

Development of a methodological process for sustainability on roads: incorporation of plastic waste into pavements

Desarrollo de un proceso metodológico para la sostenibilidad en carreteras: incorporación de residuos plásticos en pavimentos

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How to cite

D. Sepúlveda Valdez, J.A. Calderón Ramírez, I. Núñez López, and R. Cota Ramírez, "Development of a methodological process for sustainability on roads: incorporation of plastic waste into pavements" Engineering: Science, Technology, and Innovation, vol. 12, 2025. <https://doi.org/10.26495/q0q4s564>

Article information

Received: 06/05/2025
Accepted: 14/11/2025
Published: 01/12/2025

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ABSTRACT: The accumulation of plastic waste represents an environmental challenge that affects the construction industry, especially in road paving. In this context, the incorporation of recycled plastics, such as high-density polyethylene (HDPE), was explored to develop more sustainable pavements. The objective of this research was to design and evaluate a replicable methodology to compare traditional asphalt mixtures with mixtures modified with HDPE. To this end, mixtures were prepared using the dry method and subjected to performance tests, including bulk specific gravity (G_{SB}), maximum theoretical specific gravity (G_{mm}), air void content, and Hamburg wheel tracking test. The results showed that mixtures modified with HDPE exhibited less deformation and maintained porosity levels similar to conventional mixtures, although with a slight decrease in density. It is concluded that the proposed methodology facilitates the integration of recycled plastics into pavements, contributing to waste reduction and improved durability of road infrastructure.

Keywords: Modified asphalt mixtures, pavement design methodology, sustainable flexible pavements, deformation resistance, plastic waste management.

RESUMEN: La acumulación de residuos plásticos representa un reto ambiental que afecta a la industria de la construcción, especialmente en la pavimentación de carreteras. En este contexto, se exploró la incorporación de plásticos reciclados, como el polietileno de alta densidad (HDPE), para desarrollar pavimentos más sostenibles. El objetivo de esta investigación fue diseñar y evaluar una metodología replicable para comparar mezclas asfálticas tradicionales con mezclas modificadas con HDPE. Para ello, se elaboraron mezclas mediante el método seco y se sometieron a pruebas de desempeño, incluyendo gravedad específica bruta (G_{MB}), gravedad específica teórica máxima (G_{MM}), porcentaje de vacíos y prueba de la rueda cargada de Hamburgo. Los resultados mostraron que las mezclas con HDPE presentaron menor deformación y mantuvieron niveles de porosidad similares a las mezclas convencionales, aunque con ligera disminución en la densidad. Se concluye que la metodología propuesta facilita la integración de plásticos reciclados en pavimentos, contribuyendo a la reducción de residuos y a la mejora de la durabilidad de la infraestructura vial.

Palabras Claves: Mezclas asfálticas modificadas, metodología de diseño de pavimentos, pavimentos flexibles sostenibles, resistencia a la deformación, gestión de residuos plásticos.

1. INTRODUCTION

Over time, the construction industry has faced significant challenges related to sustainability and waste management, in this case plastics. The growing accumulation of plastic waste has generated global concern due to its increasing negative impact on the environment, such as ocean pollution and its persistence in nature for centuries. These issues, combined with the need to improve the quality and durability of pavements, have led to the exploration of new areas and sustainable solutions in pavement construction and engineering [1], [2]. The use of certain recycled plastic waste, such as high-density polyethylene (HDPE) or polyethylene terephthalate (PET), has emerged as an interesting alternative for modifying the properties of asphalt mixtures in order to reduce the environmental impact of this waste [2].

There are different types of plastics that can be recycled, as shown in Table 1, and these can be used in the incorporation of asphalt mixtures. One of the most common plastics used in research is polyethylene terephthalate (PET), due to the large quantity of this material available. Each type of plastic has different characteristics that can influence the properties of the asphalt mixture, such as wear resistance and durability [3], [4].

Table 1. Types of plastics.

TYPE OF PLASTIC	Polyethylene terephthalate (PET or PETE)	High-density polyethylene (HDPE)	Polyvinyl chloride (PVC)	Low-density polyethylene (LDPE)	Polypropylene (PP)	Polystyrene (PS)
SYMBOL						

Source: own elaboration.

The idea of using recycled plastics in the creation of pavements is not a new concept. Previous studies have shown that incorporating recycled plastic materials into asphalt mixtures can improve the strength and durability of pavements, as well as contributing to the reduction of plastic waste. Certain studies, such as those by [5], have pointed to significant improvements in the thermal stability and wear resistance of asphalt mixtures modified with plastics. However, research on the optimisation of concentrations and the compatibility of recycled plastics with other components of the mixtures is still limited, posing technical and practical challenges for large-scale implementation [2], [6].

Several studies have addressed the incorporation of recycled plastics into asphalt mixtures, with varying approaches in terms of methodologies and materials used. In this regard, they found that the use of recycled plastics could improve the resistance to permanent deformation and the durability of the mixtures, although this will depend on various factors such as the type of plastic or the proportion used. In their study, [5] highlighted that the use of recycled plastics such as HDPE in asphalt mixtures can be effective in reducing the viscosity of the asphalt, which facilitates compaction. Furthermore, [6] point out that recycling plastics in asphalt improves pavement sustainability, while [7] conclude that recycling plastics in asphalt mixtures

not only reduces the demand for natural resources but also helps to optimise the mechanical properties of the pavement.

These types of studies are based on theories about sustainability in construction, especially the integration of recycled materials into the construction process. According to the circular economy theory promoted by the [8], recycling plastics can contribute to reducing the demand for natural resources and promotes the reuse of materials in the construction sector.

Currently, there is no standardised and widely accepted methodology for the direct comparison between traditional asphalt mixtures and those incorporating recycled materials, especially when considering the specific conditions and characteristics of each region. Although there are studies that evaluate the performance of pavements modified with recycled plastics, these generally focus on very specific scenarios or do not include a comprehensive evaluation that allows for clear comparisons with conventional mixtures [9]. Furthermore, variability in climatic conditions, traffic types, and local aggregate properties makes the implementation of universally applicable comparison methodologies challenging. This lack of an adequate comparative approach limits the ability of engineers and infrastructure managers to adopt sustainable practices based on these resources, as there is no specific method to indicate whether effective integration of the mixtures is achieved.

Furthermore, recent studies have shown that the use of plastic waste such as PET bottles in warm-mix asphalt mixtures can improve their mechanical properties, even at reduced mixing temperatures, without compromising their durability [10]. Similarly, experimental research incorporating low-density polyethylene (LDPE) and additives such as Sasobit indicate improvements in Marshall stability, which strengthens resistance to permanent deformation [11]. The use of polymers and nano-silica in warm mixes has also been shown to increase resistance to fatigue cracking and rutting [12], providing additional technical support for the viability of integrating recycled plastics into pavements.

The objective of this study was to develop and evaluate a comparative methodology for sustainable pavement design through the incorporation of recycled plastic waste in asphalt mixtures. The proposal focuses on generating a replicable solution that can be applied to road infrastructure projects, seeking to improve pavement resistance and address the challenge of plastic pollution.

2. MATERIAL AND METHODS

The purpose of this study was to evaluate a replicable methodology for analysing the feasibility of incorporating recycled plastic materials into sustainable pavement designs, as shown in Figure 1. The proposed methodology focuses on comparing two types of approaches for asphalt mixture design: a traditional mixture without the incorporation of recycled plastics and a modified mixture with recycled plastics, which can include any type of plastic waste for integration into pavements. This approach focuses on evaluating the performance of both mixtures, assessing their behaviour through various technical tests, with or without the addition of waste. This replicable methodology seeks to offer a solution to different contexts, allowing for its replication in various areas, depending on the plastics available for integration.

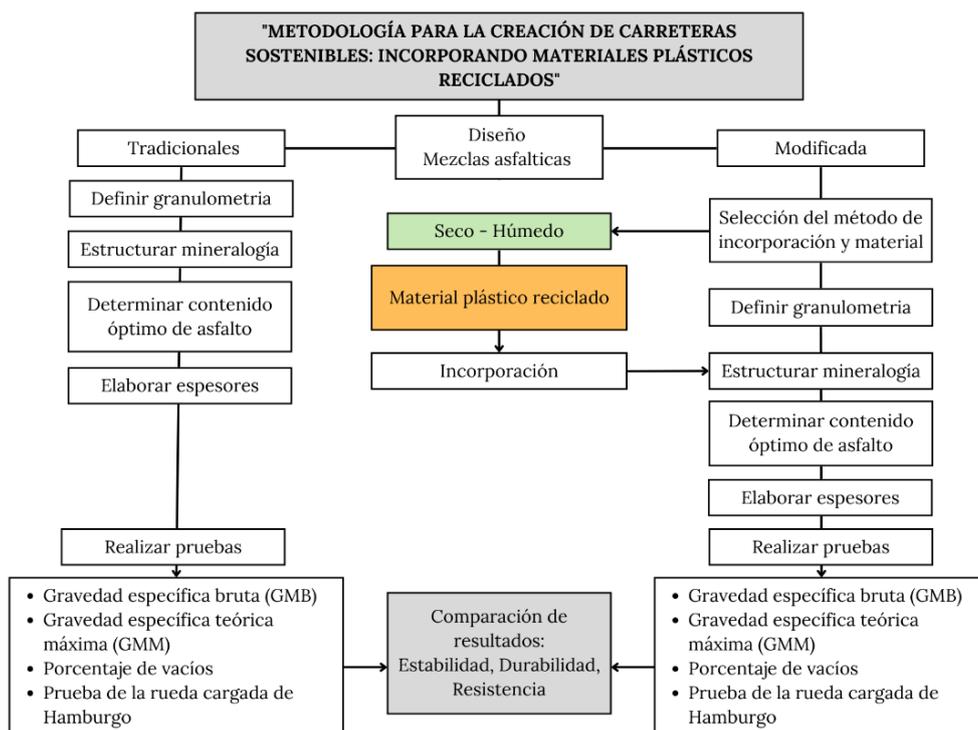


Figure 1. Methodology: Source: own elaboration.

2.1 Asphalt mixing methods

There are two main methods for creating asphalt mixtures: the Marshall method and the Superpave method. The Marshall method has traditionally been used in pavement design and focuses on determining the stability and fluidity of the mixture, making it more suitable for conventional pavements without significant modifications to their properties. However, this method has limitations when it comes to incorporating additives or recycled materials, which makes it difficult to apply in the creation of more sustainable pavements adapted to new technologies. In contrast, the Superpave method involves a more advanced and flexible approach, allowing us to incorporate various recycled materials, including plastics, into asphalt mixtures without compromising pavement quality [13]. This method is based on a continuous grading formula and analyses the strength and durability of mixtures, including the evaluation of deformation, cracking and fatigue. Due to its ability to integrate different types of additives, such as recycled plastics, the Superpave method is particularly well suited to the creation of sustainable pavements, and is the approach used in this study to compare mixtures with and without recycled plastics.

As shown in Table 2, the key differences between the two methods are detailed, highlighting the greater flexibility and adaptability of the Superpave method for incorporating recycled materials compared to the Marshall method.

Table 2. Comparison between methods for creating asphalt mixtures.

CHARACTERISTICS	ASPHALT MIXING METHOD	
	SUPERPAVE	MARSHALL
Binder selection.	Based on performance grade (PG).	Based on penetration grade or viscosity grade (PEN, AC).
Mixture design.	Continuous grading formula.	Specific maximum size mixture.
Performance testing.	Evaluation of resistance to deformation, cracking and fatigue.	Stability and flow.
Flexibility for modifiers.	High, incorporation of recycled and modified materials is permitted.	Low, less adaptable to modified materials.

Source: own elaboration.

2.2 Methods for incorporating plastics into asphalt mixtures

Currently, the most common and simplest methods for incorporating recycled plastics into asphalt mixtures are the dry process and the wet process. The difference between these lies in the way the plastic is mixed with the asphalt and aggregates. In the dry process, recycled plastic can be incorporated directly into the mineral aggregate before being mixed with the asphalt binder. This process is simpler and more economical, although it can result in a less homogeneous distribution of plastic in the mixture. On the other hand, the wet process involves melting the recycled plastic and mixing it with the asphalt binder before combining it with the aggregates. This method ensures a more uniform distribution of the plastic, but may involve higher energy and equipment costs, as shown in Figure 2.

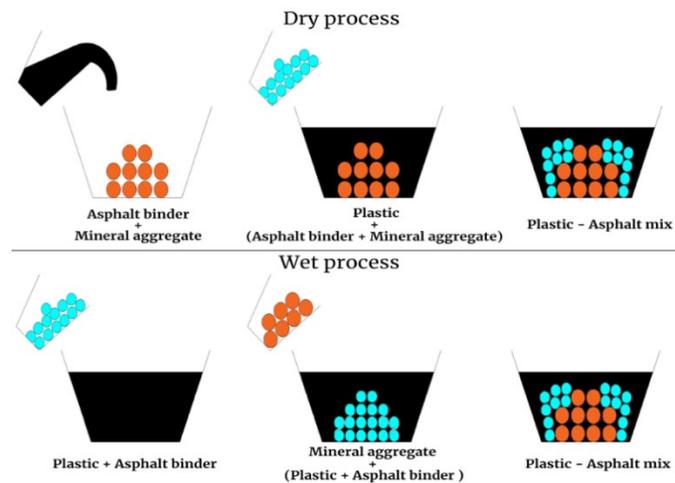


Figure 2. Incorporation process of plastic into asphalt mixtures. Source: own elaboration.

2.3 Performance tests

To assess the viability of this methodology, diverse performance tests will be carried out. These tests are essential for comparing the properties of mixtures with and without plastics, providing crucial data to determine whether the addition of plastic improves or deteriorates the behaviour of the pavement. The tests include Bulk Specific Gravity (GSB), which measures the density of the asphalt mixture and its compactability, and Maximum Theoretical Specific Gravity (Gmm), which helps to determine the maximum theoretical density of the mixture, which is essential for evaluating performance under extreme conditions. The Air Void Content Test is also performed, which evaluates the amount of air in the mixture, a key factor in ensuring its durability, and the Hamburg Wheel Tracking Test, which measures the resistance of the mixture to plastic deformation under heavy traffic conditions as described in Table 3.

Table 3. Performance tests for asphalt mixtures.

TEST	DESCRIPTION	METHOD FOR OBTAINING RESULTS	EQUIPMENT REQUIRED
Bulk Specific Gravity (GSB)	Measures the density of the asphalt mixture and its compactability.	The density of the asphalt mixture and its compactability are measured by evaluating how much material there is in a given volume of compacted sample. To do this, the sample is weighed and its volume is measured once it has been compacted in the laboratory.	Displacement cylinder equipment and precision balance.
Maximum Theoretical Specific Gravity (Gmm)	Determines the maximum theoretical density of the mixture, useful for evaluating performance.	The maximum theoretical density of the mixture is determined, which is useful for evaluating its performance. In this case, the uncompacted mixture is analysed by measuring its mass and volume to determine how densely the materials could be packed if there were no air.	Volume measurement equipment, such as pycnometer.
Air Void Content (%Va)	Evaluates the amount of air in the mixture, which is crucial for durability.	The amount of air present in the mixture is evaluated, which is crucial for its durability. This value is obtained by comparing the actual density of the compacted mixture with the maximum theoretical density, allowing us to know how many air voids there are in the structure.	Compaction equipment and void volume meter.
Hamburg Wheel Tracking Test	Measures the resistance of the mixture to plastic deformation under heavy traffic conditions.	The resistance of the mixture to plastic deformation is measured under conditions similar to real traffic, using equipment with a loaded wheel (Hamburg wheel). The sample is subjected to repeated loads, and the amount of permanent deformation over time is observed.	Hamburg wheel tracking equipment (specific device for this test).

Source: own elaboration.

Conducting these tests is crucial to ensure that asphalt mixtures modified with recycled plastics are viable and safe for use in paving. These tests not only allow traditional mixtures to be compared with modified ones, but also offer a standardised way of evaluating the performance of mixtures in any location or area. This makes the proposed methodology replicable, provided that these tests are carried out in a standardised manner, ensuring that the results are consistent and comparable under different local conditions. Comparing the results obtained from modified and unmodified mixtures facilitates decision-making on the viability of recycled plastics in pavements, contributing to the development of a more sustainable and resilient road infrastructure.

3. RESULTS

To implement this methodology, two specific types of mixtures were prepared: one with HDPE plastic and one without plastic, using traditional mixtures. The results obtained from tests carried out on traditional asphalt mixtures and those modified with recycled plastics, specifically with different concentrations of high-density polyethylene (HDPE), are presented below. These mixtures were prepared using the dry method, as detailed in the proposed methodology, with the aim of determining the feasibility of using this type of plastic in asphalt mixtures. As can be seen in the following graphs, the results focus on four key parameters: air void content (%Va), maximum theoretical specific gravity (Gmm), bulk specific gravity (GSB) and deformation under the Hamburg wheel tracking test.

3.1 Bulk Specific Gravity (GSB)

Figure 3 shows a comparison of the bulk specific gravity (GSB) between the different mixtures. As with the maximum theoretical specific gravity (Gmm), the traditional mix has a higher value than the mixtures modified with HDPE. This difference reinforces the hypothesis that the use of recycled plastic can influence the density of the asphalt mixture, although the variation is not significant. Bulk specific gravity is a crucial parameter in the design of asphalt mixtures, as it provides information on the compaction and density of the mixture. Knowing this value is essential to ensure the durability and stability of pavements, as higher density is generally associated with greater resistance to deformation and a longer pavement service life.

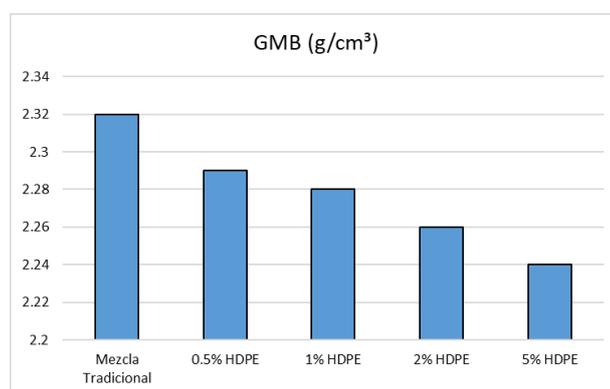


Figure 3. GSB results. Source: own elaboration.

3.2 Maximum Theoretical Specific Gravity (Gmm)

Figure 4 shows the maximum theoretical specific gravity (Gmm) values for the different mixtures, noting that the traditional mixture has a higher value than those modified with HDPE. As the concentration of HDPE increases, Gmm decreases, suggesting a reduction in the density of the mixture due to the incorporation of recycled plastics. This test is essential for evaluating the quality of asphalt mixtures, as it provides a measure of the density and compaction of the mixture, which directly influences its strength and durability. A lower Gmm is generally associated with lower wear resistance and higher porosity, which is important to consider to ensure optimal pavement performance.

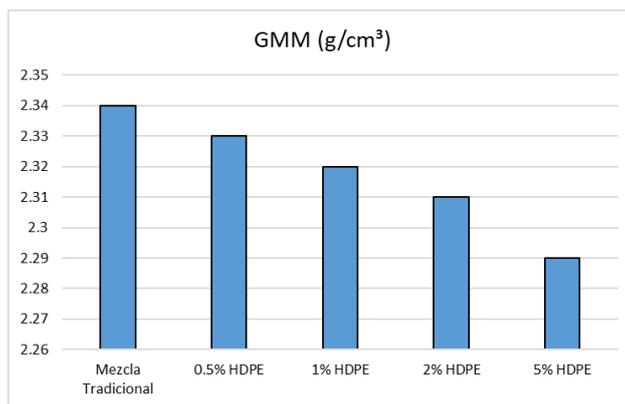


Figure 4. Gmm results. Source: own elaboration.

3.3 Air Void Content (%Va)

Figure 5 shows the comparison of the air void content (%Va) between traditional mixtures and those modified with different concentrations of HDPE (0.5%, 1%, 2% and 5%). It can be seen that mixtures modified with recycled plastics behave similarly to traditional mixtures, with a slight increase in voids as the HDPE concentration increases. This indicates that the use of recycled plastics does not have a significant negative impact on the porosity of the asphalt mixture. The air void content is a key parameter in pavement design, as it influences the compaction and strength of the mixture. An adequate air void content is necessary to prevent premature deformation and ensure the durability of the pavement.

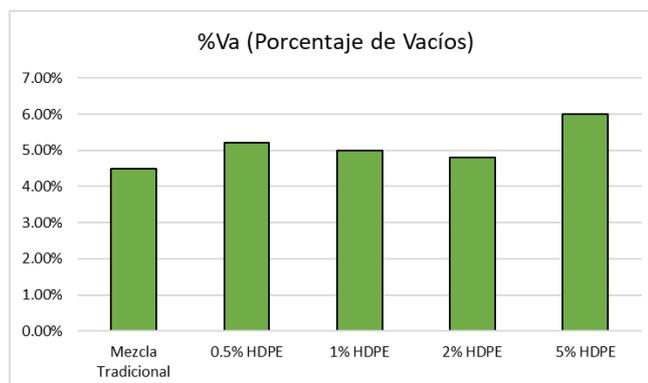


Figure 5. %Va results. Source: own elaboration.

3.4 Deformation

Figure 5 shows the results of the deformation of the mixtures under tracking tests. The mixtures modified with HDPE show less deformation compared to the traditional mixture, especially when the concentration of HDPE increases. This behaviour suggests that the incorporation of recycled plastics improves the resistance of the mixture to deformation, which could be beneficial for pavements subjected to heavy loads and heavy traffic conditions. The deformation test is essential for evaluating the ability of the mixture to resist compression and wear, which directly influences the long-term durability and performance of the pavement.

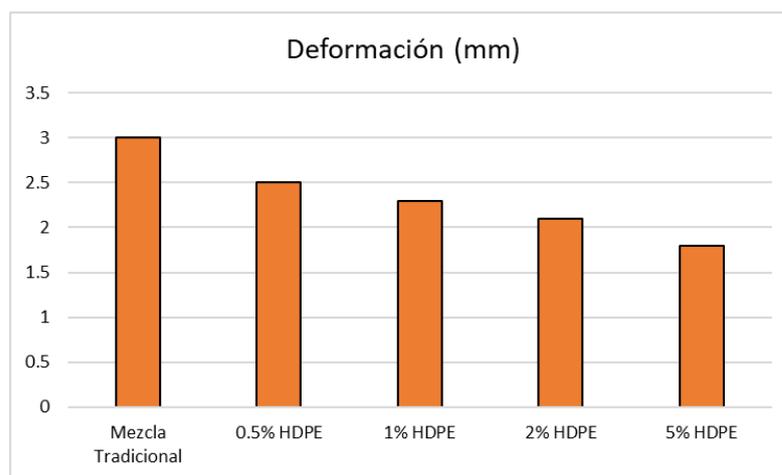


Figure 5. Deformation results. Source: own elaboration.

On the viability of recycled plastics in pavements, contributing to the development of a more sustainable and resilient road infrastructure.

4. DISCUSSION

The results obtained demonstrate that the incorporation of recycled plastics, specifically HDPE, improves the resistance of asphalt mixtures, as evidenced by the reduction in deformation under load (Figure 5). This behaviour agrees with previous studies that report improvements in stability and durability when incorporating recycled plastics. However, unlike what was reported by [5] in humid regions, this study was conducted in a semi-arid climate, where no significant deterioration in porosity or strength was detected. This finding suggests that environmental conditions can significantly influence the final performance of the mixtures, providing new evidence for poorly documented contexts.

The observed decrease in gross and theoretical maximum specific gravity Figures 3 and 4 indicates that HDPE modifies the density of the mixture. [7], pointed out that lower density could compromise strength, but this study found that, despite the reduction in density, resistance to deformation increased. This could be attributed to a better distribution of plastic particles in the asphalt matrix, reinforcing the idea that lower density does not always imply lower structural performance. However, high

concentrations of HDPE must be handled with care to avoid excessive increases in porosity that affect durability.

Compared to historical values for traditional mixtures in the same region, mixtures with HDPE showed more favourable behaviour under repeated loads, reinforcing their potential for use on high-traffic roads. From a practical point of view, these results could translate into less frequent maintenance and a direct contribution to plastic waste management, aligning with the principles of sustainability in road infrastructure. The proposed methodology, being replicable, offers engineers a tool to integrate plastic waste into pavements in a controlled and standardised manner.

One limitation is that the tests were carried out in the laboratory, using a single type of plastic and a single incorporation method. Future studies should consider field evaluations under different climatic and traffic conditions, as well as comparisons with other recycled polymers and integration techniques. This will allow the durability of the mixtures to be validated and the concentrations of recycled material to be optimised for different regional contexts.

5. CONCLUSION

This article has presented a replicable methodology for the design of sustainable pavements through the incorporation of recycled plastic waste into asphalt mixtures. The comparison between different concentrations of recycled plastics and traditional mixtures used in semi-arid regions has shown that the use of plastics, particularly HDPE, can improve the strength and durability of pavements. Through the tests carried out, it has been shown that the methodology not only facilitates the incorporation of recycled plastics into mixtures, but also promotes sustainability by reducing the amount of plastic waste, helping to mitigate the environmental impact of these materials.

This methodological model offers a viable and replicable solution for sustainable waste management in the road construction industry. Its applicability in road infrastructure projects could play a role in future paving projects, opening up new lines of research to optimise recycled plastic concentrations and adapt them to different regional and climatic conditions. Thus, this study not only addresses the challenge of plastic pollution, but also establishes a framework for the development of more resistant, durable and sustainable pavements, moving towards a more environmentally friendly road infrastructure.

6. ACKNOWLEDGEMENTS AND FUNDING

The authors would like to thank the academic institutions and laboratories that provided technical support for the development of this research. This study did not receive external funding or institutional sponsorship.

CONFLICTS OF INTEREST

The authors declare that there are no personal, academic, commercial, or financial conflicts of interest that could have influenced the results or interpretation of the data presented in this article.

DECLARATION OF AUTHORSHIP

All authors contributed equally to the development of the research, writing, and revision of the manuscript.

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