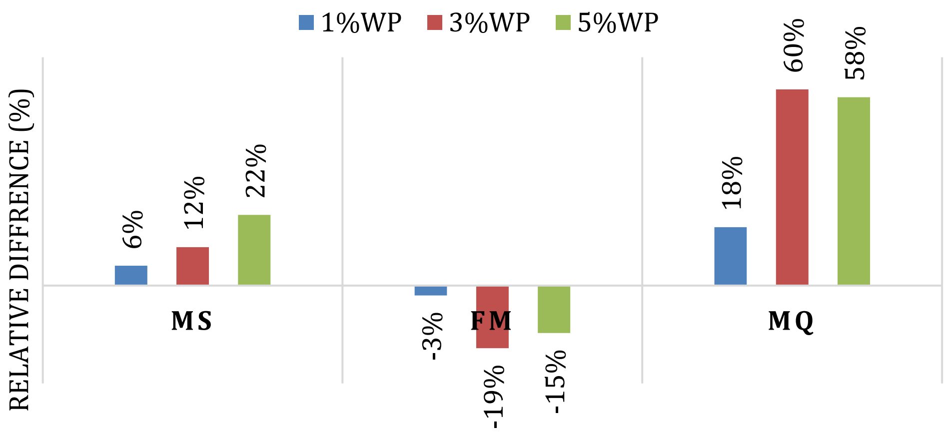

Fig. 14. Relative variation of Marshall properties of WP-modified asphalt mixtures with respect to the control mixture

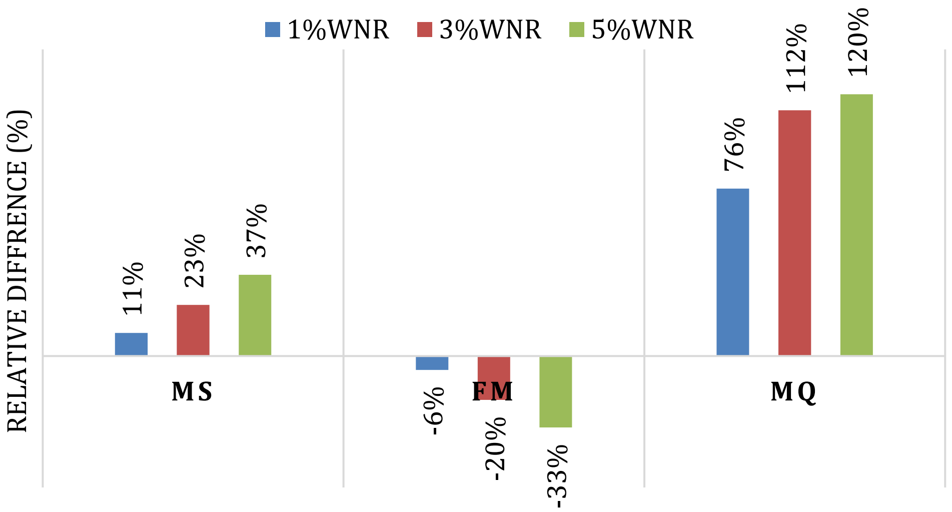

Fig. 15. Relative variation of Marshall properties of WNR-modified asphalt mixtures with respect to the control mixture

4.3. Multi-Criteria Assessment of WP- and WNR-Modified Mixtures

To provide a comprehensive assessment of the effects of WP and WNR on asphalt mixture performance, the volumetric and Marshall parameters were normalized with respect to their maximum values and represented using radar charts (Figures 16 and 17). This approach enables simultaneous visualization of the evolution of multiple performance indicators and facilitates identification of the most balanced modifier content. For WP-modified mixtures, the radar plot shows a progressive expansion of the performance envelope with increasing additive content. Marshall Stability, Marshall Quotient, bulk density, and VFB increase continuously, whereas air voids decrease significantly. The most notable improvement occurs between 0% and 3% WP, beyond which only marginal changes are observed. In particular, Marshall Quotient and air void content exhibit a clear stabilization between 3% and 5% WP, indicating that additional plastic provides limited mechanical and volumetric benefits. This observation is consistent with the plateau previously identified in the Marshall Flow and volumetric analyses. Consequently, 3% WP appears to represent a practical optimum, offering substantial improvements in stiffness, stability, and densification while avoiding unnecessary additive consumption.

A different behavior is observed for WNR-modified mixtures. The radar chart reveals a continuous expansion of the performance envelope over the entire dosage range investigated. Marshall

Stability, Marshall Quotient, bulk density, and VFB continue to improve from 1% to 5% WNR, while air void content decreases markedly. This trend confirms the strong influence of nitrile rubber on both the volumetric structure and mechanical behavior of asphalt mixtures. The swelling of rubber particles within the bitumen increases the effective binder volume and promotes the formation of a viscoelastic network, resulting in enhanced aggregate-binder cohesion and improved stress redistribution under loading. Although the 5% WNR mixture exhibits the highest overall mechanical performance, the radar chart also highlights a substantial reduction in air void content and VMA. This indicates that the gains in strength and stiffness are accompanied by a progressively denser internal structure. Excessive densification may reduce the mixture's tolerance to thermal expansion and increase susceptibility to bleeding or rutting under severe service conditions. Therefore, while 5% WNR provides the highest Marshall performance, a dosage around 3% may offer a more balanced compromise between mechanical enhancement and volumetric requirements. A comparison between the two modifiers clearly demonstrates that WP and WNR improve asphalt mixtures through different mechanisms. WP mainly acts as a stiffening agent, producing rapid improvements that tend to stabilize beyond 3%. In contrast, WNR provides a combined effect of volumetric densification and viscoelastic reinforcement, resulting in continuous performance enhancement across the investigated dosage range.

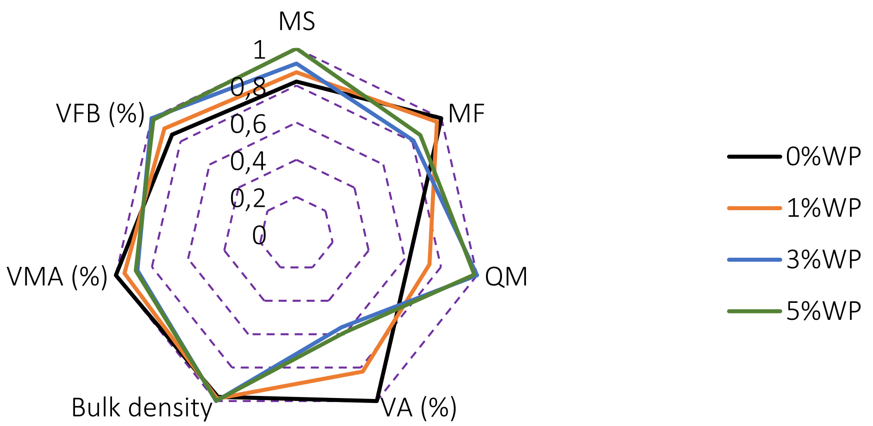

Fig. 16. Normalized multi-criteria performance assessment of asphalt mixtures modified with waste plastic (WP)

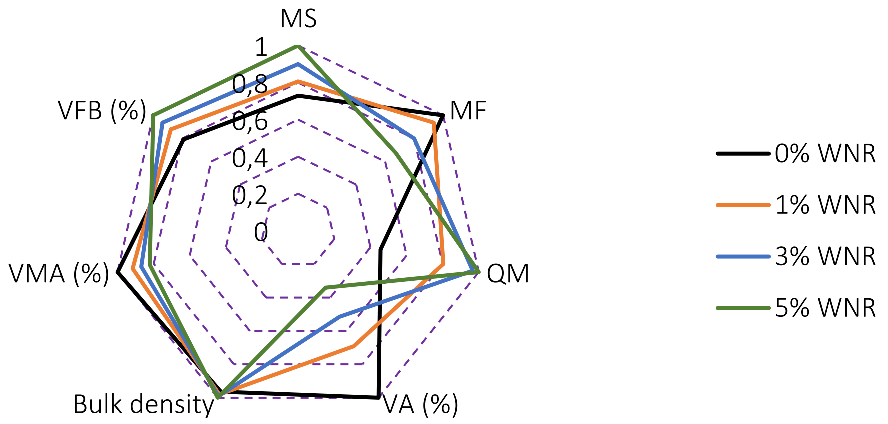

Fig. 17. Normalized multi-criteria performance assessment of asphalt mixtures modified with waste nitrile rubber (WNR)

5. Conclusion

The management of plastic and rubber waste represents a major environmental and economic challenge in Algeria, where increasing quantities of non-biodegradable waste pose significant risks to ecosystems and public health. In this context, the valorization of waste materials in road construction emerges as a highly promising solution. The incorporation of waste plastic (WP) and waste nitrile rubber (WNR) into asphalt materials not only contributes to reducing environmental pollution but also offers substantial economic benefits by lowering the demand for virgin materials and improving pavement performance.

The objective of this study was to evaluate the effect of WP and WNR on both the physical properties of bitumen and the mechanical and volumetric performance of asphalt mixtures, with the aim of assessing their suitability for large-scale implementation in Algeria using locally available waste resources. The main findings of this study can be summarized as follows:

- Marshall Stability increased continuously with additive content. Relative to the control mixture, the increase reached approximately 22% for 5% WP and 37% for 5% WNR, confirming the enhanced load-bearing capacity of the modified mixtures.
- Marshall Flow decreased by about 15% for 5% WP and 33% for 5% WNR, indicating a significant reduction in deformation susceptibility under loading.
- Marshall Quotient exhibited the most pronounced improvement, increasing by approximately 58% for 5% WP and 120% for 5% WNR, demonstrating a substantial enhancement in stiffness and resistance to permanent deformation.
- The incorporation of both modifiers improved the volumetric characteristics of asphalt mixtures by increasing bulk density and reducing air voids. WNR produced the most significant densification effect due to its swelling behavior, resulting in lower VA, lower VMA, and higher VFB values than WP-modified mixtures.
- The integrated analysis revealed that WP mainly acts as a stiffening modifier, whereas WNR provides a combined effect of volumetric densification and viscoelastic reinforcement, leading to superior overall performance.

Based on the multi-criteria assessment, an optimum content of approximately 3% WP was identified, as higher dosages provided only marginal additional benefits. For WNR, the best mechanical performance was obtained at 5%; however, a dosage around 3–5% appears to provide the best compromise between mechanical enhancement and volumetric requirements. Overall, the results demonstrate that both WP and WNR constitute viable and sustainable alternatives for asphalt modification. Their use in Algeria would simultaneously contribute to waste management, resource conservation, and pavement performance enhancement, particularly in regions exposed to high service temperatures.

Future work should focus on pilot-scale implementation, long-term field monitoring under traffic and climatic conditions, and life-cycle assessment to support the large-scale deployment of these recycled materials in Algerian road infrastructure.

References

[1] Bentata A, Kebaili N, Chaib H, Boucherba M. Experimental characterization of design performance of sand-grained asphalt concrete for worn pavement. International Journal of Sustainable Construction Engineering and Technology. 2024;15(2):54–62. https://doi.org/10.30880/ijscet.2024.15.02.005

[2] Bouacha N, Bouguerra A, Bouafia A. Improving the resilience of the road network in Algeria: a comparative analysis of flexible, geosynthetically reinforced, and rigid pavements. Sustainability. 2023;15(19):14426. https://doi.org/10.3390/su151914426

[3] Moudjari M, Belachia M. Comparative study of the deflection of a flexible pavement under the effect of a low traffic. International Review of Civil Engineering (IRECE). 2019;10(5):249–255. https://doi.org/10.15866/irece.v10i5.16539

[4] Airey GD. Styrene butadiene styrene polymer modification of road bitumens. Journal of Materials Science. 2004;39:951–959. https://doi.org/10.1023/B:JMSC.0000012927.00747.83

[5] Yildirim Y. Polymer modified asphalt binders. Construction and Building Materials. 2007;21:66–72. https://doi.org/10.1016/j.conbuildmat.2005.07.007

[6] Lu X, Isacsson U. Low-temperature properties of styrene–butadiene–styrene polymer modified bitumens. Construction and Building Materials. 1998;12(8):405–414. https://doi.org/10.1016/S0950-0618(98)00032-4
[7] AND. Rapport sur l'état de la gestion des déchets en Algérie. Agence Nationale des déchets, Alger. 2020. https://and.dz/site/wpcontent/uploads/rapport%20DMA2.pd
[8] Cheniti H, Kerboua K, Sekiou O, Aouissi HA, Benselhoub A, Mansouri R, Zeriri I, Barbari K, Gilev JB, Bouslama Z. Life cycle assessment of municipal solid waste management within open dumping and landfilling contexts: a strategic analysis and planning responses applicable to Algeria. Sustainability. 2024;16(16):6930. https://doi.org/10.3390/su16166930
[9] Chamas A, Moon H, Zheng J, Qiu Y, Tabassum T, Jang JH, Mahdi AO, Susannah LS, Suh S. Degradation rates of plastics in the environment. ACS Sustainable Chemistry & Engineering. 2020;8(9):3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635
[10] Basik AA, Sanglier JJ, Yeo CT, Sudesh K. Microbial degradation of rubber: Actinobacteria. Polymers. 2021;13(12):1989. https://doi.org/10.3390/polym13121989
[11] Sun Y, Duan C, Cao N, Ding C, Huang Y, Wang J. Effects of microplastics on soil microbiome: the impacts of polymer type, shape, and concentration. Science of the Total Environment. 2022;806:150516. https://doi.org/10.1016/j.scitotenv.2021.150516
[12] Baensch-Baltruschat B, Kocher B, Stock F, Reifferscheid G. Tyre and road wear particles (TRWP)—a review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment. Science of the Total Environment. 2020;733:137823. https://doi.org/10.1016/j.scitotenv.2020.137823
[13] Mennekes D, Nowack B. Tire wear particle emissions: measurement data where are you? Science of the Total Environment. 2022;830:154655. https://doi.org/10.1016/j.scitotenv.2022.154655
[14] Ziari H, Babagoli R, Akbari A. Investigation of fatigue and rutting performance of hot mix asphalt mixtures prepared by bentonite-modified bitumen. Road Materials and Pavement Design. 2015;16:101–118. https://doi.org/10.1080/14680629.2014.982156
[15] Çeloğlu M, Yalçın E, Kök B, Alataş T, Norambuena-Contreras J, Garcia A, Yılmaz M. Effects of different bitumen modifiers on the rutting and cracking resistance of hot mix asphalts. International Journal of Pavement Engineering. 2018;21(6):703–712. https://doi.org/10.1080/10298436.2018.1506122
[16] Navarro FJ, Partal P, García-Morales M, Martín-Alfonso MJ, Martínez-Boza F, Gallegos C, Bordado JCM, Diogo AC. Bitumen modification with reactive and non-reactive (virgin and recycled) polymers: a comparative analysis. Journal of Industrial and Engineering Chemistry. 2009;15(4):458–464. https://doi.org/10.1016/j.jiec.2009.01.003
[17] Sengoz B, Isikyakar G. Evaluation of the properties and microstructure of SBS and EVA polymer modified bitumen. Construction and Building Materials. 2008;22(9):1897–1905. https://doi.org/10.1016/j.conbuildmat.2007.07.013
[18] Airey GD. Rheological evaluation of ethylene vinyl acetate polymer modified bitumens. Construction and Building Materials. 2002;16(8):473–487. https://doi.org/10.1016/S0950-0618(02)00103-4
[19] Brovelli C, Hilliou L, Hemar Y, Pais J, Pereira P, Crispino M. Rheological characteristics of EVA modified bitumen and their correlations with bitumen concrete properties. Construction and Building Materials. 2013;48:1202–1208. https://doi.org/10.1016/j.conbuildmat.2013.07.032
[20] Khadivar A, Kavussi A. Rheological characteristics of SBR and NR polymer modified bitumen emulsions at average pavement temperatures. Construction and Building Materials. 2013;47:1099–1105. https://doi.org/10.1016/j.conbuildmat.2013.05.093
[21] Brasileiro L, Moreno-Navarro F, Tauste-Martínez R, Matos J, Rubio-Gámez MC. Reclaimed polymers as asphalt binder modifiers for more sustainable roads: a review. Sustainability. 2019;11(3):646. https://doi.org/10.3390/su11030646
[22] Ibrahim H, Zuhair A, Gohar A, Faheem AA. Performance enhancement of asphalt binders using upcycled waste tires and plastics: a UAE-based study on alternatives to SBS-modified binders. Construction and Building Materials. 2025;463:140070. https://doi.org/10.1016/j.conbuildmat.2025.140070
[23] Al-Hadidy AI, Yi-qiu T. Effect of polyethylene on life of flexible pavements. Construction and Building Materials. 2009;23(3):1456–1464. https://doi.org/10.1016/j.conbuildmat.2008.07.004
[24] Mashaan N, Chegenizadeh A, Nikraz H. Laboratory properties of waste PET plastic-modified asphalt mixes. Recycling. 2021;6(3):49. https://doi.org/10.3390/recycling6030049
[25] Ghani U, Zamin B, Bashir MT, Ahmad M, Sabri Sabri MM, Keawsawasvong S. Comprehensive study on the performance of waste HDPE and LDPE modified asphalt binders for construction of asphalt pavements application. Polymers. 2022;14(17):3673. https://doi.org/10.3390/polym14173673
[26] Genet M, Sendekie Z, Jembere A. Investigation and optimization of waste LDPE plastic as a modifier of asphalt mix for highway asphalt: case of Ethiopian roads. Case Studies in Chemical and Environmental Engineering. 2021;4:100150. https://doi.org/10.1016/j.cscee.2021.100150

[27] Suksiripattanapong C, Uraikhot K, Tiyasangthong S, Wonglakorn N, Tabyang W, Jomnonkwao S, Phetchuay C. Performance of asphalt concrete pavement reinforced with high-density polyethylene plastic waste. Infrastructures. 2022;7(5):72. https://doi.org/10.3390/infrastructures7050072
[28] Brohomo P, Shakik A, Mizan M. Waste plastic utilization in asphalt mix for sustainability and enhancing rheological parameters. Transportation Research Interdisciplinary Perspectives. 2025;31:101456. https://doi.org/10.1016/j.trip.2025.101456
[29] Jexembayeva A, Konkanov M, Aruova L, Kirgizbayev A, Zhaksylykova L. Performance optimization approach of polymer-modified asphalt mixtures with PET and PE waste. Polymers. 2024;16(23):3308. https://doi.org/10.3390/polym16233308
[30] Li H, Zhou L, Sun J, Wang S, Zhang M, Hu Y, Temitope A. Analysis of the influence of production method, plastic content on the basic performance of waste plastic modified asphalt. Polymers. 2022;14:4350. https://doi.org/10.3390/polym14204350
[31] Kakar MR, Mikhailenko P, Piao Z, Bueno M, Poulikakos L. Analysis of waste polyethylene (PE) and its by-products in asphalt binder. Construction and Building Materials. 2021;280:122492. https://doi.org/10.1016/j.conbuildmat.2021.122492
[32] Subhy A, Pires GM, Lo Presti D, Airey G. The effects of laboratory ageing on rheological and fracture characteristics of different rubberised bitumens. Construction and Building Materials. 2018;180:188–198. https://doi.org/10.1016/j.conbuildmat.2018.05.273
[33] Li D, Leng Z, Zou F, Yu H. Effects of rubber absorption on the aging resistance of hot and warm asphalt rubber binders prepared with waste tire rubber. Journal of Cleaner Production. 2021;303:127082. https://doi.org/10.1016/j.jclepro.2021.127082
[34] Turbay E, Martínez-Argüelles G, Paternina-Uribe R, Covilla-Valera E, Fuentes L, Giustozzi F. Rheological behaviour of WMA-modified asphalt binders with crumb rubber. Polymers. 2022;14(19):4148. https://doi.org/10.3390/polym14194148
[35] Akkenzheyeva A, Haritonovs V, Bussurmanova A, Merijs-Meri R, Imanbayev Y, Riekstins A, Serikbayeva A, Sydykov S, Aimova M, Mustapayeva G. Study of the viscoelastic and rheological properties of rubber-bitumen binders obtained from rubber waste. Polymers. 2024;16(1):114. https://doi.org/10.3390/polym16010114
[36] Gawdzik B, Matynia T, Błażejowski K. The use of de-vulcanized recycled rubber in the modification of road bitumen. Materials. 2020;13(21):4864. https://doi.org/10.3390/ma13214864
[37] Rodríguez-Fernández I, Cavalli MC, Poulikakos L, Bueno M. Recyclability of asphalt mixtures with crumb rubber incorporated by dry process: a laboratory investigation. Materials. 2020;13(12):2870. https://doi.org/10.3390/ma13122870
[38] Wang H, Liu X, van de Ven M, Lu G, Erkens S, Skarpas A. Fatigue performance of long-term aged crumb rubber modified bitumen containing warm-mix additives. Construction and Building Materials. 2020;239:117824. https://doi.org/10.1016/j.conbuildmat.2019.117824
[39] Jamal M, Giustozzi F. Chemo-rheological investigation on waste rubber-modified bitumen response to various blending factors. International Journal of Pavement Research and Technology. 2022;15(2):395–414. https://doi.org/10.1007/s42947-021-00045-x
[40] White G, Kidd A. Analysis of the effects of rubber dosage and digestion time on the mechanical properties of low dosage crumb-rubber-modified asphalt concrete mixtures. Materials. 2025;18(7):1419. https://doi.org/10.3390/ma18071419
[41] Li X, Wang Y, Zhang H, Liu J, Chen Z. Study on performance and aging mechanism of rubber-modified asphalt under variable-intensity UV aging. Materials. 2025;18(13):3186. https://doi.org/10.3390/ma18133186
[42] Kumar A, Berwal P, Al-Mansour AI, Khan MA, Alam S, Lee SM, Malik A, Iqbal A. Impact of crumb rubber concentration and plastic coated aggregates on the rheological performance of modified bitumen asphalt. Sustainability. 2022;14(7):3907. https://doi.org/10.3390/su14073907
[43] Alemu G, Melese D, Mahdi T, Negesa A. Combined performance of polyethylene terephthalate waste plastic polymer and crumb rubber in modifying properties of hot mix asphalt. Advances in Materials Science and Engineering. 2023. https://doi.org/10.1155/2023/6320490
[44] Fethiza Ali B, Soudani K, Haddadi S. Effect of waste plastic and crumb rubber on the thermal oxidative aging of modified bitumen. Road Materials and Pavement Design. 2020;23:222–233. https://doi.org/10.1080/14680629.2020.1820893
[45] Chen JS, Liao MC. Evaluation of internal resistance in hot-mix asphalt (HMA) concrete. Construction and Building Materials. 2002;16(6):313–319. https://doi.org/10.1016/S0950-0618(02)00037-5

[46] Zhou Y, Ma S, Gan C, Wang W, Yu P, Zheng X, Zhang P, Liu B, Zhao H. The effect of air void on the laboratory properties of polyurethane mixtures. Coatings. 2025;15(2):228. https://doi.org/10.3390/coatings15020228

[47] Bańkowski W, Król J, Kowalski K, Horodecka R. Implementation of high air voids asphalt mixtures on trial section—performance evaluation case study. Applied Sciences. 2025;15(20):11298. https://doi.org/10.3390/app152011298

[48] Ghanizadeh A, Amlashi A, Bahrami A, Isleem H, Dessouky S. A formulation for asphalt concrete air void during service life by adopting a hybrid evolutionary polynomial regression and multi-gene genetic programming. Scientific Reports. 2024;14:13254. https://doi.org/10.1038/s41598-024-61313-x

[49] Shah MM, Yousaf J, Khalid U, Li H, Yee J, Naqvi S. Plastic roads: asphalt mix design and performance. Discover Applied Sciences. 2024;6:195. https://doi.org/10.1007/s42452-024-05772-x

[50] Sani W. Volumetric properties of waste-modified asphalt mixtures through Marshall stability. Current Problems in Research. 2025;1(1):1. https://doi.org/10.70028/cpir.v1i1.29

[51] Mohammed H, Adefesobi SA. Evaluation of the potential of Sasobit polymer as an additive in bitumen and asphaltic concrete. Ife Journal of Science. 2020;22(1):177–181. https://doi.org/10.4314/ijs.v22i1.17

[52] Nizamuddin S, Jamal M, Gravina R, Giustozzi F. Recycled plastic as bitumen modifier: the role of recycled linear low-density polyethylene in the modification of physical, chemical and rheological properties of bitumen. Journal of Cleaner Production. 2020;266:121988. https://doi.org/10.1016/j.jclepro.2020.121988

[53] Hassan F, Ismael M. Enhancement of the rutting resistance of asphalt mixtures modified by nano clay and crumb rubber. Engineering, Technology & Applied Science Research. 2024;14(5):17438–17444. https://doi.org/10.48084/etasr.8531

[54] Nouali M, Derriche Z, Ghorbel E, Chuanqiang L. Plastic bag waste modified bitumen: a possible solution to the Algerian road pavements. Road Materials and Pavement Design. 2020;21:1713–1725. https://doi.org/10.1080/14680629.2018.1560355

[55] Hmoud H. Evaluation of VMA and film thickness requirements in hot-mix asphalt. Mathematical Models and Methods Modern Applied Science. 2011;5(4):166. https://doi.org/10.5539/mas.v5n4p166