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Contributions to Incorporation of Non-Recyclable Plastics in Bituminous Mixtures

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Abstract: Over the past 50 years, global plastic production has surged exponentially. Around 40% of this plastic is used for packaging, most of which is single-use, while 20% is used in construction. Despite the vast quantities produced, only about 6% of discarded plastics are properly recycled, 10% are incinerated, and the majority are disposed of without proper management. With low recycling rates and some plastics being non-recyclable or with limited recycling cycles, it is important to explore new ways of reusing this waste as secondary raw materials. This study explores the potential of incorporating non-recyclable plastic waste into bituminous mixtures. The objective is to develop a sustainable solution for surface courses with similar or better performance than traditional bituminous mixtures by incorporating plastic waste using the dry method. A bituminous mixture containing 10% non-recyclable plastic was formulated and tested for water sensitivity, wheel tracking, and stiffness modulus. Additionally, environmental and economic comparisons were performed with a standard surface mixture. Results showed increased water resistance, high resistance to permanent deformation, reduced stiffness, lower susceptibility to frequency and temperature variations, and greater flexibility. These findings suggest that adding plastic not only enhances mechanical properties but also reduces costs, offering a sustainable alternative for non-recyclable plastics in road construction.

Keywords: bituminous mixtures; dry method; incorporation of plastic; recycling; surface course

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1. Introduction

Plastics are indispensable in the modern world due to their unique properties and cost-effectiveness. They are widely used for packaging, cosmetics, and clothing, among many other things. The plastic industry is massive. In 2021, raw materials producers, plastics manufacturers and recyclers, and machinery producers represented a chain that employed more than 1.5 million people in Europe [1]. These companies contributed a turnover of around 40 billion in European finances [1]. Every year, the production of plastic continues to increase, especially in recent decades. Approximately 380 million tonnes of plastic is produced annually, and half of this is single-use plastics [2].

Plastics made from synthetic organic polymers are the result of the distillation of oil and natural gas, accounting for 99% of the world's plastic production [3]. With the exponential growth of plastic production, it is estimated that the carbon dioxide equivalent (CO_2e) emissions over the entire life cycle of plastics (from the extraction of the raw material to the end of life) will amount to 2.80 Gigatonnes, equivalent to 615 coal-fired power stations with a capacity of 500 megawatts operating at full capacity by 2050 [3].

As a non-biodegradable material with a recycling rate of only 9%, plastic waste is found in large quantities worldwide, contributing significantly to one of the main environmental crises of the 21st century [2].

2. Background

2.1. Literature Review

Thousands of patented plastics differ in their characteristics from one another. Examples of synthetic polymers include polystyrene (PS), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), and polyvinyl chloride (PVC). Plastics are divided into two large groups: thermoplastics and thermosets. The first group, thermoplastics, exhibit the property of softening when exposed to heat, allowing them to be re-melted and reshaped into new forms through the moulding process. Thermoplastics are materials that can recycled; however, their recycling rate is constrained due to the degradation of their properties over successive recycling cycles. These are used to produce films, bottles, clothes, expanded and extruded polystyrene, and other products. In contrast, thermosets cannot be re-melted after their initial production, as they retain their rigidity even when heated. These materials are used to manufacture rigid, non-deformable components and can be reinforced with fibres such as glass, basalt, or carbon for enhanced strength. Thermosets are widely employed across various industries, including construction (e.g., electrical sockets and pipes), energy production (e.g., wind turbine towers), and transportation (e.g., vehicles, aircraft, trains, and ships), among others. Despite their differences, both share the fact that they do not decompose in the environment and, are therefore a waste product that presents an increasing problem due to their exponential growth.

Larger plastics, such as plastic bottles and packaging, become fragile when they are landfilled or discarded indiscriminately on land or in the sea, due to ageing caused by weathering and erosion, fragmenting and disintegrating into small particles. As the process of the fragmentation and erosion of plastics is continuous, depending on their speed and the conditions they are exposed to, these plastics eventually form microscopic particles (microplastics) or even smaller scales (nanoplastics). Despite the nomenclature of microplastics and nanoplastics, it should be noted that in the literature, these terms often inaccurately represent the true micro (10^{-6}) and nano (10^{-9}) scales, as microplastics are typically defined as particles smaller than 5 mm and nanoplastics as particles smaller than 0.1 mm [4–7]. These proposed dimensions still vary, leading to greater confusion about the actual size of plastic particles [7]. Thus, the terminology can be misleading, resulting in misperceptions about the real size of these particles. Once in the environment, microplastics are increasingly found in marine ecosystems, where they are ingested by animals. These particles can then enter the food chain, ultimately affecting humans [8,9]. Their ingestion has been linked to serious health risks, including reproductive disorders, cancer, and antimicrobial resistance [10,11].

Incorporating recycled materials and waste into bituminous mixtures is a widely accepted practice. Various materials, including ashes [12–14], slags [15,16], oils [17], reclaimed asphalt [18,19] fillers and aggregates from quarry waste, and concrete have been thoroughly tested and successfully integrated into bituminous mixtures.

Although the use of recycled plastics in paving is relatively recent, with the first studies having been carried out in the early 1990s, these studies have shown promising data for their use in the paving industry [20–22]. This type of application could be a viable option for helping to mitigate the disposal of plastic in landfills or incineration, potentially reducing the emissions produced during the latter process. It could also reduce the amount of micro and nanoplastics produced, as these materials, when incorporated into a bituminous mixture, could become encapsulated into the bitumen matrix.

Recycled plastic, being a petroleum derivative similar to the polymers used to modify bitumen (i.e., SBS), has been internationally considered as an additive in the production of bituminous mixtures to partially replace bitumen (usually 2% to 10% of its mass). Since 2001, India has been a pioneering country in the use of recycled plastic in bituminous mixtures, initially with LDPE (plastic bags) and PET (plastic bottles) [23]. In 2016, India implemented the mandatory use of recycled plastic in bituminous mixtures. After two decades, India has more than 34,000 km of roads paved with recycled plastics (PE, PP, and PS), most of which are rural [23]. According to Vasudevan et al. [23], on-site applications have demonstrated good performance due to improved bitumen behaviour, greater resistance, and better functional characteristics compared to conventional bituminous mixtures.

Over the last 30 years, several studies have been carried out on the incorporation of different types of plastic, using different methods, namely the wet method [24–46] and the dry method [21,23,47–64], with different incorporation rates and also combined with different materials, such as reclaimed asphalt pavement [65,66] and recycled tire rubber [33,67,68]. In addition, some additives have been used to promote the dissolution of the plastic in the bituminous mixtures, to ensure greater homogeneity. However, it should be noted that more than 90% of the studies conducted are limited to laboratory research on plastic-modified bitumen or the behaviour of the bituminous mixtures, with little experience in real-scale applications. Existent studies have generally shown that the mechanical behaviour of the mixture improves with the incorporation of a plastic percentage, both by dry and wet methods. In summary, the following findings have been observed regarding bitumen behaviour, mechanical and functional behaviour of the bituminous mixtures, life cycle analysis (LCA), and environmental assessment:

Bitumen behaviour:

- Increase in softening temperature;
- Reduced penetration;
- Increased viscosity;
- Increased ductility;
- Increased resistance to ageing;
- Ensuring stability.

Mechanical behaviour of the bituminous mixture:

- Increased Marshall stability;
- Decrease in Marshall deformation;
- Increase in the Marshall quotient;
- Increased modulus of deformability;
- Increased resistance to permanent deformation;
- Increased resistance to fatigue;
- Decreased sensitivity to water;
- Increased durability of the mixture;
- Increased resistance to fuels;
- Increased resistance to indirect traction.

Functional behaviour of the bituminous mixture:

- Decrease in macrotexture;
- Decreased resistance to friction;
- Reduced layer thickness.

Life cycle analysis:

- Decrease in the production cost of the mixture;
- Increased durability of the layer;
- Increased maintenance cycles.

Environmental assessment:

- The leachate collected from the mixtures with plastics did not show an increase in contaminants.

2.2. Objectives

In response, this study proposes an innovative and sustainable solution for managing non-recyclable plastic waste by incorporating it into bituminous mixtures for pavement surface courses. The primary objectives are to enhance the mechanical behaviour of the mixtures, aiming to improve their durability, polishing resistance and water resistance, being all crucial for the performance of pavements [6,69]. Additionally, the ultimate goal of the study is to reduce the consumption of raw materials, specifically the amount of bitumen and aggregates required for their production [70] and to assess the economic feasibility of this approach by offsetting raw material usage through the incorporation of plastic waste. It should be noted that most of the plastics incorporated and studied in the production of new bituminous mixtures consist of plastic that has been specifically processed for this purpose, such as plastic pellets.

The incorporation of non-recyclable plastic waste was carried out at a rate of 10% of the total mass of bituminous mixture using the dry method. The decision to adopt this 10% incorporation rate was driven by the goal of addressing the plastic crisis, and in line with previous studies [71–73], it was concluded that this percentage could be viable. The dry method was selected, as it typically enables the incorporation of a larger quantity of plastic waste compared to alternative techniques [6]. Laboratory tests such as melting point analysis, water sensitivity, permanent deformation, and stiffness were conducted to evaluate the compatibility and performance of the plastic bituminous mixture. The obtained results indicated that this solution not only reduced bitumen consumption but also improved the mechanical characteristics of the pavement, leading to a more sustainable bituminous mixture.

Moreover, the environmental and economic benefits of incorporating plastic waste into road construction were evaluated, which showed that this approach is clearly a promising alternative to conventional materials.

3. Materials

This study investigates the incorporation of a specific type of plastic waste into bituminous mixtures. A dense graded bituminous mixture with a maximum aggregate size of 14 mm and a neat bitumen with a nominal penetration of 35/50 (AC 14 surf 35/50), was used as a reference. The plastic waste was central to the research, focusing on its potential to enhance the properties of the mixture. To complement this investigation, various aggregates and bitumen were selected for their standard application in pavement construction. This approach ensures a thorough evaluation of how plastic waste can modify and improve the overall performance of the bituminous mixture. The modified mixture was compared with the reference mixture, to assess its performance relative to a traditional bituminous mixture. For the bituminous mixture produced with plastic, a neat nominal penetration bitumen of 50/70 was used, as the modification of bitumen properties was expected.

3.1. Plastic Samples

A plastic sample described as "Rejected aluminium capsules" by the recycling centre was collected (Figure 1).

Figure 1. Plastic sample.

The sample exhibits heterogeneity, comprising ten distinct types of plastic waste, primarily including floating material divided into mixed paper capsules, transparent plastics, and white and blue plastic capsules, as identified by visual inspection. Figure 2 presents the constituents of the sample, with constituent representativeness expressed as percentages. A density test in tap water was conducted to classify the sample constituents into floating (density < 1 g/cm^3) and non-floating (density > 1 g/cm^3) fractions. Subsequently, the plastic was shredded for incorporation into the bituminous mixture.

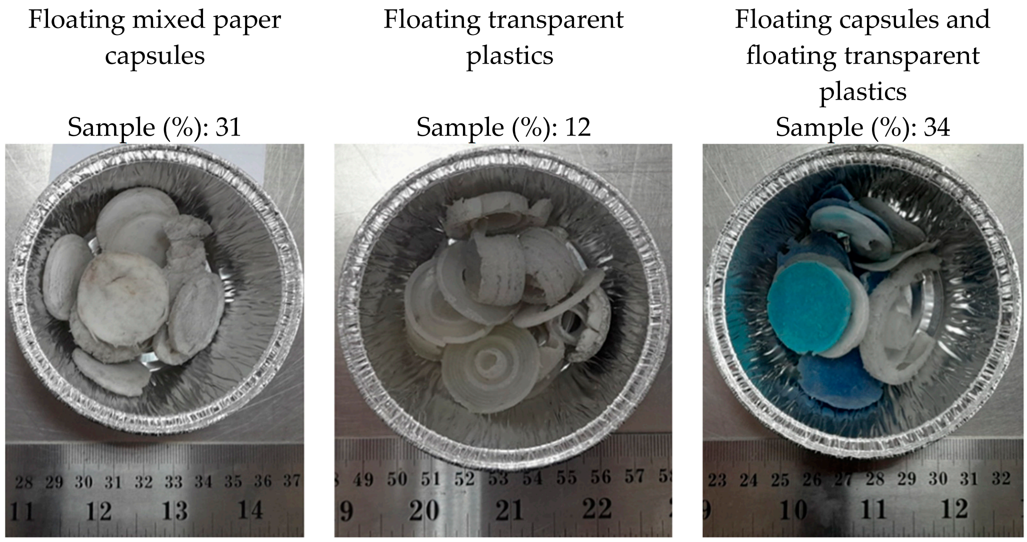

Figure 2. Representative constituents: presentation and percentages.

3.2. Aggregates

This study involved different fractions of basalt aggregates (0/4 mm, 4/12 mm, 10/16 mm), limestone aggregates (0/4 mm) and a commercial filler, all of which comply with the applicable standards and specifications. Figure 3 shows the aggregates grading curve used to produce both bituminous mixtures and the grading envelop defined in the Portuguese specifications for this type of bituminous mixture [74].

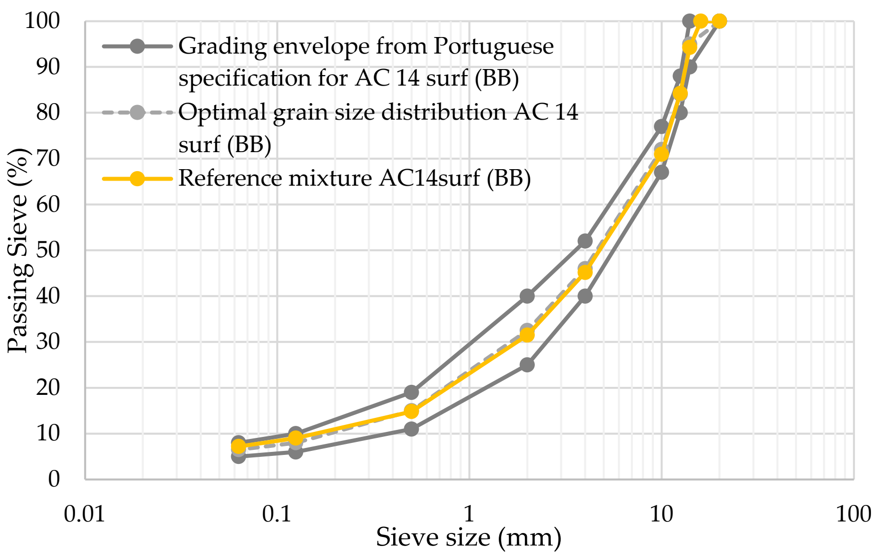

Figure 3. Grading curve.

3.3. Bitumen

The bitumen used for producing the plastic bituminous mixture was a 50/70 nominal penetration neat bitumen accordingly with EN 12591 [75]. The bitumen used presented a penetration of 48.8×10^{-1} mm and a softening temperature of 54.9 °C. The bitumen 35/50 had a penetration of 44×10^{-1} mm and a softening point of 54.6 °C.

4. Experimental Procedures

To evaluate the effectiveness of incorporating plastic waste into bituminous mixtures, a set of laboratory tests were performed. These included a melting point analysis of the plastics to assess their suitability for incorporation by dry method and to evaluate their potential interactions with bitumen for modifying its characteristics. Additionally, the Marshall test was performed to determine the optimum bitumen content (OBC), and a set of performance tests were conducted to assess the mechanical behaviour of the mixtures. Specifically, tests were performed to evaluate water sensitivity, permanent deformation, and stiffness, providing insight into the impact of plastic waste on the overall performance of the bituminous mixture.

4.1. Melting Point

To assess the suitability of the sample for incorporation into bitumen, a melting point analysis was carried out on the most representative constituents of the sample. Each constituent was placed in a ventilated oven for 45 min and subjected to sequential heating at 50 °C, 75 °C, and 100 °C, followed by incremental temperature increases of 10 °C up to a maximum of 200 °C. A lower melting temperature indicated a higher likelihood of effective incorporation into the bituminous matrix, facilitating better integration of the plastic waste into the mixture.

4.2. Formulation and Optimum Bitumen Content

The Marshall specimens were prepared using the dry method with a 90% aggregate to 10% plastic ratio, based on a reference mixture (AC 14 surf 35/50). The plastic was mixed with the aggregate at 200 °C for 2 min, followed by the addition of bitumen at 175 °C for an additional 3 min. The methodology used for the test specimens' production was conducted in accordance with the standard EN 12697-35 [76].

To determine the OBC, Marshall specimens were produced with 3.5%, 4.0% and 4.5% bitumen contents, considering that the reference mixture formulation had an OBC of 5.0%. It is important to note that the incorporation of plastic modifies the bitumen properties, leading to a reduction in the required bitumen content. The formulations for each OBC are listed in Table 1.

Table 1. Marshall's specimens formulation with the different OBC studied.

Constituents [%]	Formulation			
	Reference Mixture	Plastic Bituminous Mixture		
		3.5%	4.0%	4.5%
Bitumen	5.0	3.5	4.0	4.5
Basalt 10/16	24.0	24.0	24.0	24.0
Basalt 4/12	33.0	33.0	33.0	33.0
Limestone 0/4	29.0	19.0	19.0	19.0
Basalt 0/4	11.0	11.0	11.0	11.0
Commercial filler	3.0	3.0	3.0	3.0
Plastic	0	10.0	10.0	10.0

Following the preparation of the Marshall specimens, various tests were conducted to determine the desired OBC, including bulk density, maximum density, the Marshall test, porosity, and voids in the mineral aggregate. The test standards are presented in Table 2.

Table 2. Optimum bitumen content tests.

Test	Standard
Bulk Density	EN 12697-6 [77]
Maximum Density	EN 12697-5 [78]
Marshall Test	EN 12697-34 [79]

4.3. Mechanical Tests

The performance of the mixture was evaluated based on mechanical characteristics such as water sensitivity, permanent deformation, and stiffness determination. Table 3 presents the test standards and testing conditions.

Marshall specimens were used for the determination of water sensitivity, while prismatic specimens were used for the wheel tracking test. Smaller prismatic specimens were obtained by sawing the prismatic specimens for the stiffness test. The roller compactor was used to produce and compact prismatic specimens in accordance with EN 12697-33 [80].

Table 3. Mechanical tests.

Scope (Standard)	Conditions
Determination of the water sensitivity (EN 12697-12) [81]	Method A: Indirect tensile strength Temperature: 15 °C Specimen conditioning: 72 h (dry and wet conditions)
Determination of permanent deformation Wheel tracking test (EN 12697-22) [82]	Method: Small size device; Procedure B in air Temperature: 60 °C Specimen conditioning: 6 h at 60 °C
Stiffness (EN 12697-26) [83]	Method: Four-point bending test (4PTB) Temperature: 10 °C, 20 °C and 30 °C Frequencies: 1, 3, 5, 10, 20, 30 and 1 Hz

5. Results and Discussion

5.1. Melting Point

It was observed that the most representative constituents floating mixed paper capsules, floating capsules, and floating transparent plastics melted at a temperature of approximately 120 °C, resulting in approximately 77% of the sample showing promising characteristics for incorporating in bitumen. The aspect of the constituents at the mentioned temperature can be observed in Figure 4. It was also found that the floating constituents (with a lower density than water) were easier to melt at lower temperatures.

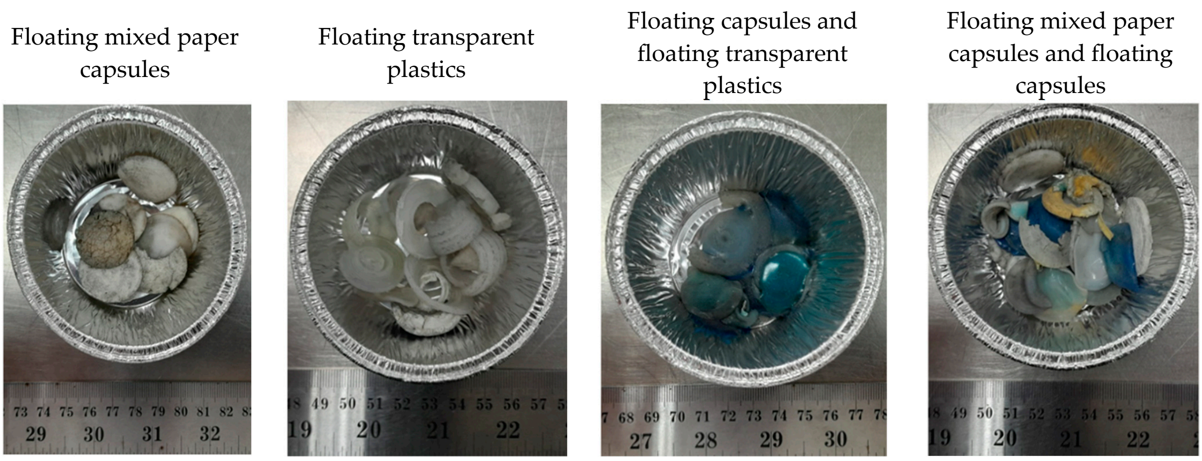

Figure 4. Melting point at 120 °C.

5.2. Formulation and OBC

To determine the OBC for the mechanical tests, porosity, Marshall stability, voids in mineral aggregates (VMA), and deformation were evaluated for the three tested bitumen contents (Figure 5).

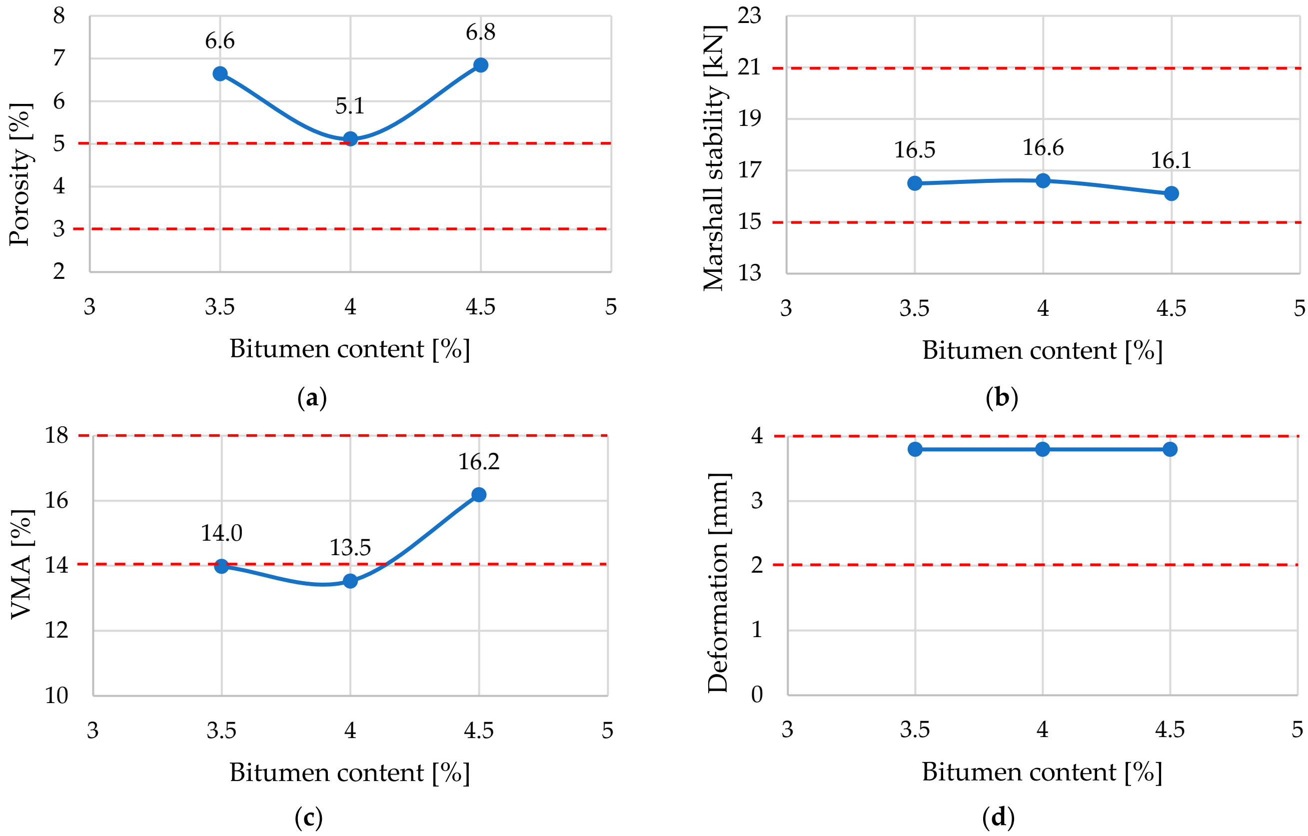

Figure 5. (**a**) Porosity; (**b**) Marshall stability; (**c**) VMA; (**d**) deformation.

The red dotted lines in the graphics represent the limits defined on specifications. A comprehensive analysis indicated that a 4% bitumen content was optimal for managing porosity. All Marshall stability values were within the specified range for each bitumen content tested, supporting the selection of 4% for stability considerations. It was observed that only a 4.5% bitumen content met the desired range for VMA. Deformation values remained consistent across bitumen contents, though density testing revealed that a 4% bitumen content achieved the highest density. A 4.5% bitumen content was selected for deformation, targeting an average of 4% across the four selected factors. The Optimum Binder Content (OBC) was thus determined to be 4.2%, as an average of these factors. The resulting formulation based on the selected OBC is presented in Table 4.

Table 4. OBC formulation.

Constituents	OBC Formulation [%]
Bitumen	4.2
Basalt 10/16	24.0
Basalt 4/12	33.0
Limestone 0/4	19.0
Basalt 0/4	11.0
Commercial filler	3.0
Plastic	10.0

5.3. Determination of the Water Sensitivity

Figure 6 illustrates the determination of the water sensitivity through the indirect tensile strength ratio (ITSR).

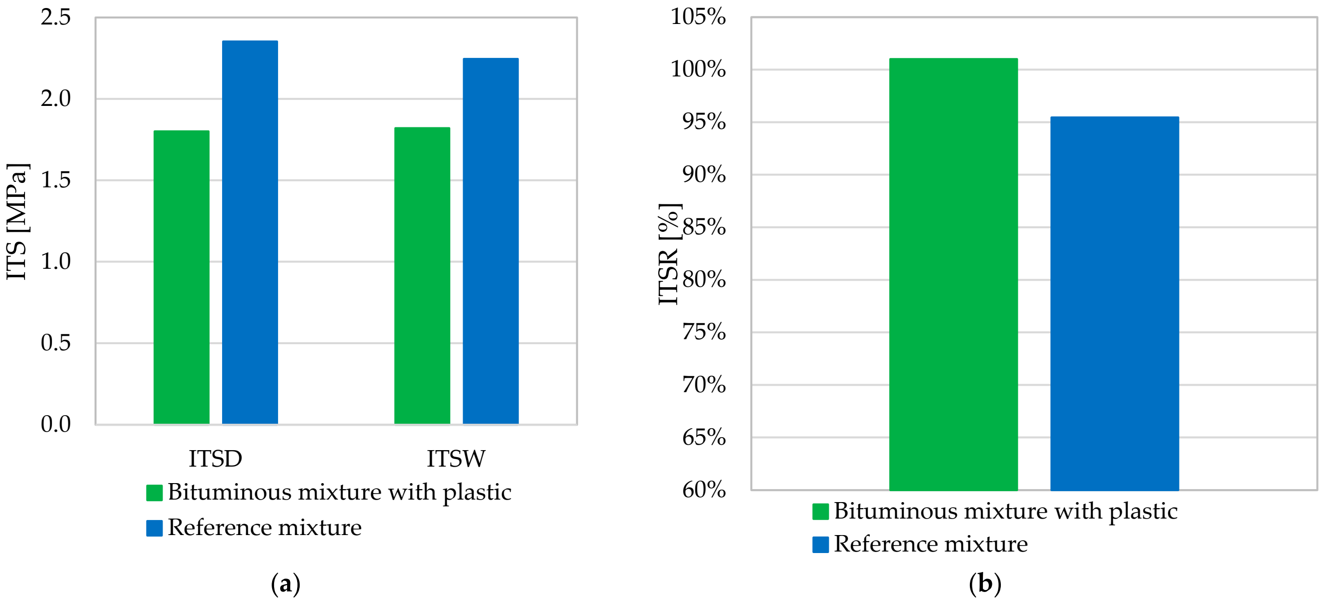

Figure 6. Evaluation of water sensitivity: (**a**) indirect tensile strength in dry and wet conditions; (**b**) indirect tensile strength ratio.

Figure 6a shows the results for indirect tensile strength of dry specimens (ITSD) and wet specimens (ITSW) of the bituminous mixture with plastic and the reference mixture. Under dry conditions, the mixture with plastic exhibited an ITSD of 1.80 MPa, while the reference mixture showed 2.35 MPa. Under wet conditions, the mixture with plastic reached 1.82 MPa and the reference mixture obtained 2.25 MPa for ITSW.

Figure 6b illustrates that the mixture with plastic achieved an ITSR of approximately 101%, exceeding 100%. This value over 100% is due to the selection process of specimens to perform the tests under wet and dry conditions. In contrast, the reference mixture presented an ITSR of approximately 95%, indicating a 5% reduction in tensile strength when exposed to water compared to the dry condition.

These results demonstrate the advantage of incorporating plastic in bituminous mixtures, as it increases the water resistance of the mixtures. The high ITSR value reflects the enhanced durability and resilience of the mixture with plastic, even under extreme conditions.

5.4. Wheel Tracking

The performed test evaluated three main parameters: the mean rut depth at 10.000 cycles [RD_{AIR}], the slope in the air [WTS_{AIR}], which relates the rut depth to the number of loading cycles, and the mean proportional rut depth [PRD_{AIR}], that represents the rut depth in relation to the thickness of the bituminous layer. The data for the two tested mixtures are presented in Table 5.

Table 5. WTS_{AIR} and PRD_{AIR}.

Property	Bituminous Mixture with Plastic	Reference Mixture
WTS_{AIR} [mm/10^3 cycles]	0.0	0.28
PRD_{AIR} [%]	0.3	11.70

Figure 7 shows the relation between rut depth and the number of cycles for both the bituminous mixture with plastic and the reference mixture.

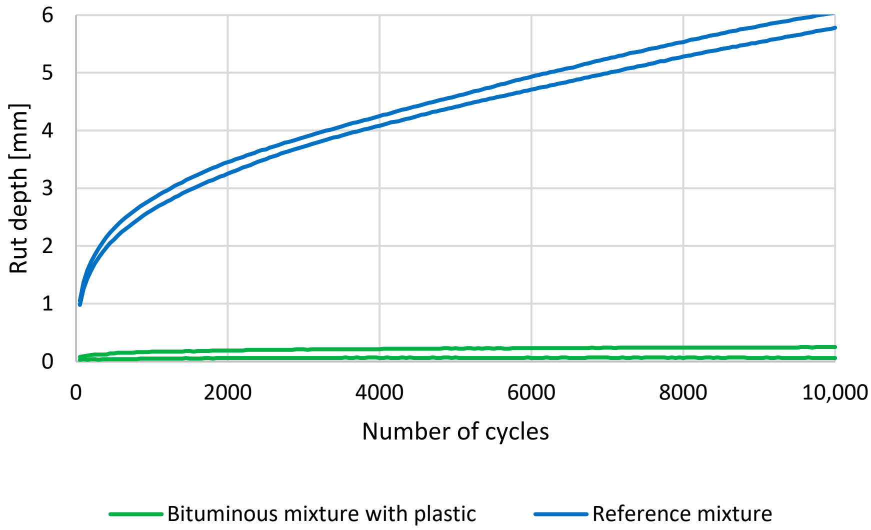

Figure 7. Permanent deformation.

The rut depth in the bituminous mixture with plastic is minimal, resulting in a RD_{AIR} of 0.2 mm, compared to 5.9 mm for the reference mixture. These results suggest that, for surface course applications, the plastic-modified bituminous mixture demonstrates a high resistance to permanent deformation, significantly enhancing pavement durability and resistance to load-induced wear.

5.5. Stiffness

Figure 8a–d compares the stiffness behaviour, phase angles (ϕ), storage modulus (E_1) values, and loss modulus (E_2) values of both bituminous mixture with plastic and reference mixture at different temperatures and frequencies, respectively.

In Figure 8a, the mixture with plastic has lower stiffness, particularly at 10 °C and 20 °C, but demonstrates greater stability with smaller variations across temperatures. In contrast, the reference mixture shows more significant increases in stiffness as frequency rises. Notably, at 30 °C, the plastic mixture exhibits slightly higher stiffness than the reference mixture. Overall, while the mixture with plastic has lower stiffness than the reference mixture, it shows greater stability in stiffness variation with testing temperature.

The reference mixture demonstrates larger ϕ, particularly at 30 °C, which decrease with frequency (Figure 8b). In contrast, the mixture with plastic exhibits smaller and more consistent ϕ across all temperatures (Figure 8b). This indicates that the mixture with plastic is less susceptible to frequency variations, suggesting a reduced tendency for viscous deformation, especially at lower temperatures (Figure 8b).

The reference mixture demonstrates higher E_1 values at 10 °C and 20 °C, whereas the plastic mixture exhibits lower E_1 values with greater stability as frequency increases (Figure 8c). At 30 °C, the mixture with plastic shows higher E_1 values compared to the reference mixture. Overall, the mixture with plastic generally displays lower E_1 values, indicating enhanced flexibility relative to the reference mixture.

The reference mixture shows higher (E_2) values across all temperatures (Figure 8d). In contrast, the mixture with plastic exhibits lower E_2 values, indicating reduced rigidity compared to the reference mixture. However, it demonstrates enhanced stability in response to variations in frequency (Figure 8d).

Overall, the mixture with plastic exhibits lower stiffness, reduced susceptibility to frequency variations, and increased flexibility compared to the reference mixture. This indicates its potential for applications in pavements subjected to variable traffic and climate conditions, ensuring consistent performance.

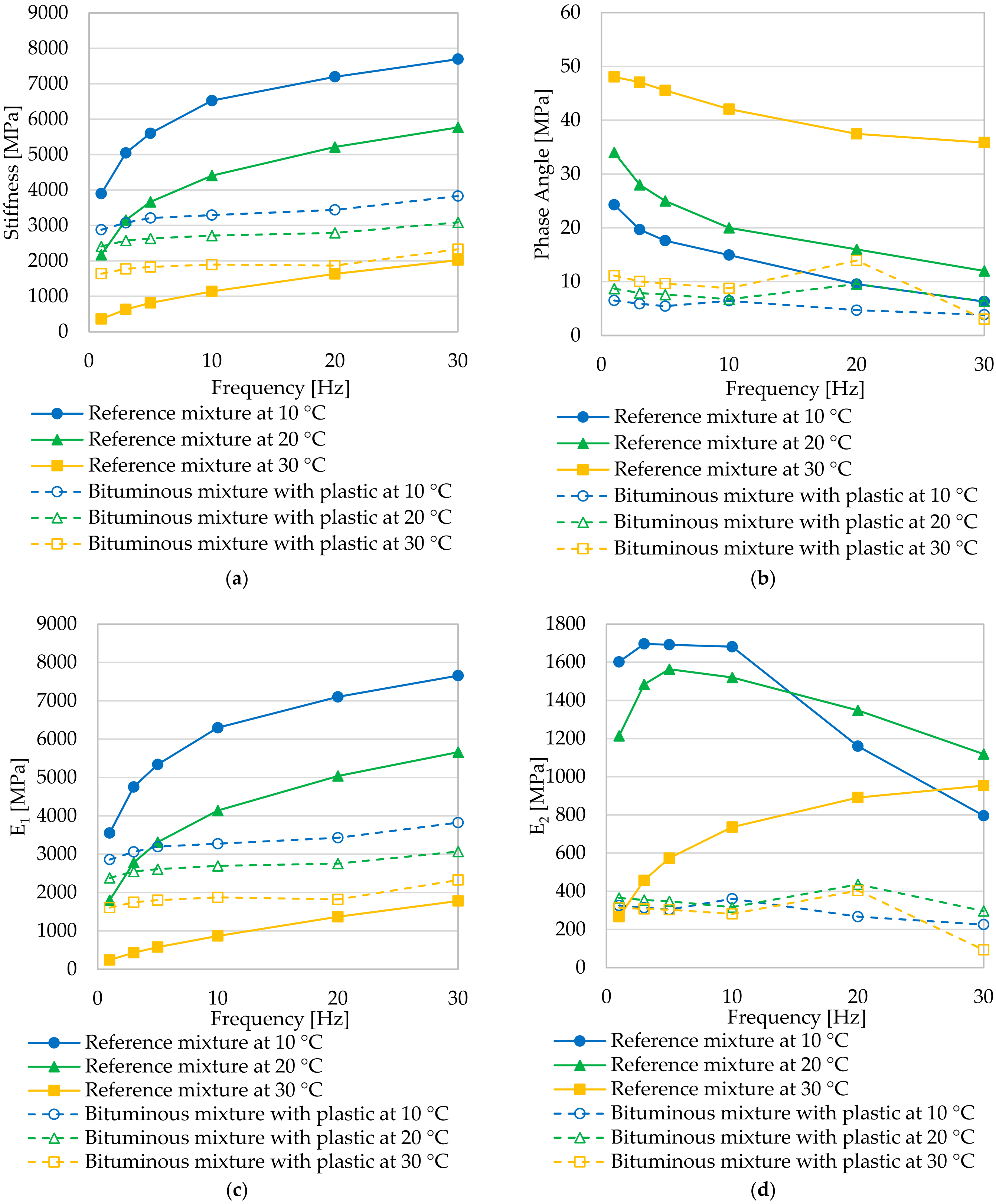

Figure 8. (**a**) Stiffness modulus; (**b**) phase angle; (**c**) storage modulus (E_1); (**d**) loss modulus (E_2).

6. Environmental and Economic Analysis

The disposal of plastics in landfills generates significant CO_2 emissions, estimated at 253 g/kg [70]. This is primarily due to the degradation of plastic, which releases CO_2 and methane into the atmosphere [84]. Another problem related to the end-of-life of plastic in landfills is the release of microplastics, which is considered the main source of their dispersion. It is estimated that landfills contributed to the release of approximately 4.1 million megatonnes of the 9.2 million megatonnes of microplastics to the environment in 2015 [85].

Although incinerating plastic emits greenhouse gases, mainly CO_2, it can also emit dangerous chemicals into the environment, depending on the type of plastic and how its waste is treated [86]. The incineration of plastic, especially packaging, is responsible for a significant amount of greenhouse gas emissions. CO_2 emissions can vary, reaching 4605 g per kg of plastic incinerated, depending on the type of polymer and the incineration practices adopted [70]. According to the European Environmental Agency, the incineration of plastic for energy valorisation emits between 50 and 80 million tonnes of CO_2 each year, with each tonne of plastic incinerated having a greater impact than each tonne of plastic produced [10]. Recycling reduces emissions by between 1.1 and 3.0 tonnes of CO_2e compared to the energy recovery process [10].

In order to compare the quantity of materials and the cost of using a bituminous mixture with plastics as opposed to the reference bituminous mixture, a case study was carried out regarding a surface course for a 1 km long road with two 3 m wide lanes, one in each direction, and 1 m wide roadsides. Table 6 shows the dimensions of the case study road and the required mass of the bituminous mixture.

Table 6. Analysed section—characteristics of surface course characteristics.

Property	Unit	Reference Mixture	Bituminous Mixture with Plastic
Thickness	[m]	0.06	
Width	[m]	8	
Length	[m]	1000	
Volume	[m^3]	480	
Bulk density	[Mg/m^3]	2.56	2.19
Required mass	[Mg]	1228.8	1051.2

The quantities of each constituent material of the bituminous mixture were determined according to the corresponding density of the mixture and the construction costs per kilometre of the road was obtained through consultation with national companies and based on the above-mentioned cross-sectional profile, are shown in Table 7.

Table 7. Costs of reference mixture and bituminous mixture with plastic.

Constituent	Reference Mixture			Bituminous Mixture with Plastic		
	Mass [Mg]	Unit Price [€/Mg]	Cost [€]	Mass [Mg]	Unit Price [€/Mg]	Cost [€]
Bitumen	58.5	976	57,110	42.4	976	41,354
Basalt 10/16	280.9	15	4213	242.1	15	3632
Basalt 4/12	386.2	15	5793	332.9	15	4994
Limestone 0/4	339.4	16	5430	191.7	16	3067
Basalt 0/4	128.7	15	1931	111.0	15	1665
Commercial filler	35.1	15	527	30.3	15	454
Plastic	0.0	0	0	100.9	0	0
Total	1228.8	-	75,004	1051.2	-	55,165

The unit price of the materials presented above does not take transport distances into account, since similar transport distances were assumed for the various materials used.

Comparing the results shown in more detail in Figure 9, the quantities of basalt aggregate and commercial filler are similar between the two mixtures, resulting in no significant cost variation, as expected.

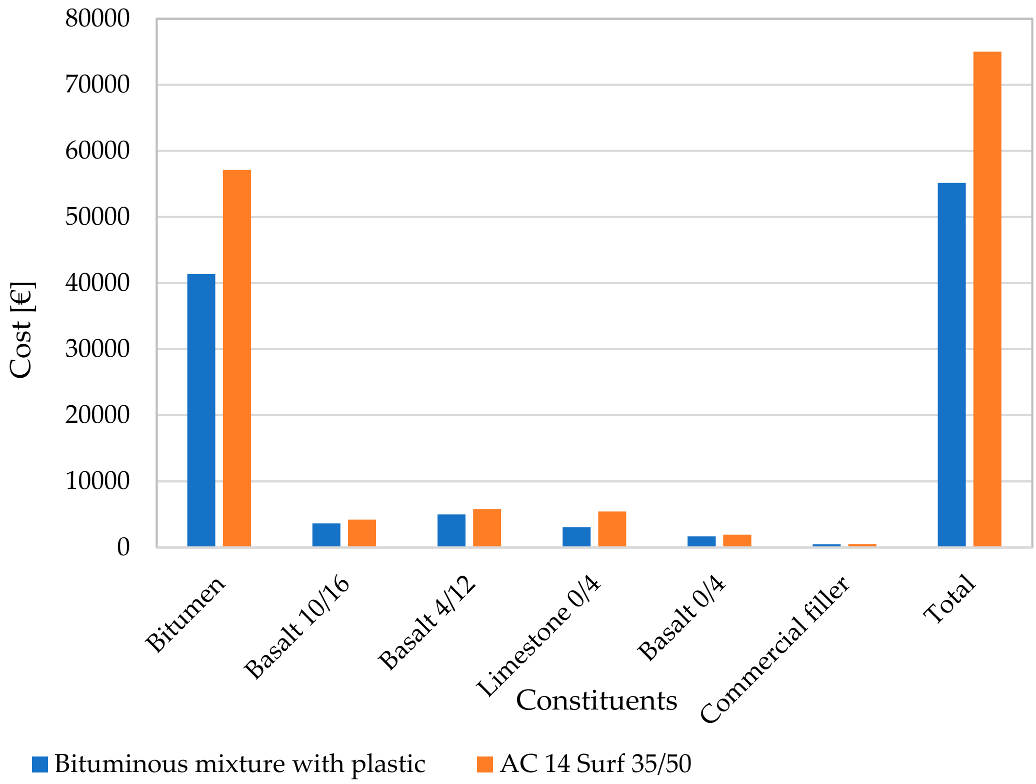

Figure 9. Cost analysis of bituminous mixtures components.

For the bituminous mixture with plastic, 147.7 megagrams less limestone is needed compared to the reference mixture, which translates into a cost of 2363 €/km. The greatest contribution of the mixture investigated is the reduction in the amount of bitumen, which reduces the cost by around 15,756 €/km.

Considering all the constituents of the bituminous mixtures under investigation, it is possible to determine a cost reduction per kilometre of road of around 19,839 €, corresponding to a percentage reduction of around 26.5% per km of road.

7. Conclusions

The research detailed in this paper delves into the incorporation of non-recyclable plastics in a bituminous mixture for surface courses. The plastic underwent initial separation using a density test in water, followed by the determination of its melting point. Subsequently, the plastic was shredded before being incorporated into the bituminous mixture by the dry method. Laboratory tests were then carried out on water sensitivity, wheel tracking and stiffness to assess the improvement in the properties of the bituminous mixture.

The main findings of this study were as follows:

- The most suitable plastics for incorporating using the dry method are those presenting the lowest melting point.
- The optimum bitumen content for plastic bituminous mixtures was found to be 4.2%. This value is lower than that of the reference mixtures, as melted plastic can acquire binding properties similar to bitumen.

- The plastic bituminous mixture displayed excellent water resistance and did not degrade when exposed to water, implying durability in adverse weather conditions for use as a surface course.
- The bituminous mixture with plastic incorporation revealed a high resistance to permanent deformation and pavement strength with a RD_{AIR} of only 0.2 mm.
- The stiffness behaviour of the bituminous mixtures varies with temperature. At 10 °C, these mixtures exhibit high stiffness. However, at 20 °C and 30 °C, the stiffness decreases, suggesting that the plastic provides greater flexibility at higher temperatures. These changes enable the plastic mixture to offer good performance in cold climates by providing greater rigidity and in hot climates by offering greater flexibility, contributing to the durability and resistance of pavements under various environmental conditions.
- Economically, using a plastic bituminous mixture is significantly more cost-effective compared to the AC 14 surf 35/50 reference mixture, with a 26.5% reduction in the cost per kilometre of road due to reduced raw material requirements.

In summary, integrating plastic waste into bituminous mixtures has significant potential to revolutionise waste management and road pavement construction. The anticipated benefits in terms of enhanced durability, water resistance, and cost reduction are quite promising. It is imperative to continuously develop methodologies to address current limitations in order to fully exploit these opportunities. Embracing sustainable and innovative practices will not only contribute to environmental sustainability but also pave the way for more efficient and long-lasting road infrastructure for future generations.

A considerable portion of the bibliography studies regarding the incorporation of plastics in bituminous mixtures consists of plastic that has been specifically processed for this purpose, such as plastic pellets. Although the incorporation of non-recyclable plastics offers similar benefits to those of processed plastics, it is still at an early stage, and for it to be implemented on a large scale and serve as a viable solution in the market, it requires further research and refinement. The proposed studies include assessing the macro and micro-texture of the pavement surface, analysing the mixture's fatigue behaviour over time, continuing research and development of the formulation used, since varying the percentage of plastic incorporated can change the properties of the bituminous mixture, and investigating the end-of-life phase of this mixture, including the potential release of microplastics into the environment due to vehicle polishing and weathering.

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