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Optimization of Mechanical Performance and Sustainability of Asphalt Mixtures through the Incorporation of Recycled Rubber Crumb

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Optimization of Mechanical Performance and Sustainability of Asphalt Mixtures through the Incorporation of Recycled Rubber Crumb

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Abstract

Road infrastructure is a key indicator of a country's development. Traditionally, hot dense asphalt mixtures (HMA) have been used due to their ability to withstand traffic loads and adverse weather conditions. However, a growing emphasis on sustainability in road construction drives the search for technologies that reduce environmental impact without compromising durability and safety. One solution is the incorporation of recycled rubber crumb (RRC) into asphalt mixtures, reusing tire waste and enhancing performance.

This study evaluates the impact of RRC on HMA through an experimental process developed in four phases. In Phase 1, the materials used (aggregates, asphalt binder, and RRC) were collected and characterized according to INVIAS 2022 specifications. Tests were conducted on the aggregates to assess hardness, durability, cleanliness, and gradation; the asphalt binder was evaluated in terms of viscosity, penetration, and softening point. The RRC was characterized based on particle size distribution, and moisture, and fiber content. In Phase 2, conventional and RRC-modified asphalt mixture briquettes were designed and fabricated with RRC proportions of 1%, 2%, and 3% (dry process), compacted according to current regulations. Phase 3 involved the characterization of the briquettes testing rutting (INV E 756-13), moisture susceptibility (INV E 725-13), the resilient modulus (INV E 749-13), and fatigue resistance. Finally, in Phase 4, a technical and statistical analysis of the results was conducted, comparing the mechanical and functional performance of the mixtures in terms of durability, structural resistance, and behavior under environmental and load-related factors.

The results indicate that the addition of 1% RRC significantly improves fatigue resistance, structural stability, and safety under wet conditions, surpassing the performance of conventional mixtures. The environmental and economic impact assessment demonstrates that the use of RRC not only extends pavement service life but also reduces tire waste and CO_2 emissions associated with virgin asphalt production, contributing to the circular economy and sustainable development.

It is important to recognize some limitations in this study. The tests were carried out under controlled conditions which do not fully replicate the real conditions of the variables already mentioned. The granular material used was obtained from a quarry in the region of Tunja, Boyacá, which limits the applicability compared to material obtained from other regions with different climatic, geotechnical, or traffic characteristics. Other modification techniques besides RRC, which could offer variations in the mechanical and environmental performance of the mixtures, were not evaluated. This research did not directly quantify the environmental impact of the use of RRC through each stage of the life cycle of an asphalt pavement: it does not include an experimental

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or quantitative environmental evaluation. Finally, the sustainability component was developed through a referential review of updated scientific literature. This study provides scientific and applied evidence for the implementation of more sustainable technologies in road construction, establishing RRC as an effective and environmentally responsible modifier. Its alignment with international standards and its potential to optimize waste management position it as a viable strategy for modernizing flexible pavements on a global scale.

Keywords: recycled rubber crumb (RRC); mechanical performance and pavement durability; environmental impact mitigation through RRC; sustainable pavements; modified asphalt mixtures.

Introduction

Road infrastructure is essential for any nation's economic and social development, as it facilitates the mobility of people and goods, driving commercial and industrial activity. As transportation demands increase, road structures must be capable of withstanding heavier loads and more extreme climatic conditions. Sustainability and environmental preservation have become crucial factors that must be integrated into the design and construction of these infrastructures. Therefore, road engineering requires a new approach that combines durability, efficiency, and ecological responsibility.

In this context, the use of recycled materials such as recycled rubber crumb (RRC) in asphalt mixtures has emerged as an innovative strategy to enhance the mechanical performance of pavements while reducing the environmental impact associated with the disposal of end-of-life tires. The incorporation of RRC not only contributes to more efficient waste management but also improves the properties of asphalt mixtures, including resistance to rutting, fatigue, and water-induced damage—key factors in extending the service life of road infrastructure (Peláez et al., 2017; Khiong et al., 2021). Moreover, the use of RRC in asphalt mixtures represents a step toward the circular economy by decreasing the demand for virgin materials and promoting resource recycling.

Hot dense asphalt mixtures (HMA), traditionally preferred for their ability to withstand traffic loads and adverse weather conditions, can significantly benefit from modification with recycled rubber crumb (RRC). This material, derived from tire recycling, possesses properties that enhance the durability and strength of pavements while contributing to environmental sustainability. Various studies have documented the benefits of RRC in improving Marshall stability, resistance to plastic deformation, and reduced sensitivity to water-induced damage (Milad et al., 2020; Plati & Cliatt, 2021).

This article presents the results of an experimental study evaluating the mechanical properties and sustainability of asphalt mixtures modified with recycled rubber crumb (RRC). The objective is to determine, under laboratory conditions, the effect of the incorporation of RRC in dry form in proportions of 1%, 2%, and 3%, in order to identify the optimum addition percentage that should be incorporated into asphalt mixtures to maximize both mechanical performance and environmental benefits. The research includes specific tests on rutting resistance, fatigue, and durability, along with an environmental analysis comparing the impact of RRC-modified mixtures against conventional mixtures. Likewise, the potential environmental impact of these modified mixtures is analyzed in a referential manner, based on a review of specialized literature and secondary data, with the purpose of highlighting their contribution to the sustainability of road infrastructure through the use of tire waste and the reduction of the use of virgin materials. The scope of this study is limited to experimental laboratory conditions, not including tests under real traffic conditions nor an environmental assessment based on life cycle analysis with primary data.

Mbereyaho et al. (2021) investigated the properties of bitumen with the addition of tire waste powder compared to standard quality 60/70 grade bitumen. It was established that more suitable results were obtained with 5% replacement in terms of penetration, softening point, and viscosity. Also, in terms of the estimated cost of this new bitumen, a reduction of approximately 5.3% was achieved. In Vietnam, the use of granulated rubber modified asphalt has decreased the flexibility of modified asphalt mixtures compared to unmodified mixtures, resulting in reduced fatigue cracking resistance, Do et al (2020).

Palma et al. (2024) conducted an investigation with the use of granulated rubber from disused tires in a hot asphalt mixture and found that the incorporation of 2.0% rubber produced significant improvements in the properties of the mixture, with values such as a void percentage of 4. 3%, a mineral aggregate voids percentage of 16.1%, asphalt-filled voids percentage of 73.4%, powder/asphalt ratio of 0.64%, flow of 13.2 mm, stability of 9.9 KN, stability/flow ratio of 3019.9 kg/cm, a retained strength of 83%, a compressive strength of 4.0Mpa, and a retained strength of 81%. They determined that a 2% rubber percentage meets the standards established by the regulations and improves asphalt properties by 26.53% compared to the conventional mix.

Cubas et al. (2025), studied the behavior of the mechanical and microstructural properties of a hot dense asphalt mix with the addition of pulverized recycled rubber and found that the addition of recycled rubber significantly influences the physico-mechanical properties of the mix.

Labbafi et al. (2025), compared conventional and recycled rubber crumb modified hot mix asphalt mixtures, with results showed that, in general, the recycled rubber crumb mixes outperformed conventional asphalt by approximately 25%, making them a viable option for sustainable pavements. Despite the higher material and construction costs, an economic analysis revealed that these mixes are more cost-effective in the long term due to their longer service life. Bastidas et al. (2021) concluded that the incorporation of recycled rubber crumb minimizes the changes in mechanical properties due to aging compared to mixtures without this material.

Recycled granulated rubber from used tires could serve as a viable alternative for achieving eco-friendly pavements, opening up new and attractive markets for global investors. The addition of granulated rubber to flexible pavements enhances their performance while ensuring environmental sustainability. This review study determined that, compared to traditional asphalt mixtures, rubber-modified asphalts exhibit superior performance and a longer service life (Bilema et al., 2023).

Díaz Claros and Castro Celis (2017) synthesized various international studies demonstrating that implementing recycled rubber crumb (RRC) in pavements effectively addresses mechanical issues in road surfaces while mitigating the environmental impacts associated with improper tire disposal. The incorporation of RRC in asphalt mixtures translates into numerous benefits, as research conducted in recent years has shown that these modified mixtures are more durable than conventional ones, more cost-effective in the long term due to reduced maintenance needs and contribute to minimizing negative environmental impacts. Specifically, they help prevent the indiscriminate burning of discarded tires, which leads to CO_2 emissions—one of the most harmful pollutants responsible for global warming, among other environmental concerns.

This study aims to provide empirical evidence and a solid scientific foundation for the widespread adoption of asphalt mixtures modified with recycled rubber crumb (RRC) in Colombia and other regions with similar climatic and traffic conditions. The findings of this research have the potential not only to optimize road engineering practices but also to influence the development of technical regulations for the use of recycled materials in the construction of sustainable road infrastructure.

Regarding the sustainability component, this research does not contemplate an environmental evaluation using life cycle indicators or other quantitative methodologies. A referential analysis was carried out based on previous studies that document the environmental benefits of the use of RRC, in terms of circular economy, waste reduction and reduction of emissions associated with the use of virgin materials.

This article is structured to provide a clear understanding of the impact of RRC-modified asphalt mixtures, covering the background and rationale of the study, as well as the obtained results and their practical implications. Throughout the following sections, the methods employed for data collection and analysis are detailed, key findings are presented, and recommendations for their implementation in sustainable road projects are discussed.

Methods

The research was conducted in four phases.

In **Phase 1**, the collection and characterization of granular materials, asphalt binder, and recycled rubber crumb (RRC) were carried out in accordance with the general road construction specifications of INVIAS (2022). Such characterization was performed following the corresponding INV E standards, ensuring the suitability of the materials for the design of MDC-19 mixes. This step is essential to establish a baseline of physical and chemical properties that directly affect the workability, durability, and compatibility of the modified mix.

The characterization of the aggregates included tests for hardness, durability, cleanliness, gradation, and particle geometry. The asphalt binder was evaluated through Saybolt-Furol viscosity tests, penetration tests, softening point determination, and safety tests. The RRC was analyzed by mass in terms of particle size distribution, moisture content, and fiber content, ensuring compliance with current regulations.

Since the research was carried out based on INV E standards, a comparison was made between the local standards used (INV E) and the EN, ACI, ASTM, and ISO standards. In Colombia, the ACI standard refers to the Regulation Requirements for Structural Concrete, which are the requirements established by the American Concrete Institute (ACI) for the design and construction of concrete structures. INV E standards do not explicitly mention EN (European) or ISO standards; their focus is to align with North American ASTM standards; however, **Table 1** shows the correspondence between standards.

Table 1

Equivalence of international norms

Property evaluated	Norm INV E (Colombia)	Equivalent ASTM	Equivalent EN	Equivalent ISO
Asphalt penetration	INV E 706	ASTM D 5 - 06	EN 1426	-
Softening point	INV E 712	ASTM D36 / D36M-09	EN 1427	ISO 4625
Viscosity (60°C y 135°C)	INV E 716 / 717	ASTM D2171 / D2127M	EN 13302	ISO 3104 / ISO 3219
Penetration index	INV E 724	ASTM D946	-	-
Rutting	INV E 756	-	EN 12697-22	-
Moisture susceptibility	INV E 725	ASTM D4867/ D4867M – 09	EN 12697-12	-
Resilient modulus	INV E 749	ASTM D7369-11	EN 12697-26	ISO 6721-1
Indirect traction - fatigue	INV E 784	ASTM D6931	EN 12697-24	-
Marshall stability and flow	INV E 748	ASTM D 6926 – 10 / ASTM D 6927 – 06	EN 12697-34	-
Slip/Skid resistence	INV E 792	ASTM E–303–93 (Reaproved 2008) / ASTM E–501–08	EN 13036-4 / EN 13036-1	ISO 23671
RRC characterization	INV E 706	ASTM D1864	-	-
Aggregate gradation	INV E 213 / 233 / 239	ASTM C136-06 / C1252	EN 933-1 / EN 933-6	ISO 3310
Hardness (Los Angeles)	INV E 218	ASTM C131-06	EN 1097-2	ISO 20290-3

Property evaluated	Norm INV E (Colombia)	Equivalent ASTM	Equivalent EN	Equivalent ISO
Degradation of the Micro-Deval equipment	INV E-238	ASTM D 6928 – 10	EN 1097-1 / EN 1097-2	-
Accelerated rolling polishing coefficient	INV E-232	-	EN 1097-8	ISO 13174
Losses in the sulfate soundness test (magnesium sulfate), fine and coarse aggregates	INV E - 220	ASTM C 88 – 05	EN 1367-2	-
Impurities in coarse aggregate	INV E - 237	-	EN 933-1	-
Plasticity index	INV E - 125/126	ASTM D 4318 – 10	EN ISO 17892-12	ISO 17892-12
Sand equivalent	INV E - 133	ASTM D 2419 – 09	EN 933-8	-
Methylene Blue Value	INV E - 235	-	EN 933-9	-
Flat and elongated particles, w5:1 ratio	INV E - 240	ASTM D 4791 – 10	EN 933-3	-
Fractured es	INV E - 227	ASTM D 5821 – 01 (Re-aproved 2006)	EN 933-5	-
Fine fraction angularity: Method A	INV E - 239	ASTM C 1252 – 06	EN 933-6	-

In **Phase 2**, briquettes of conventional asphalt mixtures and those modified with RRC incorporated via the dry process at 1%, 2%, and 3% by weight of the total mixture were designed and fabricated. The distribution of RRC within the asphalt matrix was ensured through a homogeneous mixing procedure, and the briquettes were compacted according to the specifications established by INVIAS. The choice to use the dry incorporation method responds to its ease of implementation in conventional plants without the need to modify the mixing or storage system, which makes its use feasible at the national road infrastructure level.

The selection of the percentages of 1%, 2%, and 3% of recycled rubber crumb for incorporation in asphalt mixes by the dry process was based on technical background and previous studies that indicate that these proportions allow for evaluating a functional range that does not compromise the workability and structural integrity of the mix. Several authors have reported that incorporations between 0.5% and 5% in total mix weight offer significant improvements in properties such as rutting resistance, durability and fatigue behavior, without negatively affecting the stability and cohesion of the system (Milad et al., 2020; Hassan et al., 2019; Herrera Fierro, 2022). Studies such as those by Ochoa and Higuera (2023) and Higuera et al. (2019) indicate that levels higher than 3% can induce a loss of cohesion in the mix, difficulties in homogeneous mixing, and decreases in mechanical properties such as Marshall stability or resilient modulus.

In **Phase 3**, the mechanical and functional performance of the briquettes was evaluated through standardized tests. Plastic deformation resistance was determined using the rutting test (INV E 756-13), which simulates vehicular traffic and measures permanent deformation under repeated loading. Moisture susceptibility was analyzed using the indirect tensile strength test (INV E 725-13), while the resilient modulus, an indicator of the mixture's ability to withstand repeated loads without excessive deformation, was determined according to the INV E 749-13 standard. Fatigue resistance was assessed through indirect tensile tests on cylindrical specimens, allowing for the characterization of the mixture's behavior under cyclic stresses and its performance in pavements exposed to continuous traffic.

Finally, in **Phase 4**, a comparative analysis of the results obtained for each percentage of RRC was conducted. Statistical methods were applied to identify trends and assess the impact of RRC on the mechanical and functional properties of the asphalt mixtures. The interpretation of the results considered durability, structural resistance, and susceptibility to damage from environmental and load-related factors, providing a foundation for the implementation of sustainable technologies in road infrastructure.

Results

Collection and physical characterization of materials

The results of the asphalt cement characterization are shown in Table 2.

Table 2

Asphalt cement characterization

Norm	Test	Requirement	Result	Control
INV E - 706	Penetration	60 - 70	63.4	Complies
INV E - 712	Softening Point (°C)	48 - 54	51.4	Complies
INV E - 724	Penetration Index	-0.6 - 1.2	-0.3	Complies
INV E - 716	Viscosity 60°C (Pa*s)	150	217.5	Complies
INV E - 717	Viscosity 135°C (Pa*s)	0,4	0.74	Complies

The granular material was sourced from a quarry in the Tunja, Boyacá region of Colombia. It was subjected to physical and mechanical characterization for the design of a dense hot mix (DHM-19), following the specifications established by the National Institute of Roads (INVIAS) (2022) for a traffic level NT2. The results of the characterization are presented in Table 3.

For the design of asphalt mixtures with the addition of RRC, the central gradation of the specified granulometric range was used, as shown in Fig. 1. This approach was aimed at ensuring repeatability in the preparation of the mixtures and the execution of the tests.

Table 3

Characterization of granular material

Test	INV Regulation	NT2 Requirement	Result	Control
Hardness, Coarse Aggregate (O)				
Los Angeles Abrasion Test, maximum (%)	INV E -218	25%	22.2%	Complies
Degradation by abrasion in the Micro-Deval apparatus, maximum (%)	INV E-238	25%	24.9%	Complies
Accelerated Polishing Coefficient for Traction, Minimum	INV E-232	45	65	Complies
Durability (O)				
Losses in the sulfate soundness test (magnesium sulfate), fine and coarse aggregates, maximum (%)	INV E - 220	18%	2.20%	Complies
Cleanliness, Coarse Aggregate (F)				
Impurities in coarse aggregate, maximum (%)	INV E - 237	0.5%	0.1%	Complies
Cleanliness, Combined Gradation (F)				
Plasticity Index, maximum (%)	INV E - 125/126	NP	NP	Complies
Sand Equivalent, minimum (%)	INV E - 133	50%	51%	Complies
Methylene Blue Value, maximum	INV E - 235	10	5	Complies

Test	INV Regulation	NT2 Requirement	Result	Control
Particle Geometry, Coarse Aggregate (F)				
Flat and elongated particles, 5:1 ratio, maximum (%)	INV E - 240	10%	7,2%	Complies
Fractured faces, minimum (%)	INV E - 227	45%	90%	Complies
Particle Geometry, Fine Aggregate (F)				
Fine fraction angularity, Method A, minimum (%)	INV E - 239	45%	48%	Complies

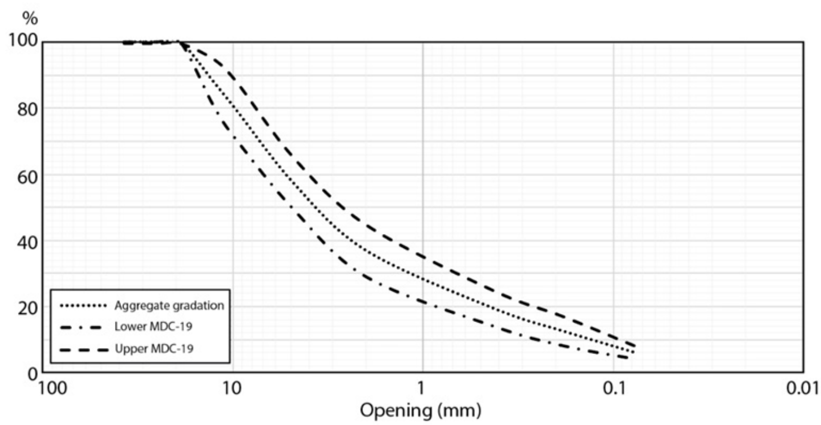


Fig. 1
Specified and used gradation curve

The characterization of the recycled rubber crumb is shown in Table 4.

Table 4
Characterization of granular material

Regulation	Test	Requirement	Result	Control
ASTM 1864/D 1864INV E - 706	Moisture (%)	0.75%	0.03%	Complies
ASTM 3289	Specific gravity	0.05 - 1.15	0.5	Complies
ASTM 5603	Fiber content by mass, maximum (%)	4%	0%	Complies
	Non-Ferrous Metal Content	No visible presence	NP	Complies

Design and manufacturing of conventional asphalt mixtures and those with the dry addition of different percentages of RRC

A conventional hot dense mix (MDC-19) was designed in accordance with the specifications of the Instituto Nacional de Vías (INVIAS) (2022). The optimal asphalt content was estimated using the voids polygon method and the Ramsoft software. The result indicated an optimal asphalt content of 6.36%, and three briquettes were fabricated. These briquettes exhibited a flow value of 3.92 mm, which was very close to the specification limit. Therefore, the asphalt content was reduced to 6.1%, a value that falls within the void's polygon, as shown in Fig. 2.

Three new briquettes were produced, yielding a flow value of 3.73 mm. These mixtures met the stability and flow specifications as well as volumetric properties, making the preliminary design satisfactory. The results are presented in Table 5.

Fig. 2

Voids polygon with its optimal asphalt percentage

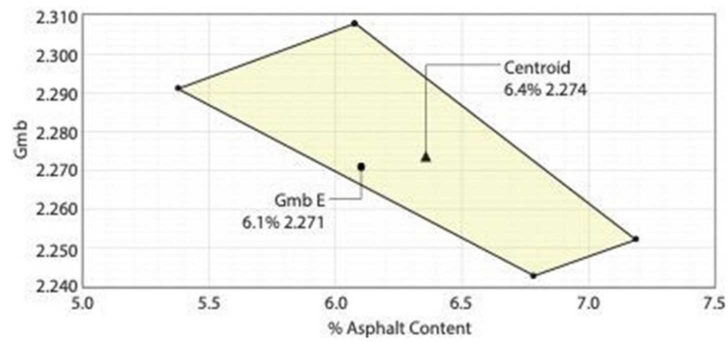


Table 5

Preliminary design results of asphalt mixtures

Rubber	Asphalt	Gmm	Gse	Gmb	Gsb	Aggregate (Ps)	Va	VAM	VFA
0%	0.0%	2.36	2.56	2.275	2.55	93.9%	3.6%	16.2%	77.8%
1%	6.1%	2.39	2.60	2.290	2.55	94.0%	4.2%	15.6%	73.2%
2%	6.1%	2.41	2.62	2.298	2.55	94.0%	4.6%	15.3%	69.6%
3%	6.1%	2.42	2.64	2.302	2.55	94.1%	4.9%	15.1%	67.7%

Mixture performance

In this research phase, laboratory performance tests were conducted on the mixtures to determine the percentage of RRC addition that yields the best results. There are four damage mechanisms of asphalt mixtures in service, as reported in the literature, which must be considered when designing a pavement structure: rutting, moisture susceptibility, resilient modulus, and fatigue (Gómez, 2019).

Rutting Test

Rutting in asphalt pavements has been a dilemma in terms of pavement performance and safety, posing challenges for both road users and road authorities. Therefore, it is crucial to understand the mechanism, potential causes, and techniques for reducing rutting to offer a prolonged lifespan and safe roads. Rutting is typically classified by severity level: low (6-13 mm), medium (13-25 mm), and high (greater than 25 mm) (Albayati, 2023).

According to Abril Zuleta et al. (2022), the stability-flow ratio affects the behavior of HMA in mechanical tests. Greater stability improves rutting performance and reduces fatigue behavior.

The rutting test results are shown in **Fig. 3** for the conventional mixture and mixtures with 1%, 2%, and 3% RRC additions, respectively.

According to the results, for the conventional mixture, after 120 minutes of testing, a maximum deformation of 5.15 mm was obtained, which is low compared to the 15 mm threshold established to determine if the test is conducted properly.

The average deformation rate estimated in the last time interval was 23.33 μm/min, 6.67 μm/min, 10.00 μm/min, and 13.33 μm/min, and the total deformation after 120 minutes of testing was 5.15 mm, 2.75 mm, 3.65 mm, and 4.95 mm for the conventional mixture, and with 1%, 2%, and 3% RRC additions, respectively. This indicates that the mixture with the 1% RRC addition is the most resistant to rutting, as it shows a lower deformation rate and total deformation compared to the other three mixtures, while its deformation is lower than the 3.5 mm reported by Caro Spinel et al. (2003) for an MDC-2 after 120 minutes. Likewise, it can be noted that the addition of RRC reduces rutting in asphalt mixtures compared to the conventional mixture.

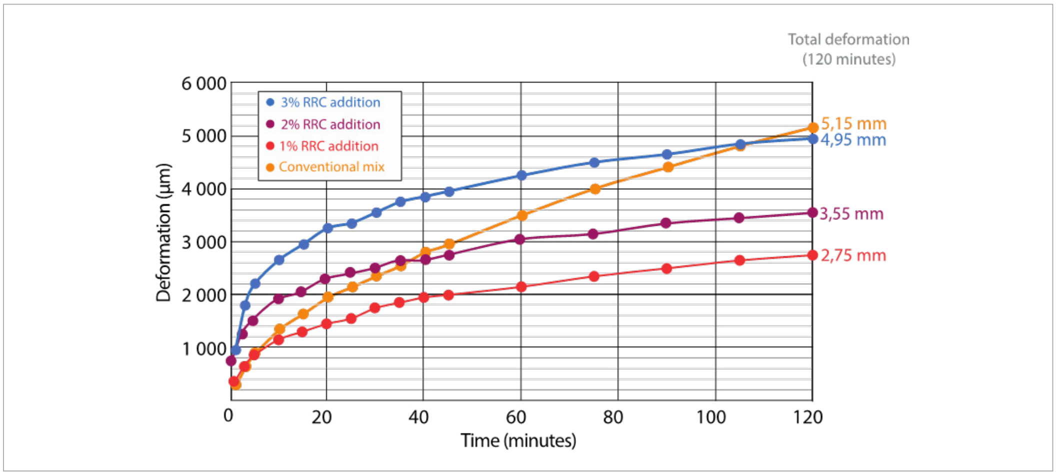


Fig. 3
Rutting

Regarding deformation, the results obtained in this study reinforce the concept put forth by Ochoa and Higuera (2023), which states that the addition of RRC improves the conditions of the asphalt mixture in relation to resistance to plastic deformation. This is because it provides a more solid mineral skeleton, which reduces voids and offers a better response to traffic action. These findings also align with those reported by Higuera et al. (2019), who indicate that favorable behavior is observed in asphalt mixtures with the addition of 0.5% RRC, where reductions of up to 5.3% in rutting are seen compared to the conventional asphalt mixture with the addition of recycled rubber crumb via dry process.

Moisture susceptibility

Moisture damage in asphalt mixtures can be defined as the deterioration of the mixture's structural capacity caused by the presence of water, either in liquid or gaseous form, within its microstructure (Plaza Torralvo & Rincón Caicedo, 2014).

Many studies have been conducted to understand the mechanisms of moisture damage due to the loss of bond strength between the binder and the aggregate, as well as to find ways to improve and strengthen the bond to mitigate the effects of moisture. It is clear that various factors, such as high temperatures, dust, and the chemical and physical properties of the binder and aggregates, contribute to these mechanisms and accelerate the onset of stripping (Hend et al., 2020).

Granulated rubber is one of these recyclable materials and has been proposed as one of the components of pavement in this study because it can improve pavement performance and is also considered a waste material. The most important motivation behind the use of RRC in the pavement industry is improving pavement performance and extending pavement lifespan by increasing resistance to moisture damage, resistance to permanent deformation, and enhancing the resilient modulus (Khaled et al., 2020).

The results obtained are shown in **Table 6**, where it is observed that as the percentage of RRC addition to the mixture increases, the saturation percentage also increases. However, all four mixtures meet the condition that the resistance of the wet-cured group is at least eighty percent (80%) of the resistance of the dry-cured group, to be considered resistant to moisture. The higher the RRC addition to the conventional mixture, the greater the susceptibility to moisture.

Based on the results, it can be inferred that the addition of RRC to the conventional mixture slightly reduces the retained tensile strength (RRT). In this sense, the mixture with the best retained strength performance is the one with 1% RRC addition, as its result indicates that even under saturated conditions, its resistance decreases by only 17% compared to the dry state.

Table 6

Tensile strength ratio

Mixture	Saturation (%)	Average dry tensile strength (RRS) kPa	Average wet tensile strength (RRH) kPa	Tensile strength ratio (RRT) (%)
Conventional	86	963	828	86
1% RRC addition	78	911	759	83
2% RRC addition	85	716	585	82
3% RRC addition	88	528	425	80

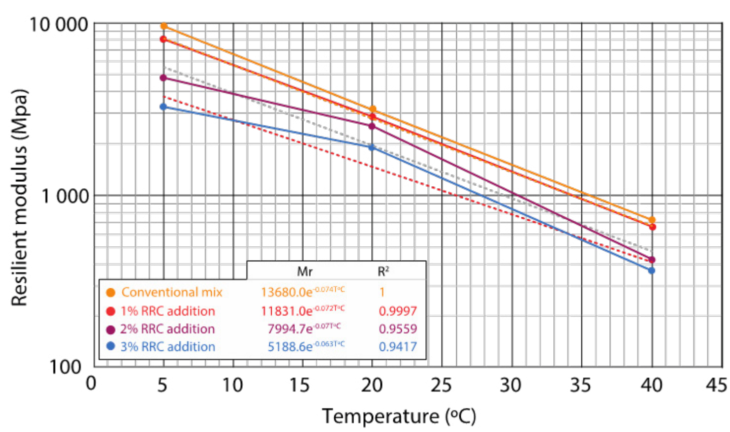
Resilient modulus

The results obtained in this study are presented in Fig. 4, where it can be observed that, for the analyzed temperatures, a higher RRC content in the asphalt mixture leads to a reduction in the resilient modulus compared to the conventional mixture. This behavior is consistent with the findings of Abdilah et al. (2019), who reported that the incorporation of rubber into conventional asphalt mixtures can decrease the resilient modulus by up to 6.95% at 25 °C.

This decrease in stiffness could influence the structural performance of the mixture, affecting its ability to withstand repetitive loads without permanent deformation. On one hand, reduced stiffness may improve thermal cracking and fatigue resistance by allowing greater flexibility and tension absorption capacity. However, it could also increase susceptibility to permanent deformation, particularly in hot climates or under heavy traffic conditions. Therefore, assessing the balance between flexibility and stability is essential to ensure optimal behavior of the mixture in service.

Fig. 4

Resilient Modules of the different mixtures



Fatigue resistance

Delgado Jojoa et al. (2018) report an increase in asphalt fatigue resistance when modified with recycled rubber crumb. RRC can be added to asphalt cement or incorporated as part of the aggregates in a hot dense mix (MDC-19) used in road construction, improving fatigue resistance and reducing premature aging caused by traffic loads (Alarcón Figueroa et al., 2020).

The mixture with asphalt modified with RRC exhibits greater fatigue resistance compared to MDC-19. This provides a significant benefit, as these mixtures would be more durable and perform better under applied loads (Barreto, 2016).

Each year, tons of discarded tires are produced, posing a serious environmental problem. As a result, granulated rubber (GR) is increasingly being used in asphalt mixture design due to its fundamental properties, such as durability and resistance. A literature review found that the optimal GR percentages in asphalt mixtures range from 1% to 20% by total mix weight. Additionally, incorporating GR offers various benefits to the mixture, including improved indirect tensile strength, reduced susceptibility to moisture, enhanced rutting resistance, lower permeability, and delayed aging. It also extends the fatigue life of asphalt mixtures and helps reduce noise levels (Muñoz Pérez et al., 2021).

To determine which type of mixture exhibits the best performance under structural fatigue stresses, it is crucial to consider the linear correlation of the data obtained in this test. In this case, the coefficient of determination was used for each mixture.

The results of this study indicate that the mixture with a 3% RRC addition exhibited the best performance. However, its coefficient of determination was only 0.74, which is relatively low. Given this, and considering the behavior of the mixture with a 1% RRC addition, the latter appears to have the best life expectancy when it comes to fatigue. This is because it has a lower slope, meaning that as the number of loading cycles increases, the stress level does not change significantly. This suggests that the 1% RRC mixture responds better to varying traffic loads, as illustrated in **Fig. 5**.

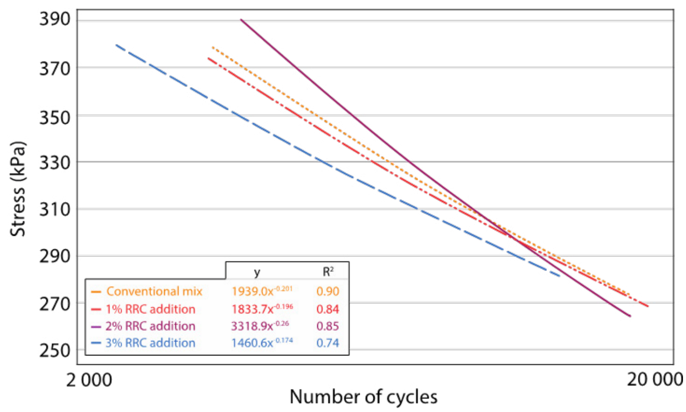


Fig. 5

Fatigue laws

Skid resistance

Pomoni and Plati (2022) found that the RRC-modified mixture exhibited similar behavior to the conventional mixture as the temperature changed. An increase in temperature from 15 to 25 °C led to a decrease in skid resistance levels. The RRC modified mixture performed slightly better in terms of measured skid resistance levels compared to the conventional mixture in almost all simulated climate variations.

This study determined skid resistance according to the INV E-792-13 regulation. The results are shown in **Fig. 6**, where it can be observed that a higher RRC content leads to a lower skid resistance coefficient in both dry and wet conditions. However, all three mixtures meet the requirement for continuously

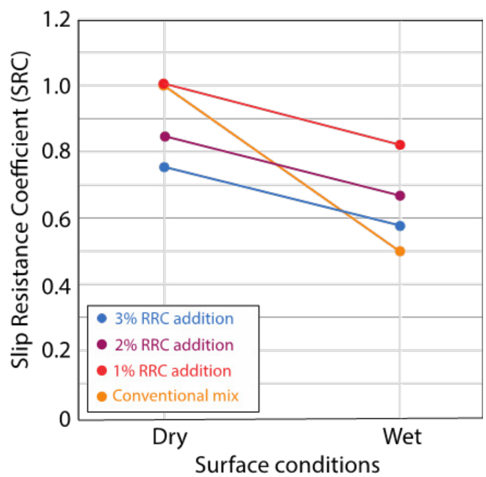


Fig. 6

Skid resistance coefficient according to RRC addition graded mixtures established in the general road construction regulations of INVIAS for traffic level NT2, which is at least 0.5. Additionally, the mixtures with 1% and 2% RRC showed improved skid resistance compared to the conventional mixture. This result is consistent with the findings of Ariyapijati et al. (2019), who reported that HMA pavements modified with RRC are more impermeable and provide better skid resistance.

Stability

The results reported by Ochoa and Higuera (2023) indicate that the incorporation of RRC increases Marshall stability. In the present study, the stability behavior of the different mixtures is shown in Table 7, where it is observed that a higher percentage of RRC addition results in lower stability compared to the conventional mixture. However, all mixtures meet the minimum requirement of 7500 N, in accordance with the general road construction regulations (INVIAS, 2022).

Table 7
Stability/flow ratio

	Stability (N)	Flow (mm)	Stability/flow ratio
0%	**17457**	3.8	4.6
1%	15750	**3.2**	**4.9**
2%	13757	3.5	4.0
3%	11347	3.5	3.3

Herrera Fierro (2022) concludes that when adding RRC to a HMA within the range of 0 to 2%, the mixture complies with the specifications established by INVIAS. However, all results indicate that when more than 2% RRC is added, the asphalt mixture tends to decline in many physical-mechanical properties, which could lead to future issues.

Flow

The results show an inverse behavior to stability, as the addition of 1% RRC generates the lowest flow (3.2 mm) compared to the other mixtures. Additionally, it is observed that mixtures with RRC addition have lower flow than the conventional mixture. As is known, a mixture with low Marshall flow generally has a lower capacity for plastic deformation, which may indicate greater stiffness. However, this also makes it more susceptible to fatigue cracking and thermal fissuring. On the other hand, an excessively high Marshall flow suggests a softer and more deformable mixture, which may be prone to permanent deformations or rutting, especially under high temperatures and heavy loads.

Stability/Flow ratio

The stability/flow ratio offers a comprehensive view of the balance between strength and ductility, classifying the mixture based on its behavior. A high ratio (Rigid mixture) may show good resistance to permanent deformations and rutting, but a high probability of fatigue cracking or thermal cracking due to its low ductility. A low ratio (Ductile mixture) indicates that the mixture has a better capacity to absorb deformations without cracking, ideal for cold climates or moderate loads, but it is more susceptible to rutting under high temperatures or heavy traffic.

The behavior of the mixtures concerning the stability/flow ratio is shown in Table 7, where it can be observed that all three mixtures meet this requirement for an MDC-19 mixture (3 to 5 kN/mm).

Environmental sustainability analysis

This study did not directly quantify the environmental impact of the use of RRC throughout each stage of the life cycle of asphalt pavement. However, the sustainability component was developed through a referential review of updated scientific literature to contextualize the potential environmental benefits of the use of recycled rubber crumb in asphalt mixtures.

As road infrastructure faces increasing traffic demands and stricter environmental requirements, the incorporation of recycled materials in road construction has gained relevance as an integral strategy to promote sustainability. In this context and based on the literature review, the use of RRC in asphalt mixtures is presented as an innovative alternative that contributes to the efficient management of tire waste and to the sustainability of pavements. Several studies have shown that the addition of RRC favors the circular economy, reduces dependence on virgin materials, and reduces the environmental footprint associated with road infrastructure. The main environmental impacts, functional benefits and life cycle assessment results associated with the use of RRC in asphalt mixtures are presented below, highlighting the potential to transform problematic waste into a valuable resource for the development of sustainable pavements.

According to the results of this research, it was determined that improvements are generated in the mechanical performance of asphalt mixtures modified with 1% RRC, particularly in terms of fatigue resistance, plastic deformation and stability under load. This improvement in durability has direct implications on environmental sustainability, since more resistant pavements require less maintenance and rehabilitation interventions.

Despite its advantages, large-scale implementation of RRC faces significant barriers, including meeting the challenge of making homogeneous blends during mixing, variability in recycled rubber quality, and compatibility with certain types of binders.

The initial cost of adoption may be higher due to process adjustment needs, especially in plants that have not worked with this type of additives; however, Labbafi et al. (2025) demonstrated that the initial costs are compensated by the longer useful life and lower maintenance needs.

The absence of clear regulatory frameworks and even the lack of explicit fiscal incentives limits the adoption of RRC in many countries. The inclusion of sustainability criteria in technical specifications, such as EN 15804 or ISO 14044, is essential to promote this transition.

The use of asphalt mixtures modified with RRC represents a sustainable strategy to reduce tire waste, minimize the consumption of natural aggregates, and mitigate the emission of pollutants. The reuse of these waste materials in pavements not only contributes to the sustainable management of solid waste but also improves the durability and resistance of the pavement, enhancing its long-term performance (Hassan et al., 2024).

Environmental impact and waste management

The global increase in vehicle ownership has led to a significant accumulation of waste tires, resulting in considerable environmental impact. Several end-of-life solutions have been developed to reuse these tires, and a promising approach is to convert them into rubber for use in road infrastructure as a stabilizing agent in asphalt mixtures. This application mitigates environmental damage and often improves the mechanical performance of these materials. Additionally, rubber crumb serves as a low-carbon material, offering environmental benefits such as a reduced carbon footprint. The results suggest that, in appropriate doses in asphalt mixtures, RRC can transform from an environmental burden into a valuable resource for various road infrastructure applications (Guerrero et al., 2024).

Previous studies have shown that the addition of RRC helps reduce the reliance on virgin materials, thus decreasing the environmental impacts associated with their extraction and processing (García et al., 2020).

Functional benefits and sustainability in performance

The use of RRC in asphalt mixtures has demonstrated significant functional benefits. It has been observed that the addition of up to 10% rubber improves the cohesion of the asphalt binder, increasing resistance to fatigue and reducing plastic deformation of the pavement (Shunyam et al., 2021). Additionally, its incorporation contributes to reducing noise generated by vehicle traffic, improves traction on wet roads, and decreases road accidents (Barišić et al., 2021).

At the same time, the use of these materials in pavements reduces the need for maintenance and extends the service life of roads, leading to lower long-term operational costs (Hassan & Rodríguez, 2024). However, the implementation of these technologies requires specific studies on their technical and economic feasibility in each geographical and climatic context.

This study describes the different stages that the Institute of Urban Development (UD) has undertaken to achieve the proper and correct application of asphalt mixtures with granulated rubber. A full-scale pavement test track was constructed, including a section with rubber asphalt via the dry process. The adaptation of this technology to the Colombian environment is providing a solution for the disposal of a difficult-to-eliminate solid waste, contributing to environmental preservation while simultaneously producing a high-performance material that will result in significant savings in maintenance and conservation costs. All these advantages help support the three pillars of sustainability: economy, environmental protection, and social benefits, to achieve sustainable road infrastructure (Martínez Arguelles et al., 2018).

Life cycle and emissions assessment

According to Siverio et al. (2022), to quantify the environmental impact of the use of RRC in pavements, the life cycle analysis (LCA) methodology should be applied, which allows the environmental effects of conventional and modified asphalt mixtures to be evaluated. In this study, indicators such as non-renewable energy demand and global warming potential were analyzed over a 45-year period. The results indicate that the addition of RRC through the dry process increases the required binder content, increasing environmental impacts compared to conventional mixes. If the structures with RRC extend their useful life by at least 20%, lower impacts are generated in the indicators analyzed.

The strategic reuse of substantial volumes of end-of-life tires in asphalt mixtures presents a practical and compelling solution to the growing problem of waste accumulation. This study evaluated the environmental, functional, and economic performance of hot mix asphalt (HMA) with various compositions to determine the most sustainable solution in the local context. The compositions included unmodified HMA and the novel recycled compound produced with devulcanized rubber and residual low-density polyethylene (DVR + LDPE compound). The research findings indicate that HMA modified with a DVR + LDPE compound outperforms traditional counterparts by significantly reducing Greenhouse Gas Protoco (GHG) emissions by 54.5% compared to unmodified HMA. The same can be extended to the cost analysis. The discussion emphasizes the practicality and importance of the novel waste composite and emphasizes the adoption of a full life cycle perspective for asphalt sustainability assessment (Ibrahim et al., 2024).

Conclusions

The materials used, aggregates, asphalt binder, and recycled rubber crumb (RRC), complied with the requirements established by the General Specifications for Road Construction of INVIAS (2022). The RRC presented adequate characteristics for its dry incorporation, highlighting its low moisture and fiber content, which favors its compatibility with the asphalt mix.

All the mixes designed complied with the requirements established by the National Road Institute regarding stability, flow and voids, for MDC-19 mixes and traffic level NT2. Although the stability decreases slightly with increasing RRC content, the values remain within the admissible ranges, which confirms their technical feasibility.

The addition of 1% recycled rubber crumb (RRC) in HMA improves resistance to plastic deformation, providing a more solid structure and reducing voids. This translates into greater durability against dynamic traffic loads.

The results indicate that the mixture with 1% RRC exhibits the best fatigue resistance, with less variability in the response to repetitive loading cycles, making it a more efficient alternative compared to the conventional mixture.

Although the increase in RRC content may slightly reduce the skid resistance, all the mixtures evaluated meet road safety standards. In particular, the mixtures with 1% and 2% RRC show an improvement in the coefficient of friction in the wet state compared to the conventional mixture.

It was observed that as the RRC content increases, the resilient modulus decreases, which may affect the structural stiffness of the mixture. This aspect should be considered in the pavement design for different traffic and temperature conditions.

From an environmental perspective, the incorporation of RRC in asphalt mixtures represents a viable alternative to mitigate the environmental impact of discarded tires and improve pavement performance. However, its large-scale implementation must evaluate the availability of raw materials, production costs, environmental regulations, and the behavior of the mixtures under different climatic and loading conditions.

A literature review identified relevant environmental benefits associated with the addition of RRC to HMA, including a reduction in the use of virgin materials, a decrease in waste from scrap tires, and a lower carbon footprint in production processes. The incorporation of RRC in asphalt mixtures represents a viable alternative to mitigate environmental impact, however, its large-scale implementation should evaluate the availability of raw materials, production costs, environmental regulations, and the behavior of the mixtures under different climatic and load conditions, since this analysis was neither experimental nor quantitative.

Following the need to adopt innovative solutions that combine structural efficiency and environmental responsibility in road infrastructure, the results demonstrate that the modification of asphalt mixtures with RRC is an effective and viable strategy. It optimizes the mechanical performance of the mixes and, at the same time, responds to the challenge of tire waste management in Colombia.

Overall, the mixture with 1% RRC stands out as the most viable option, achieving an optimal balance between durability, fatigue resistance, and safety. Its application in NT2 traffic pavements offers advantages both mechanically and environmentally, contributing to the sustainability of road infrastructure.

Recommendations

Long-term evaluation under real conditions. Although laboratory tests provide valuable information, conducting behavior studies of RRC-modified mixtures in pavement structures in service is essential. Implementing monitoring studies on highways is suggested to evaluate durability and resistance under different climatic and traffic conditions.

Exploration of new incorporation methodologies. Since this study used the dry method, comparing its effectiveness with the incorporation of RRC through the wet method or other emerging techniques would be valuable. This would allow for determining which method maximizes performance and sustainability improvements in pavement structures.

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