

Article

Rebound Effect Generated by Waste HDPE in Hot Asphalt Mixtures

David Sepúlveda-Valdez , Julio Calderón-Ramírez , Ricardo Cota-Ramírez , José Manuel Gutiérrez-Moreno , Marco Montoya-Alcaraz , Leonel García-Gómez  and Atondo Sánchez-Atondo 

Civil Engineering Laboratory, Department of Civil Engineering, Engineering Faculty, Autonomous University of Baja California, Mexicali 21360, Mexico; ricardo.cota@uabc.edu.mx (R.C.-R.); 27364@uabc.edu.mx (J.M.G.-M.); marco.montoya@uabc.edu.mx (M.M.-A.); leonel.gabriel.garcia.gomez@uabc.edu.mx (L.G.-G.); sanchez.alejandro29@uabc.edu.mx (A.S.-A.)

* Correspondence: sepulveda.david@uabc.edu.mx (D.S.-V.); julio.calderon@uabc.edu.mx (J.C.-R.)

Abstract

The feasibility of using high-density polyethylene (HDPE) waste in hot asphalt mixtures was analyzed, with particular focus on the rebound effect generated during compaction. Traditional asphalt mixtures without additives were evaluated alongside mixtures modified with varying percentages of HDPE waste (0.5%, 0.62%, 1%, 4%, and 5%) through the dry method. In this method, crushed HDPE was incorporated as an aggregate within the asphalt mixture structure, added prior to the introduction of the asphalt binder. Laboratory tests assessed compaction, specific gravity (Gmb and Gmm), void content, and resistance to permanent deformation via the Hamburg wheel tracking test. The results indicated that high percentages of HDPE (4% and 5%) triggered a rebound effect that hindered proper compaction of the mixtures, thereby compromising structural integrity. Conversely, mixtures with lower HDPE percentages (0.5% and 0.62%) exhibited better compaction, although they remained comparable to the traditional mixtures without plastic. In conclusion, HDPE does not constitute a viable option for enhancing the properties of asphalt mixtures at high percentages due to elastic behavior during compaction, which introduces densification irregularities. However, some benefits were observed in mixtures with low HDPE percentages, including improvements in stability and resistance to deformation. Nonetheless, these advantages are insufficient to justify replacing traditional asphalt mixtures.

Keywords: asphalt mixtures; HDPE; plastic waste; pavements; sustainability



Academic Editors: José Neves and Ana Cristina Freire

Received: 7 February 2025

Revised: 27 March 2025

Accepted: 5 April 2025

Published: 26 June 2025

Citation: Sepúlveda-Valdez, D.; Calderón-Ramírez, J.; Cota-Ramírez, R.; Gutiérrez-Moreno, J.M.; Montoya-Alcaraz, M.; García-Gómez, L.; Sánchez-Atondo, A. Rebound Effect Generated by Waste HDPE in Hot Asphalt Mixtures. *Recycling* 2025, 10, 127. <https://doi.org/10.3390/recycling10040127>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The design and construction of road infrastructures are pivotal for socioeconomic development globally [1]. These systems, predominantly constructed using asphalt mixtures, facilitate community connectivity and efficient transportation of goods and services. Asphalt mixtures, comprising mineral aggregates and an asphalt binder, have been widely utilized due to their capacity to withstand heavy traffic loads, resist harsh weather conditions, and provide a safe and efficient surface for road users [2,3]. Nevertheless, the sector grapples with ongoing challenges related to sustainability, material performance limitations, and the urgent need for innovative solutions to mitigate the environmental impact of such infrastructures [4,5].

In regions such as northwestern Mexico, particularly states like Baja California, sub-standard aggregate quality exacerbates pavement instability and curtails service life. Local aggregate sources frequently fail to meet the minimum standards for strength and durability, negatively impacting pavement stability and service life [6]. This issue intersects with

global environmental crises, notably plastic waste accumulation, which poses a significant threat to terrestrial and marine ecosystems. Annually, approximately 460 million tons of plastic are produced worldwide, yet only 9% is recycled; the remainder pollutes landfills and natural environments [7,8].

Recent studies have shown that pavements modified with plastic waste can act as emitters of microplastics, generated through vehicle traffic friction and material degradation [9–11]. These particles, transported by runoff or wind, reach terrestrial and aquatic habitats, where their persistence and potential for contamination raise environmental concerns [12,13]. This potential emission represents an environmental risk that should be considered in future evaluations.

The improper management of plastic waste has led to an environmental crisis requiring urgent solutions. Among the most prevalent plastics is high-density polyethylene (HDPE), widely used in bottles and containers, renowned for its exceptional mechanical strength, minimal water absorption, and robust thermal stability [14,15]. These properties make HDPE an ideal candidate for applications in asphalt mixtures. However, the use of this material is not free of challenges; its elastic behavior and inconsistent melting points complicate its uniform integration into mixtures, particularly in methods such as the dry process [16,17].

The incorporation of plastic waste into asphalt mixtures offers a dual benefit: enhancing the mechanical performance of pavements while simultaneously mitigating environmental pollution caused by plastic accumulation. However, technical challenges related to compaction and cohesion continue to limit widespread adoption in road construction projects [18,19].

Since the 1970s, various methods have been developed and refined to incorporate recycled materials into asphalt mixtures, with the most common approaches being the wet method and the dry method [20]. The wet method entails blending plastic with the asphalt binder at high temperatures, ensuring better integration but requiring specialized equipment and thermal control to prevent material degradation [20,21]. Conversely, the dry method incorporates shredded plastic directly into the aggregates before adding the binder, simplifying the process and reducing costs, but it poses challenges such as thermal incompatibility and uneven dispersion of plastic particles [22,23].

Several studies have investigated the inclusion of recycled plastics into asphalt mixtures as a sustainable strategy to improve the mechanical performance. The results have shown that the integration of HDPE can enhance pavement resistance to fatigue, permanent deformation, and moisture damage, depending on the method of application and the type of mixture used. However, these benefits are contingent upon the percentage and method of plastic incorporation, as well as the specific conditions of each project [20,24,25].

Technological advancements in asphalt mixture design, including the Superpave method, have enabled more precise assessments of plastic additives under realistic traffic loads and climatic conditions. This approach combines laboratory testing with computational simulations to optimize material proportions and predict the long-term performance of pavements [20,26,27]. Despite these improvements, challenges persist regarding the cohesion and compaction of mixtures incorporating HDPE, especially in hot climates [22,28,29].

This study aims to evaluate the impact of HDPE as an additive in hot asphalt mixtures, with particular emphasis on the rebound phenomenon during densification. The objective is to determine how different percentages of HDPE (0.5%, 0.62%, 1%, 4%, and 5%) relative to the aggregate affect key properties such as resistance to permanent deformation, void content, and volumetric stability of the mixtures. Additionally, these results are compared with those of traditional mixtures without plastic to assess their technical feasibility as a sustainable solution for road construction in hot climates.

2. Materials and Methods

2.1. Materials

The study utilized three primary materials: mineral aggregates, asphalt binder, and shredded HDPE, as illustrated in Figure 1.

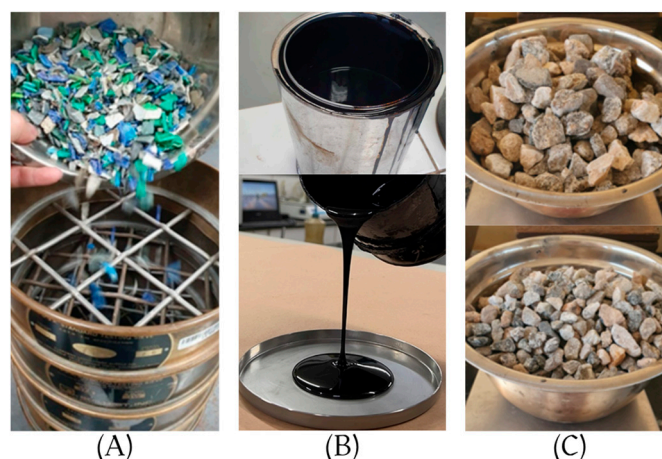


Figure 1. (A) HDPE in sieves, (B) PG 64 binder, (C) Classified aggregates.

The mineral aggregates, sourced from local quarries in Baja California, were classified into coarse, fine, and mineral dust based on particle size, meeting the specifications of the Superpave method, as shown in Table 1.

Table 1. Aggregate classification.

Type of Aggregate	Particle Size
Coarse aggregates	>4.75 mm
Fine aggregates	0.075–4.75 mm
Mineral dust	<0.075 mm

The binder selected was of grade PG 64-22, chosen for its resistance to aging and its ability to withstand extreme climatic conditions [30]. The rheological properties of the binder are directly related to the flow and deformation under different stresses, which were determined through specific tests as shown in Table 2.

Table 2. Rheological properties of PG 64 binder.

Property	1	2	3	Units
	Accepted	Accepted	Fail	
Complex modulus (G^*)	3.96	1.74	0.814	kPa
Phase angle (δ)	85.1	86.7	87.8	°
$G^*/\sin\delta$	3.98	1.75	0.815	kPa
Shear stress	473.40	209.03	97.57	Pa
Test temperature	58.01	64.00	70.01	°C
Frequency	10.03	10.03	10.03	rad/s
Strain	11.96	12.00	11.99	%

The rheological properties obtained for the PG 64 binder indicate suitable elasticity and aging resistance under test conditions. The values of G^* and δ suggest a good resistance to deformation at high temperatures, confirming its suitability for moderate traffic conditions. However, the relationship between $G^*/\sin\delta$ and the HDPE percentage still requires further

analysis to determine its impact on the durability and mechanical performance of the modified mixtures.

The shredded HDPE, sourced from recycled materials, was adjusted to match the aggregate gradation. Key physical properties of HDPE are summarized in Table 3, while its visual appearance is shown in Figure 1.

Table 3. Physical properties of HDPE.

Properties	Value
Tensile strength	0.20–0.40 N/mm ²
Density	0.944–0.965 g/cm ³
Melting point	131 °C
Melt flow index	6.12 g/10 min

2.2. Preparation of Asphalt Mixtures

During the preparation of the asphalt mixtures, adjustments to the aggregate gradation were made to ensure that the proportions of aggregates and HDPE adhered to the Superpave method requirements. Table 4 illustrates the gradation distribution of the asphalt mixtures, specifying the masses of each aggregate fraction used in the compaction tests (Gmb), theoretical maximum specific gravity (Gmm), and rutting resistance tests with the Hamburg wheel.

Table 4. Aggregate gradation of asphalt mixture.

Sieve Size	Gmb	Gmm	Hamburg Wheel
	Mass (gr)	Mass (gr)	Mass (gr)
1 1/2"	0.0	0.0	0.0
1"	0.0	0.0	0.0
3/4"	301.5	167.5	151.4
1/2"	436.5	242.5	219.2
3/8"	558.0	310.0	280.3
N°4	1269.0	705.0	637.4
N°8	472.5	262.5	237.3
N°16	364.5	202.5	183.1
N°30	288.0	160.0	144.7
N°50	279.0	155.0	140.1
N°100	216.0	120.0	108.5
N°200	130.5	72.5	65.5
Passing 200	184.5	102.5	92.7
Total	4500.0	2500.0	2260.2

Particularly, it is noteworthy that sieve No. 4 contains the largest aggregate mass compared to the others, underscoring its critical role in the structural integrity of the mixtures. On the other hand, Table 5 details the incorporation of HDPE in different percentages (0.5%, 0.62%, 1%, 4%, and 5%), showing how the inclusion of plastic affects the masses in compaction and theoretical maximum specific gravity tests. These tables provide a comprehensive overview of the behavior of the mixtures under different conditions and compositions, emphasizing the impact of HDPE on volumetric and mechanical stability.

The HDPE percentages (0.5%, 0.62%, 1%, 4%, and 5%) were selected based on insights from previous studies and technical evaluations. Lower concentrations (0.5% and 0.62%) were used to assess the initial effects of plastic inclusion without significantly compromising mechanical properties. In contrast, higher percentages (1%, 4%, and 5%) were chosen to investigate the potential benefits of larger amounts of plastic. However, findings indicated

that, as the percentage increased, HDPE induced a rebound effect that negatively impacted compaction, suggesting a threshold beyond which its effectiveness in the mixtures diminishes.

Table 5. HDPE aggregate gradation.

Asphalt Mix	Mass (Gmb)		Mass (Gmm)	
	N° 4 (gr)	HDPE (gr)	N° 4 (gr)	HDPE (gr)
No plastic	1269	N/A	705	N/A
0.5%	1246.5	22.5	692.5	12.5
0.62%	1241.1	27.9	689.5	15.5
1%	1224	45	680	25
4%	1089	180	605	100
5%	1044	225	580	125

2.3. Methods and Tests

The dry method was selected for the incorporation of crushed HDPE due to its straightforward application and adaptability. This method consists of mixing the HDPE with aggregates prior to the addition of the asphalt binder and is noted for its simplicity and compatibility under local conditions. As outlined in Table 6, a comparison is made between the wet and dry methods, while Figure 2 provides a graphical representation of both processes.

Table 6. Comparison of HDPE incorporation methods.

Método	Ventajas	Limitaciones
Wet	Improves cohesion between HDPE and binder.	Requires specialized equipment and thermal control.
Dry	Simpler and more economical.	Issues with thermal compatibility and cohesion.

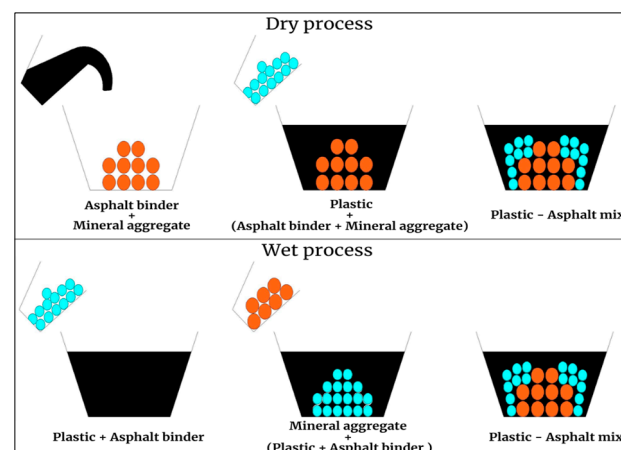


Figure 2. Plastic Incorporation Processes in Asphalt Mixtures.

The properties of the asphalt mixtures were evaluated through various laboratory tests, using the dry method for incorporating crushed HDPE. This method entails mixing the HDPE with the aggregates prior to the addition of the asphalt binder, noted for its simplicity and compatibility with local conditions. As presented in Table 6, a comparative analysis of the wet and dry methods is provided, while Figure 2, graphically depicts the application of both processes. The densification of the asphalt mixture was performed using a gyratory compactor to simulate traffic conditions and assess both density and air void content, in accordance with the Superpave method specifications [31].

The Hamburg wheel test allowed for the analysis of rutting resistance and permanent deformation under cyclic and immersion conditions, allowing for a performance comparison between conventional mixtures and those modified with HDPE [5,29]. Additionally, the rheological properties of the PG 64 asphalt binder were determined using a dynamic shear rheometer, assessing the complex modulus (G^*), phase angle (δ), and shear stress at different temperatures [31].

3. Results and Discussion

3.1. Evaluation of Asphalt Mix Compaction

The results gathered from the compaction tests revealed a clear correlation between the percentage of HDPE incorporated into the asphalt mixtures and their compaction behavior. As presented in Table 7, mixtures with lower HDPE percentages (0.5% and 0.62%) exhibited good and excellent compaction, respectively. Notably, the mixture with 0.62% HDPE exhibited superior densification and a significant improvement in durability, suggesting an effective integration of the plastic additive within the asphalt mixture.

Table 7. Compaction results of asphalt mixes.

Mix	Compaction Ability	Observations
Without plastic	Good	Cohesive and stable mixture
0.5% HDPE	Good	Improved stability, reduced voids
0.62% HDPE	Excellent	Better compaction, improved cohesion
1% HDPE	Fair	Cohesion issues, discarded
4% HDPE	Poor	Does not compact, rebound effect
5% HDPE	Poor	Does not compact, rebound effect

On the other hand, mixtures with higher HDPE percentages (1%, 4%, and 5%) exhibited notable challenges associated with the rebound effect, which hinders adequate compaction. This phenomenon is attributed to reduced internal cohesion in the mixture and a less uniform structure, as illustrated in Figure 3. This behavior highlights a threshold for HDPE incorporation in asphalt mixtures, beyond which mechanical properties are severely affected. This finding underscores the importance of strictly regulating the proportion of HDPE used to avoid issues related to compaction ability.

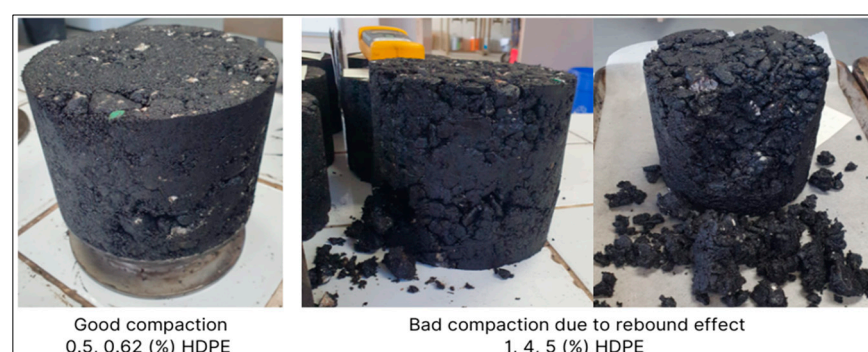


Figure 3. Compaction results.

The results indicate that incorporating HDPE in moderate percentages (0.5% and 0.62%) enhances the compaction and durability of asphalt mixtures, whereas higher proportions generate a rebound effect that affects structural stability. This phenomenon, attributed to the intrinsic elasticity of HDPE, hinders uniform compaction and reduces the internal cohesion of the mixture [31]. Additionally, the thermal behavior of the plastic may influence the overall distribution and stability of the mixtures. These findings underscore the impor-

tance of establishing an upper limit for the HDPE proportion to prevent compromising mechanical properties.

3.2. Density and Void Results

As presented in Table 8, the results obtained for the maximum specific gravity (Gmm), bulk specific gravity (Gmb), and void percentage (%Va) of the asphalt mixtures studied are summarized. The Gmm and Gmb values exhibit a direct correlation with the amount of HDPE incorporated into the mixtures. In the mixtures with 0.5% and 0.62% HDPE, the void percentages reached values of 2.06% and 2.42%, respectively, values that closely align with the optimal standards established for asphalt mixtures, in accordance with AMMAC recommendations [5].

Table 8. %Va results.

Mix	Gmm	Gmb	Va (%)
No plastic	2.477	2.386	3.68
0.5% HDPE	2.430	2.380	2.06
0.62% HDPE	2.434	2.375	2.42
1% HDPE	Material floated	Not applicable	Could not be calculated
4% HDPE	Not applicable	Not applicable	Not applicable
5% HDPE	Not applicable	Not applicable	Not applicable

The rheological properties of the PG 64 asphalt binder were determined using a dynamic shear rheometer, analyzing the complex modulus (G^*), phase angle (δ), and shear stress under varying temperature conditions.

Finally, the aggregate gradation of the mixtures was refined to ensure stability and durability, as detailed in Table 4, using the results from the Superpave gradation analysis [25,31].

In the mixtures containing 1%, 4%, and 5% HDPE, no valid results were obtained due to cohesion issues and the rebound effect—a phenomenon previously documented in studies on the use of plastic polymers in asphalt mixture [15,24]. This behavior hindered compaction and altered volumetric properties, revealing a lack of internal cohesion that compromises practical feasibility.

The results indicate that conventional mixes without plastic additives exhibit a %Va of 3.68%, within the acceptable range for asphalt mixtures. By contrast, the mixes with 0.5% and 0.62% HDPE showed a lower air void percentage, suggesting enhanced compaction efficiency. This can be attributed to more uniform particle distribution and optimized densification during compaction [20].

Conversely, mixtures with higher HDPE concentrations failed to achieve satisfactory results due to the inherent elasticity of the plastic, which triggered the rebound effect during compaction, thereby impairing internal cohesion. These findings support the hypothesis that, while HDPE, in controlled proportions, can enhance specific physical properties, excessive amounts negatively impact structural integrity and volumetric performance.

3.3. Performance Evaluation in the Hamburg Wheel Tracking Test

This test is critical for assessing resistance to permanent deformation and rutting in asphalt mixtures under repeated loading and wet conditions. It provides insight into how mixtures perform under real-world service conditions, simulating the continuous impact of heavy traffic. In this study, the influence of asphalt mixture modifications on both structural integrity and functional performance are determined.

As presented in Table 9, the main results of the compaction test conducted on the mixtures with different HDPE percentages are outlined. The results were obtained from two independent samples (M1 and M2) tested under different conditions with data obtained from Wheel 1 and Wheel 2. Notably, mixtures with 0.5% and 0.62% HDPE sustained a

maximum number of passes of 11,608 and 15,192, respectively, slightly surpassing the mixtures with 0.5% HDPE. However, these figures fell short of the performance of the traditional asphalt mixture without plastic, which endured 15,192 passes, demonstrating superior resistance.

Table 9. Hamburg loaded wheel test results.

Results	Wheel 1	Wheel 2	
		Sample 1	Sample 2
(Gmb) Bulk specific gravity	2.386	2.375	2.375
(Gmm) Theoretical max. specific gravity	2.477	2.434	2.434
(Va) Void content (%)	7	7	7
Maximum rut depth	−10	−10	−10
No. of passes at inflection point	5700	N/A	5800
No. of passes at maximum deformation	8600	N/A	6300
Maximum deformation (mm)	−11.73	−25.73	−16.54
Maximum number of passes	15,192	11,608	11,608

This behavior further reinforces the idea that HDPE, when used in low concentrations, can provide some degree of stability, but it does not surpass traditional mixtures in terms of maximum resistance.

As illustrated in Figures 4 and 5, the permanent deformation curves for the conventional and HDPE-modified mixtures are presented. On one hand, the traditional mixture without plastic demonstrates exceptional resistance to deformation, exhibiting a maximum deformation of −11.73 mm, which significantly exceeds the acceptable threshold depicted in Figure 4. On the other hand, the mixture with 0.62% HDPE shows notable improvement compared to mixtures with higher plastic content, although its performance is still inferior to the mixture without plastic, as seen in Figure 5. These findings underscore that the incorporation of HDPE does not inherently lead to a substantial enhancement in deformation resistance.

Figure 6 provides a direct comparison of the deformation curves for different asphalt mixtures, clearly illustrating the rebound effect observed at higher HDPE concentrations. This phenomenon not only diminishes the mixture's resistance to maximum deformation but also reduces the number of passes required to reach critical inflection and deformation points. Thus, although HDPE in low proportions can provide limited benefits, its excessive use severely compromises the internal cohesion and thermal compatibility of the mixtures.



Figure 4. Graph of results for Asphalt Mix without Plastic.

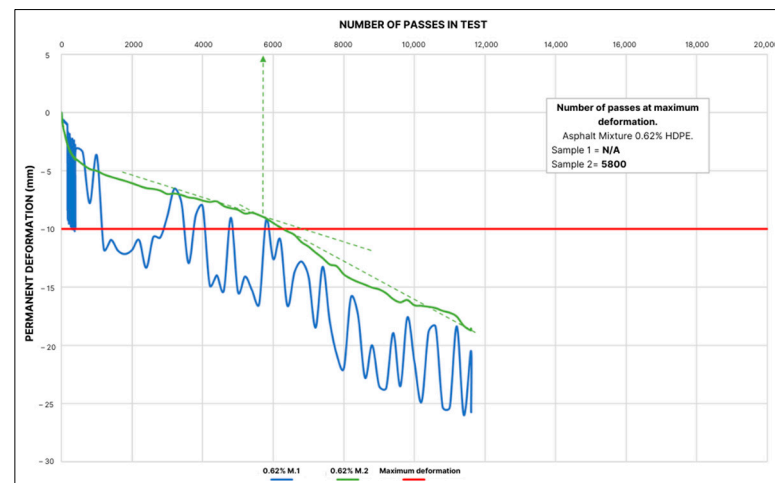


Figure 5. Graph of results for Asphalt Mix with 0.62% HDPE.

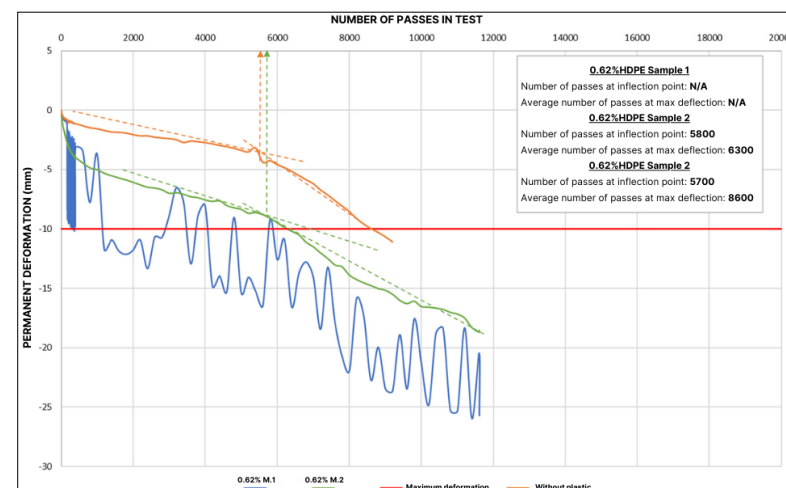


Figure 6. Comparison of Hamburg Wheel Test Result Graphs.

3.4. General Comparison of Results

The results provide a comprehensive overview of the performance of asphalt mixtures modified with varying HDPE percentages. Among the tested formulations, the mixture containing 0.62% HDPE emerged as the only viable modification, demonstrated in terms of compaction and stability compared to higher HDPE concentrations, as presented in Table 7. However, its performance remained inferior to that of the conventional plastic-free mixture, which exhibited greater resistance and stability in the Hamburg wheel test, achieving 15,192 passes compared to 11,608 for the mixture with HDPE, as seen in Table 9. The rebound effect phenomenon highlights that higher percentages of HDPE (4% and 5%) lead to unstable compaction outcomes, as depicted in Figure 6, resulting in reduced internal cohesion and deformation resistance. This adverse behavior also negatively impacted specific gravity and void content values, as seen in Table 8, limiting the feasibility of incorporating these percentages in asphalt mixtures. Overall, these findings underscore that, although shredded HDPE may hold potential as an additive, its practical application presents significant challenges, particularly in regions such as Baja California, where aggregate quality is limited. The elastic behavior of HDPE at high percentages hinders compaction and increases deformation under load, compromising the structural performance of the mixtures. These results emphasize the need to limit HDPE proportions and explore alternative methods to mitigate the negative effects of rebound.

4. Conclusions

Asphalt pavements are particularly susceptible to permanent deformation and cohesion loss under repetitive loading and high-temperature conditions. This study evaluated the use of HDPE plastic waste as a modifier in asphalt mixtures, aiming to improve properties such as compaction, structural stability, and resistance to permanent deformation. The results identified that the mixture containing 0.62% HDPE was the most viable among the evaluated percentages. This composition exhibited relative improvements in compaction and stability when compared to mixtures with higher HDPE concentrations, which experienced significant drawbacks due to the rebound effect and a loss of internal cohesion.

Regarding performance in the Hamburg wheel test, findings revealed that, while the mixture with 0.62% HDPE outperformed those containing higher plastic content, its resistance to permanent deformation remained inferior to that of the conventional plastic-free mixture. This underscores that the incorporation of HDPE does not guarantee a significant improvement in the structural resistance of the mixtures under repetitive load conditions.

Methodological analyses further demonstrated that employing the dry method for HDPE incorporation presents technical challenges, such as the difficulty in achieving a uniform distribution of the material and controlling its elastic behavior. This rebound effect was especially evident in mixtures with high percentages of HDPE (1%, 4%, and 5%), resulting in insufficient densification and inadequate performance. Although the results did not support the technical viability of HDPE as a modifier, its potential as a recycled material for sustainable applications remains noteworthy. The controlled incorporation of HDPE could help partially mitigate the environmental impact associated with plastic waste, provided that the observed technical limitations are overcome.

Although the present study focused on the mechanical and rheological properties of asphalt mixtures with HDPE addition, it is important to note that the potential release of microplastics due to surface wear was not evaluated. This represents a future line of research that is essential to understanding the possible environmental impacts of this technology.

Finally, it is recommended that future research explore alternative types of recycled plastics with properties better suited for asphalt mixtures, as well as to improve mixing and compaction methods. Future studies should focus on evaluating the influence of HDPE particle size and morphology on mixture performance, implementing advanced techniques to minimize the rebound effect, and analyzing the behavior of the mixtures under real traffic and weather conditions to ensure their long-term viability. In summary, although HDPE did not prove to be a viable solution for enhancing deformation resistance in asphalt pavements, this study establishes a foundation for future research into the application of recycled materials in sustainable construction.

Author Contributions: Conceptualization, D.S.-V. and J.C.-R.; methodology, D.S.-V. and R.C.-R.; software, D.S.-V. and J.C.-R.; validation, D.S.-V. and R.C.-R.; formal analysis, D.S.-V. and J.C.-R.; investigation, D.S.-V. and J.M.G.-M.; resources, D.S.-V. and L.G.-G.; supervision, D.S.-V. and M.M.-A.; project administration, D.S.-V. and A.S.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: This study has not generated any new data that can be shared, and no data has been uploaded to any external databases. The results and analysis of the study are available in this document.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Ivanova, E.; Masarova, J. Importance of road infrastructure in the economic development and competitiveness. *Econ. Manag.* **2013**, *18*, 263–274.
- Potti, J.J. La Producción Española de Mezclas Bituminosas Durante 2022 Alcanza Los 17,1 Millones de Toneladas; vol. 44, no. 1, pp. 5–6, 2022. Available online: <https://asefma.es/la-produccion-espanola-de-mezclas-bituminosas-durante-2022-alcanza-los-1710-millones-de-toneladas/> (accessed on 30 November 2023).
- Assefa, N. Evaluation of the effect of recycled waste plastic bags on mechanical properties of hot mix asphalt mixtures for road construction. *Sustain. Environ.* **2021**, *7*, 1957649. [CrossRef]
- Arrieta Lora, A.C.; Marulanda Restrepo, S.; Senior Arrieta, V. *Evaluación del Comportamiento Mecánico de una Mezcla Asfáltica Tipo MDC-19 Modificada con GCR y Bajo Condiciones Climáticas Severas de la Ciudad de Medellín*; Universidad Cooperativa de Colombia: Bogotá, Colombia, 2023.
- Asociación Mexicana del Asfalto, A.C. (AMMAC). *Protocolo AMAAC PA-MA 01-2011: Diseño de Mezclas Asfálticas de Granulometría Densa de Alto Desempeño*; Asociación Mexicana del Asfalto, A.C. (AMMAC): Tlalpan, Mexico, 2011.
- Rojo, T.; Moquete, F.A.; Vergel, J.E.; Garea, M. Historia del Uso de Asfalto. Available online: <https://eadic.com/blog/entrada/historia-del-uso-de-asfalto/> (accessed on 30 November 2023).
- del Toro, Y.A.; Alamilla, H.D.; Ortiz, D.V.G.; Rivera, A.Z.S. *Manual de Ensayos para Laboratorio: Mezclas Asfálticas en Caliente (MAC)—Parte 1: Para el Cálculo de Volumetría y Ensayos de Desempeño*; Instituto Mexicano del Transporte: Pedro Escobedo, Mexico, 2018.
- Programa de las Naciones Unidas para el Medio Ambiente. Informe de la ONU Sobre Contaminación por Plásticos Advierte Sobre Falsas Soluciones y Confirma la Necesidad de una Acción Mundial Urgente. 2021. Available online: <https://www.unep.org/es/noticias-y-reportajes/comunicado-de-prensa/informe-de-la-onu-sobre-contaminacion-por-plasticos> (accessed on 30 November 2023).
- Duan, Y.; Wu, K.; Serrat, C.; Arteaga-Larios, F.; Brown, H.; DuBois, C.J.; Buttlar, W.G.; Deng, B. Assessment of microplastics production from waste plastics-modified asphalt pavement. *Resour. Conserv. Recycl.* **2024**, *202*, 107329. [CrossRef]
- Enfrin, M.; Myszk, R.; Giustozzi, F. Paving roads with recycled plastics: Microplastic pollution or eco-friendly solution? *J. Hazard. Mater.* **2022**, *437*, 129334. [CrossRef] [PubMed]
- García-Haba, E.; Benito-Kaesbach, A.; Hernández-Crespo, C.; Sanz-Lazaro, C.; Martín, M.; Andrés-Doménech, I. Removal and fate of microplastics in permeable pavements: An experimental layer-by-layer analysis. *Sci. Total Environ.* **2024**, *929*, 172627. [CrossRef] [PubMed]
- Evangelidou, N.; Tichý, O.; Eckhardt, S.; Zwaafink, C.G.; Brahney, J. Sources and fate of atmospheric microplastics revealed from inverse and dispersion modelling: From global emissions to deposition. *J. Hazard. Mater.* **2022**, *432*, 128585. [CrossRef] [PubMed]
- Özen, H.A.; Mutuk, T. The influence of road vehicle tyre wear on microplastics in a high-traffic university for sustainable transportation. *Environ. Pollut.* **2025**, *367*, 125536. [CrossRef] [PubMed]
- Ismail, Z.Z.; Al-Hashmi, E.A. Use of waste plastic in concrete mixture as aggregate replacement. *Waste Manag.* **2008**, *28*, 2041–2047. [CrossRef]
- Casey, D.; McNally, C.; Gibney, A.; Gilchrist, M.D. Development of a recycled polymer modified binder for use in stone mastic asphalt. *Resour. Conserv. Recycl.* **2008**, *52*, 1167–1174. [CrossRef]
- Akinleye, M.T.; Jimoh, Y.A.; Salami, L.O. Marshall properties evaluation of hot and warm asphalt mixes incorporating dissolved plastic bottle modified bitumen. *J. Mater. Eng. Struct.* **2020**, *7*, 439–450.
- Marquez, K.P.; Arizala, C.V.D.; Soriano, V.J.; Barron, J.M.G.; Florece, A.E.A.; Caday, J.H.B.; Migo, V.P. Recycled polyethylene terephthalate as reinforcement additive of asphalt mixture for pavement application. *Philipp. J. Sci.* **2021**, *150*, 1061–1068. [CrossRef]
- Mashaan, N.; Chegenizadeh, A.; Nikraz, H. Laboratory properties of waste PET plastic-modified asphalt mixes. *Recycling* **2021**, *6*, 49. [CrossRef]
- Moghadas Nejad, F.; Arabani, M.; Hamedi, G.H.; Azarhoosh, A.R. Influence of using polymeric aggregate treatment on moisture damage in hot mix asphalt. *Constr. Build. Mater.* **2013**, *47*, 1523–1527. [CrossRef]
- López, C.; Thenoux, G.; Sandoval, G.; Armijos, V.; Ramírez, A.; Guisado, F.; Moreno, E. Estudio de mezclas asfálticas templadas con emulsión super-estabilizada. *Rev. Ing. Construcción* **2017**, *32*, 57–64. [CrossRef]
- S. Minaya González y A. Ordóñez Huamán, *Manual de Laboratorio de Ensayos para Pavimentos*, vol. I. Lima, Perú: Universidad Nacional de Ingeniería, Facultad de Ingeniería Civil, Laboratorio No. 2 de Mecánica de Suelos y Pavimentos, 2001. Available online: https://www.academia.edu/6949875/MANUAL_DE_ENSAYOS_PARA_PAVIMENTOS (accessed on 30 November 2023).
- Singh, P.; Swamy, A.K. Effect of aging level on viscoelastic properties of asphalt binder containing waste polyethylene. *Int. J. Sustain. Eng.* **2019**, *12*, 141–148. [CrossRef]
- Awad, A.; Al Adday, F. Utilization of waste plastics to enhance the performance of modified hot mix asphalt. *GEOMATE J.* **2017**, *13*, 132–139. [CrossRef]

24. Raza, S.A.; Shah, N.; Sharif, A. Time frequency relationship between energy consumption, economic growth and environmental degradation in the United States: Evidence from transportation sector. *Energy* **2019**, *173*, 706–720. [[CrossRef](#)]
25. D'Angelo, J.; Bukowski, J.; Harman, T. Superpave Asphalt Mixture Design Workshop Workbook; U.S. Department of Transportation, Federal Highway Administration, Washington, DC, USA, 2002. Available online: <https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/asphalt/mixdsgn.pdf> (accessed on 30 November 2023).
26. Sukmawan, W.; Arifin, S. Effect of Adding Plastic Waste Ldpe (Low Density Polyethylene) and Pet (Polyethylene Terephthalate) on the Behaviour of Stability Marshall Characteristics of Asphalt Concrete Mixture. *Int. J. Civ. Eng.* **2021**, *10*, 29–44.
27. Ma, J.; Hesp, S.A.M. Effect of recycled polyethylene terephthalate (PET) fiber on the fracture resistance of asphalt mixtures. *Constr. Build. Mater.* **2022**, *342*, 127944. [[CrossRef](#)]
28. Haider, S.; Hafeez, I.; Jamal, Ullah, R. Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures. *Constr. Build. Mater.* **2020**, *235*, 117496. [[CrossRef](#)]
29. Rojas, T. Todo Sobre el Polietileno de Alta Densidad (HDPE): Usos, Ventajas y Mercado Actual. Tecnología del Plástico. 2023. Available online: <https://www.plastico.com/es/noticias/todo-sobre-el-polietileno-de-alta-densidad-hdpe-usos-ventajas-y-mercado-actual> (accessed on 30 November 2023).
30. Garnica, P.; Alamilla, H.D.; Sandoval Sandoval, C.D. *Análisis Comparativo de los Métodos Marshall y Superpave para Compactación de Mezclas Asfálticas*; Instituto Mexicano del Transporte: Pedro Escobedo, Mexico, 2005.
31. Garnica, P.; Delgado, H.; Gómez, J.A.; Romero, S.A.; Alarcón, H.A. *Aspectos del Diseño Volumétrico de Mezclas Asfálticas*; Instituto Mexicano del Transporte: Pedro Escobedo, México, 2004; p. 31.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.