Assessment of Strength and Stability in Cold Asphalt Mixtures Reinforced with 0.20% and 0.25% Polypropylene Microfibers

Evaluación de la resistencia y la estabilidad en mezclas asfálticas en frío reforzadas con microfibras de polipropileno al 0,20% y 0,25%

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Highlights

- This study evaluated not only the tensile strength and stability but also swelling, water absorption, and air voids, offering a comprehensive analysis of mechanical performance.
- Utilizing recycled polypropylene fibers provides an environmentally sustainable alternative for asphalt reinforcement.
- This work contributes new data on cold asphalt mixtures reinforced with polypropylene fibers in the Latin American context, where research remains limited.

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Keywords:

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ABSTRACT

Introduction. The incorporation of new materials and technologies has opened avenues for research in asphalt mixtures. Various studies have focused on modifying conventional manufacturing methods by replacing or enhancing traditional components. Among these, synthetic polypropylene microfibers have been investigated as partial substitutes for mineral aggregates. **Objectives.** This study aimed to evaluate the indirect tensile strength and stability of cold asphalt mixtures reinforced with 0.20% and 0.25% polypropylene microfibers. **Materials and Methods.** A reference cold asphalt mixture (sand-asphalt) was prepared following the Hubbard-Field method. Two modified mixtures were produced by replacing a proportion of the aggregate with 0.20% and 0.25% microfibers by volume. The index properties of the modified mixtures were assessed and compared to the reference mixture. Indirect tensile strength tests were also conducted. **Results.** The incorporation of polypropylene microfibers increased stability under ambient conditions by up to 21% and improved indirect tensile strength by approximately 100% compared to the reference mixture. Compatibility and reduction of air voids were also enhanced. However, swelling increased notably at 0.25% microfiber content, exceeding specification limits, while water absorption remained within acceptable ranges. **Conclusions.** Reinforcing cold asphalt mixtures with polypropylene microfibers resulted in significant improvements in stability, compaction, and tensile strength without compromising essential performance criteria.

RESUMEN

Introducción. La incorporación de nuevos materiales y tecnologías ha abierto vías de investigación en mezclas asfálticas. Diversos estudios se han centrado en modificar los métodos de fabricación convencionales mediante la sustitución o mejora de componentes tradicionales. Entre estos, se han investigado las microfibras sintéticas de polipropileno como sustitutos parciales de los agregados minerales. **Objetivos.** Evaluar la resistencia indirecta a la tracción y la estabilidad de mezclas asfálticas en frío reforzadas con 0,20 % y 0,25 % de microfibras de polipropileno. **Materiales y Métodos.** Se preparó una mezcla asfáltica en frío de referencia (arena-asfalto) siguiendo el método de Hubbard-Field. Dos mezclas modificadas se elaboraron reemplazando una proporción del agregado con 0,20 % y 0,25 % de microfibras en volumen. Se evaluaron las propiedades índices de las mezclas modificadas y se compararon con la mezcla de referencia. También se realizaron ensayos de resistencia indirecta a la tracción. **Resultados.** La incorporación de microfibras de polipropileno incrementó la estabilidad en condiciones ambientales hasta un 21 % y mejoró la resistencia indirecta a la tracción aproximadamente en un 100 % respecto a la mezcla de referencia. Además, se mejoraron la compatibilidad y la reducción de vacíos de aire. Sin embargo, con un contenido de 0,25 %, la expansión aumentó notablemente, superando los límites especificados, mientras que la absorción de agua se mantuvo en rangos aceptables. **Conclusiones.** El refuerzo de mezclas asfálticas en frío con microfibras de polipropileno produjo mejoras significativas en estabilidad, compactación y resistencia, sin comprometer criterios esenciales de desempeño.

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INTRODUCTION

Asphalt mixtures, in their various forms and applications, are of significant interest to researchers in the field, primarily due to the deterioration of roadways. Moreover, asphalt layers are directly exposed to users and their vehicles, thereby affecting both comfort and safety. Globally, a large number of traffic accidents are attributable to the poor condition of road infrastructure, including pavement performance (1). In our country, the road network is reported to be in extremely poor condition, according to the Colegio de Ingenieros de Venezuela (CIV, 2013) (2).

The most recurrent failures in pavements constructed with asphalt mixtures are associated with their limited bearing capacity or stability and their low tensile strength. Such failures include fatigue due to the repeated action of traffic loads, rutting, deformations, and cracking. In efforts to improve performance and explore new technologies, the incorporation of fibers has been adopted as a strategy to reinforce or modify traditional mixtures (4-7). The use of fibers, in their different materials and forms, represents an alternative within the broad field of modified mixtures. Classified as microfibers or macrofibers based on their diameters and textures, these materials have opened new avenues for research (8-9,12).

These fibers are generally manufactured from petroleum-derived polymers of various plastic types, which exhibit high abrasion resistance and very long decomposition periods. Such plastics are part of what is known as “the plastic crisis,” generating substantial pollution as persistent solid waste and an environmental burden (10,17). The search for sustainable alternatives demands that engineering develop new techniques and methods in the construction domain. Asphalt mixtures, whether produced hot or cold, involve processes that generate environmental impacts, arising from different aspects such as the extraction and processing of mineral aggregates (17).

Incorporating materials that partially replace aggregates will undoubtedly reduce environmental impacts to a greater or lesser extent. The use of alternative materials such as synthetic microfibers represents a step in the right direction since, in addition to reducing the consumption of mineral aggregates and the associated environmental consequences of their exploitation, it also offers potential for the reuse and recycling of polymers employed in the manufacture of these fibers, thereby addressing the environmental repercussions associated with various types of plastics (10,16).

Numerous studies have been conducted employing modifying additives by either dry or wet processes, developed from natural fibers, synthetic fibers, lubricating oils, recycled materials, and tempered glass, either as reinforcement or as a partial substitute for mineral aggregates in hot or cold asphalt mixtures. These investigations have applied different methodologies to assess the index properties (IPs) of the mixtures and how these properties are influenced by the presence of fibers (4–9,12–16,18-19). All of these efforts are oriented toward improving the performance of asphalt mixtures and testing new technologies, noting that fibers have long been used in concrete reinforcement.

In this context, the present research proposes the use of synthetic polypropylene microfibers (20) as a dry-process additive, incorporated at dosages of 0.20% and 0.25% by weight of unprocessed mineral aggregates in a cold sand–asphalt mixture. The mixtures were prepared using the Hubbard-Field method (21), and their index properties were evaluated based on a reference mixture (RM) without microfiber reinforcement, comparing the results with the modified reinforced mixtures. The incorporation of microfibers is expected to positively influence the index properties, particularly stability and tensile strength, thereby substantiating their use as a reinforcing agent. Accordingly, the objective of this study is to evaluate the indirect tensile strength and stability of cold asphalt mixtures reinforced with 0.20% and 0.25% polypropylene microfibers.

MATERIALS AND METHODS

Sample Preparation

A total of 30 briquettes were prepared, comprising 15 samples for each dosage of polypropylene microfibers (PPF). For each dosage group, the samples were distributed as follows: three briquettes were designated for stability testing in air at ambient temperature; three for stability testing after 1 hour of immersion in water at 60 °C; three for stability testing after 1 hour in an oven at 60 °C; three for evaluation of stability, absorption, and swelling after 72 hours of partial immersion in water at ambient temperature; and three for indirect tensile strength testing.

Verification of Aggregate Gradation

To ensure that the aggregate gradation of the sample matched that used in the design of the reference mixture (RM) (19), an aggregate sample was collected from the same location, Las Piñuelas sector, Gavidia town, Rangel Municipality, Mérida State, Venezuela. A sieve analysis was performed (22) to confirm this correspondence, and a constructed gradation curve was generated to guarantee consistency between the gradation of the material to be used and the reference material (**Figure 1**).

Figure 1. Sieve analysis process for gradation determination. (**a**) Aggregate sample prior to sieving; (**b**) Sample passing sieve No. 4 for mixture design; (**c**) Sieves employed for the analysis.

Aggregate Separation for Cold Asphalt Mixture

After confirming the gradation match between the reference aggregate and the material selected for this study, the sample was separated using sieve No. 4, obtaining material with the particle size corresponding to sand, as required by the Hubbard-Field sand–asphalt method. According to this method, the aggregates must meet the following characteristics: the percentage passing sieve No. 200 must be less than 25%, the sand equivalent value must exceed 25%, and the plasticity index must not be greater than 6. The material separated for the gradation construction is shown in (**Figure 2a**).

Preparation of Modified Sand–Asphalt Mixtures

In the design process of cold asphalt mixtures using the Hubbard-Field sand–asphalt method, it is necessary to determine the optimum liquid asphalt content (23) and to assess the index properties (IPs) of the mixture, including stability, swelling, absorption, compaction, and void content, comparing these results with the specifications and limits established by the method (21,24). This study builds upon previous research in which the design of the reference mixture was established, resulting in an optimum liquid asphalt content of 11.00% (RC-250 optimum = 11.00%). Throughout the process—including aggregate gradation, mixture preparation, curing, briquette fabrication and compaction, and IP testing—the same methodology and conditions were applied both to the RM and to the mixtures incorporating PPF. A volumetric correction was performed to replace the mineral aggregate, which is heavier, with PPF, a lighter material occupying a greater volume in the mixture. This adjustment was based on their relative specific gravities (Gs), which differ by more than 20%. It is important to note that two PPF dosages were used: 0.20% and 0.25%. Initially, the PPF was separated to achieve uniform distribution in the preparation of the modified mixtures (**Figure 2b**). Subsequently, the liquid asphalt was heated to achieve proper fluidity and stirred to ensure a uniform temperature, maintained between 40 and 80 °C. The respective quantities of aggregate, PPF, and liquid asphalt were then weighed, as shown in (**Figure 2c**).

Figure 2. Process of preparing modified asphalt mixtures with microfiber reinforcement. (**a**) Aggregate separated for gradation construction; (**b**) Aggregate combined with microfiber; (**c**) Aggregate, microfiber, and liquid asphalt.

Mixing Processs

The 2000 g of material required to fabricate the test briquettes were mixed manually with a spoon, as established by the Hubbard-Field method (**Figure 3a**). The mixture was inspected to confirm uniform coating of the aggregate with the asphalt binder, as shown in (**Figure 3b**).

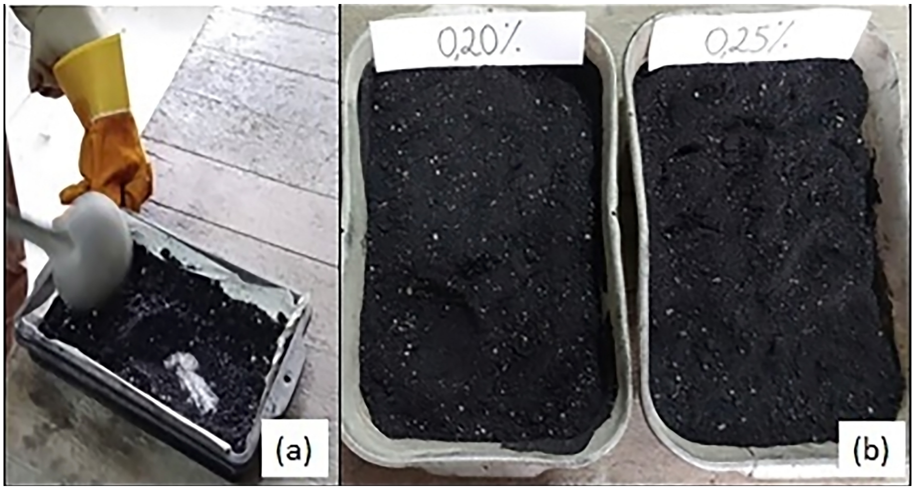

Figure 3. Mixing and final modified mixtures with PPF content. (**a**) Mixing of materials to produce the modified mixture; (**b**) Modified mixtures containing 0.20% and 0.25% PPF.

Curing of the Modified Mixtures

The mixtures were placed in properly labeled metal trays and cured at ambient temperature for 24 hours. At the end of this period, curing was confirmed by pressing a small portion of the mixture with the hands and verifying the absence of staining.

Briquette Fabrication and Compaction

For briquette fabrication, 112 g of mixture were weighed and placed into a 2-inch diameter mold to produce a briquette 1 inch in height. The following equipment was employed: 2-inch diameter molds, Hubbard-Field hammer No. 1 (1100 g), and Hubbard-Field hammer No. 2 (1100 g), as shown in (**Figures 4a and 4b**). Compaction was performed in three stages: *(i)* Using hammer No. 1 with a rectangular face, 25 blows were applied to allow the mixture to settle into the cylinder; (ii) In the second stage, 20 strong blows were applied with hammer No. 2, featuring a circular face; (iii) Finally, static compaction was performed by applying a load of 9,425 lb (4,275 kg), equivalent to 3,000 lb/in² (211 kg/cm²), for 2 minutes, as illustrated in (**Figure 4c**). The compaction time was controlled with a stopwatch.

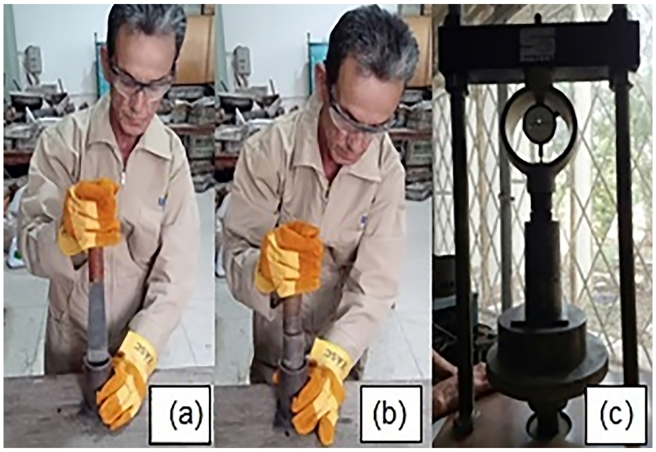

Figure 4. Fabrication and compaction processes of briquettes (**a**) Compaction with hammer No. 1; (**b**) Compaction with hammer No. 2; (**c**) Static compaction process.

After compaction, the briquettes were removed from the mold using a press or hydraulic jack and measured with calipers to ensure dimensions of 2.54 cm (1 inch) in height and 5.08 cm (2 inches) in diameter, as specified by the method (**Figure 5a**). The briquettes were then left at ambient temperature for 24 hours prior to testing (**Figure 5b**).

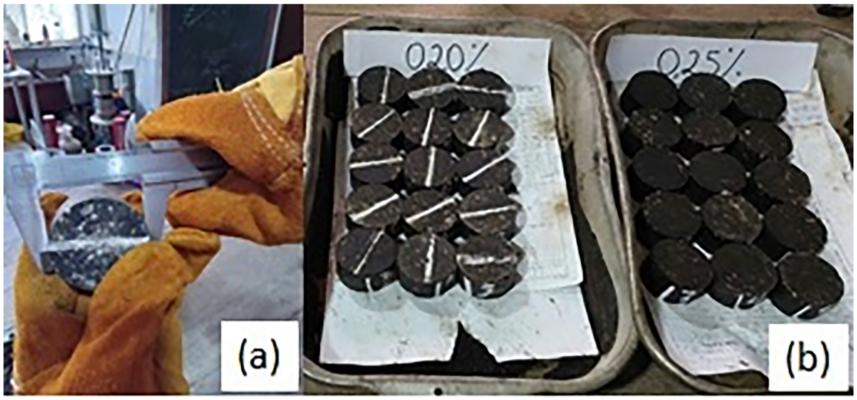

Figure 5. Briquette removal, measurement, and curing process. (**a**) Measurement of the height and diameter of the briquettes, and (**b**) Briquettes prepared with the modified mixture for testing.

Stability Test in Air

After the minimum curing time required by the Hubbard-Field method, each briquette was centered in the lower jaw of the loading apparatus, the upper jaw was positioned and aligned, and the test load was applied at a rate of 5 cm/min until failure occurred. The failure point was defined by the maximum load reading. The total load in pounds required to produce failure was recorded as the stability value. Upon completion, the stability values of all tested briquettes were averaged (**Figure 6**).

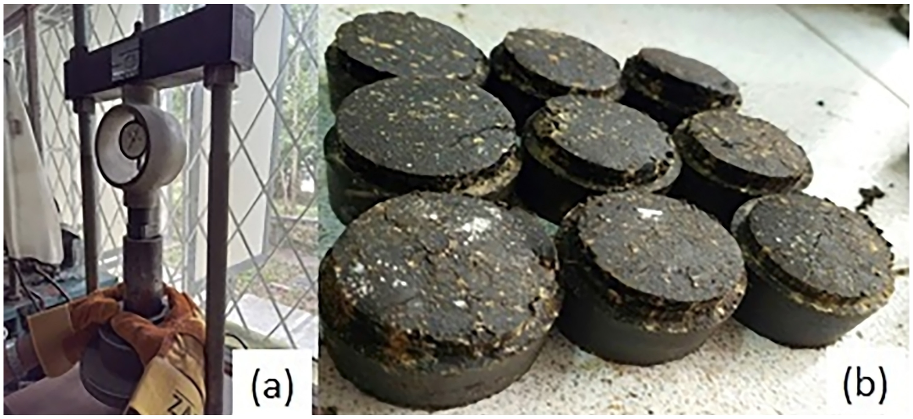

Figure 6. Stability testing of briquettes under ambient conditions (**a**) Stability test setup; (**b**) Briquettes after completion of the stability test in air.

Stability Test after 1 Hour in Water at 60 °C

Following immersion of the briquettes in water at 60 °C for 1 hour (**Figure 7a**), they were removed, superficially dried, and tested for stability following the procedure described above.

Stability Test after 1 Hour in Oven at 60 °C

After being placed in an oven at 60 °C for 1 hour (**Figure 7b**), the briquettes were removed and subjected to the same stability testing procedure.

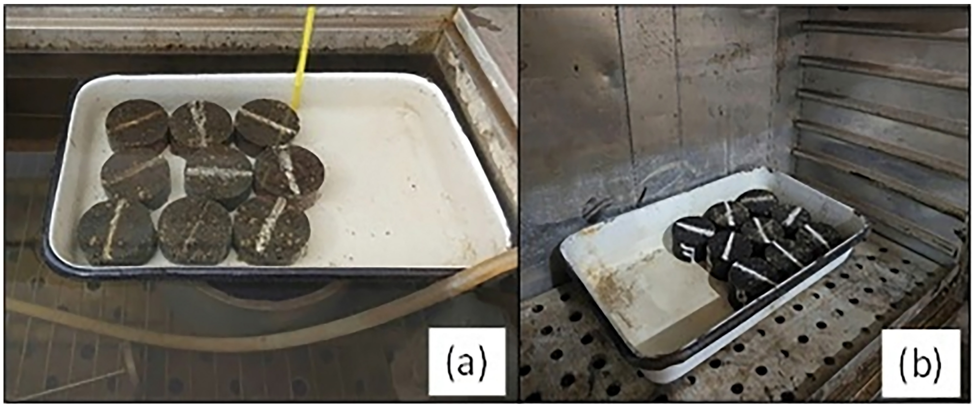

Figure 7. Briquette conditioning by immersion and thermal treatment at 60 °C. (**a**) Briquettes immersed in water at 60 °C for 1 hour; (**b**) Briquettes placed in the oven at 60 °C for 1 hour.

Absorption, Swelling, and Stability Test after 72 Hours of Partial Immersion

After 72 hours of partial immersion in water at ambient temperature, the briquettes were removed, superficially dried, and tested for stability. Each briquette was weighed and measured for height and diameter before and after immersion, thus obtaining initial and final values. All measurements were taken at the same reference point on each specimen.

Indirect Tensile Strength Test

In this test, each briquette was subjected to compressive force applied along a narrow strip across its length, inducing internal tensile stresses that ultimately caused failure. The equipment, the mounted briquette, and the characteristic tensile cracking produced during the test are shown in (**Figure 8**).

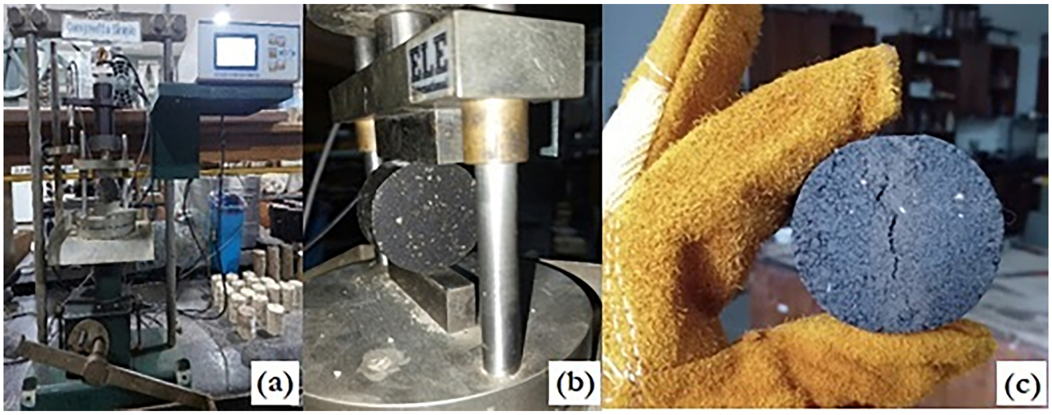

Figure 8. Equipment and Procedure for Indirect Tensile Strength Testing of Asphalt Mixtures. (**a**) Equipment used for indirect tensile strength testing; (**b**) Indirect tensile loading device; (**c**) Failure and visible tensile cracking after testing.

RESULTS

Verification of Aggregate Gradation

Table 1 presents the results of the sieve analysis performed on the reference mineral aggregate (19), including consistency limits and material classification, while (Table 2), shows the results of the constructed or adjusted gradation process.

Table 1. Characterization of the mineral aggregate.

%G	%S	%F	%LL	PI	Cu	Cc	Classification
56.63	29.11	9.64	17.39	NP	210.40	0.71	GP-GM

%G: gravel content; **%S**: sand content; **%F**: fines content; **%LL**: liquid limit; **PI**: plasticity index; Cu: coefficient of uniformity; **Cc**: coefficient of curvature; **GP-GM**: Unified Soil Classification System (USCS) classification.

Table 2. Constructed gradation.

Sieve	mm	Base aggregate gradation (19)		Constructed aggregate gradation		
		Retained weight (g)	% Retained	Retained weight (g)	Cumulative retained weight (g)	% Retained
2”	50.00	409.99	9.24	522.50	522.50	9.24
1 1/2”	37.50	154.01	3.47	196.00	718.50	3.47
1”	25.00	735.38	16.57	936.50	1,655.00	16.57
3/4”	19.00	261.69	5.90	333.50	1,988.50	5.90
3/8”	9.50	584.87	13.18	745.00	2,733.50	13.18
No. 4	4.75	366.71	8.26	467.00	3,200.50	8.26
No. 10	2.00	319.87	7.21	407.50	3,608.00	7.21
No. 20	0.84	299.45	6.75	381.50	3,989.50	6.75
No. 40	0.425	243.06	5.48	310.00	4,299.50	5.48
No. 60	0.25	192.13	4.33	245.00	4,544.50	4.33
No. 100	0.150	237.15	5.34	302.00	4,846.50	5.34
No. 200	0.075	205.12	4.62	261.30	5,107.80	4.62
	—	427.57	9.64	545.20	5,653.00	9.64
Total simple weight (g):		4,437	5,653			

Grams = g; **millimeters** = mm

Preparation of Modified Sand–Asphalt Mixtures

Table 3 provides an example of the volumetric correction applied to the mixture components for a PPF content of 0.25% and an optimum liquid asphalt content of 11.00% (RC-250 optimum = 11.00%).

Table 3. Volumetric correction.

Gs Aggregate	2.65	**Percentage of Mineral Aggregate**	89.00	1,780.00
Gs Microfiber	0.91	**Percentage of RC-250 Binder**	11.00	220.00
Total Mixture Quantity (g)	2,000.00	**Percentage of Polypropylene Microfibers**	0.25	

Material	**%**	**2,000.00 g Mixture**			**Corrected Weight**				
		89.00 % Aggregate % Retained	**Partial (g)**	**Accumulated (g)**	**Gs**	**% Aggregate x Gs**	**89.00 % Aggregate**	**Partial (g)**	**Accumulated (g)**
Aggregate N° 4	99.75	88.78	1,775.55	1,775.55	2,65	235.26	88.92	1,778.47	1,778.47
Microfiber Material	0.25	0.22	4.45	1,780.00	0,91	0.20	0.08	1.53	1,780.00
Total	100.00	89.00	1,780.00			235.46	89.00	1,780.00	

***Gs, is the relative specific weight of solids, (g) is unit in grams**

Modified Mixtures Hubbard-Field Method

Table 4 presents the average results obtained during the process of determining and verifying the index properties (IPs) of the modified cold asphalt mixtures (MCAM), after refining the data set.

Table 4. Index properties of the modified asphalt mixture and specification verification.

Property	**Reference Mixture** (19)				**This study**		**Specification Values**
Percentage of Polypropylene microfiber	**Reference pattern**	0.05%	0.10%	0.15%	0.20%	0.25%	
RC-250 (%)	11.00	11.00	11.00	11.00	11.00	11.00	—
Stability at ambient temperature (lbs)	2,340.00	1,630.20	1,501.50	2,002.00	2,745.60	2,831.40	≥1,200.00 lbs
Wet stability at ambient temperature (72 h)	2,230.00	1,372.80	1,501.50	1,849.47	1,587.30	1,758.90	≥1,000.00 lbs
Stability in water at 60 °C (lbs)	520.00	486.20	343.20	357.50	1,043.90	1,172.60	—
Stability in oven at 60 °C (lbs)	580.00	371.80	328.90	343.20	2,159.30	2,788.50	—
Swelling (%)	3.60	1.98	1.48	2.38	3.58	6.84	≤5%
Absorption (%)	3.00	0.32	0.36	0.46	1.63	1.67	≤8%
Compaction (%)	97.50	90.63	93.80	96.44	99.51	99.53	≥88%
Voids (%)	2.80	8.65	5.67	3.99	0.49	0.47	≤12%

Indirect Tensile Strength Test

Table 5 summarizes the results obtained from the indirect tensile strength tests performed on the MCAM specimens.

Table 5. Indirect tensile strength of modified samples

Indirect tensile strength σt (kg/cm²)	Reference Mixture (19)	This Study				
	Percentage of microfiber					
	Reference pattern	0.05	0.10	0.15	0.20	0.25
	1.15	0.98	1.09	1.38	2.30	2.35

DISCUSSION

Stability at Ambient Temperature. As expected, this index property increased compared to the reference mixture (RM), showing an improvement of 17.35% for 0.20% PPF and 21.00% for 0.25% PPF. As the proportion of PPF in the mixture increased, the stability increased correspondingly, especially when exceeding 0.20% PPF. The presence of polypropylene microfibers indirectly contributes to resistance by interlacing the aggregates within the mixture, despite the fact that the fibers themselves do not possess compressive strength. The values obtained largely exceeded the minimum specification requirements of the method. This finding is consistent with previous studies reporting enhanced stability due to synthetic fiber incorporation (3,12) and aligns with Ali et al., who documented that polypropylene and other synthetic fibers improve the cohesion and stability of asphalt mixtures, both in hot and cold applications (25). Furthermore, although the study by Majeed et al. was conducted on hot asphalt mixtures, the observed improvement in stability with polypropylene fibers supports the general trend of enhanced mechanical properties (26).

Stability after 1 Hour Immersion in Water at 60 °C. When subjected to adverse moisture and temperature conditions, the briquettes exhibited a significant increase in stability compared to the RM, with improvements of 100.75% for 0.20% PPF and 125.50% for 0.25% PPF. As the PPF content increased, the stability also improved markedly, confirming the same reinforcing benefit attributed to the microfibers described above. Notably, this condition is not associated with any minimum requirement in the method. Similar improvements in resistance to moisture were reported by Yung (6), Mardones et al. (12), and Ali et al., who concluded that synthetic fibers effectively increase moisture susceptibility resistance (25).

Stability after 72 Hours of Partial Immersion in Water at Ambient Temperature. In contrast to other conditions, the stability under prolonged immersion showed a decrease compared to the RM, with reductions of 28.82% and 21.13% for 0.20% and 0.25% PPF, respectively. This trend, which was also observed in previous research (19), indicates that while the incorporation of PPF contributes to increased stability under certain conditions, it may result in diminished performance when the mixture is subjected to long-term water exposure. Nonetheless, all values remained above the minimum limits required by the methodology. . These observations are comparable to the findings of Cárdenas (8) who noted that the effectiveness of synthetic fibers can vary depending on environmental conditioning and dosage (25).

Swelling. Although it was initially assumed that PPF does not absorb water, the incorporation of microfibers into the mixture first caused a decrease in swelling relative to the RM. However, a progressive recovery and increase were observed as the PPF content rose, eventually surpassing the swelling of the RM. Specifically, reductions of 0.56% and a substantial increase of 90% were recorded for 0.20% and 0.25% PPF, respectively. The final swelling value for the higher dosage exceeded both the method's limit and the RM value, highlighting the need to carefully consider the potential deformation due to volume increase. Similar trends have been observed by Martínez (13) and Ali et al., who reported that fiber additions can modify internal void structure and potentially increase swelling if the dosage exceeds optimal levels (25).

Absorption. Compared to the RM, this study showed a reduction in absorption for all PPF dosages, with decreases of 45.67% and 44.33% for 0.20% and 0.25%, respectively. This trend aligns with the expectation that the inclusion of hydrophobic polymer fibers reduces water absorption. Nonetheless, it remains important to confirm the aggregate's absorption characteristics and the actual behavior of the PPF. The relationship between swelling and absorption followed the expected pattern, as higher swelling typically corresponds to increased absorption. In this case, the values did not exceed those of the RM, consistent with Vanegas (7), Martínez (13), and Ali et al., who documented lower water absorption in fiber-reinforced mixtures due to the hydrophobic nature of polypropylene (25).

*Compaction***.** As anticipated, compaction exceeded the levels achieved by the RM. However, increasing the PPF percentage did not result in a significant improvement, with an approximate increase of 2.00%. Further increases in PPF content are unlikely to substantially affect compaction. An average compaction percentage of 99.00% was obtained, which exceeds the minimum requirement of 88.00% specified by the method. These findings are consistent with Vanegas et al. (14) and Ali et al., who noted that fiber reinforcement may enhance compaction moderately, although the effect tends to plateau beyond certain dosages (25).

Voids. The PPF dosages evaluated in this study led to an average reduction in void content of approximately 80% compared to the RM. The resulting void percentages remained within the maximum limits established by the methodology. This outcome reflects the expected inverse relationship between compaction and voids: higher compaction results in lower void content. Similar reductions in voids were documented by Rojas et al. (4), Muñoz (11), Ali et al., and Majeed et al., confirming that polypropylene fibers contribute to improved internal density and reduced air voids (25-26).

Indirect Tensile Strength Test. From the outset, it was expected that the inclusion of PPF would increase the tensile strength of the MCAM. For the 0.20% and 0.25% PPF dosages, the tensile strength increased by approximately 100% compared to the RM. This substantial improvement confirms the reinforcing capability of polypropylene microfibers in enhancing tensile resistance. These findings are consistent with those reported by Mardones et al. (12), Jiménez (15), Ali et al., and Majeed et al., who demonstrated that synthetic fibers markedly improve indirect tensile strength in asphalt mixtures (25-26).

Cost-Benefit Analysis. Based on the recommended dosage of 0.20% polypropylene microfibers (PPF), the following economic considerations were calculated: (i) For each ton of mixture, 610.40 grams of PPF are added, given that 1.22 grams of fiber are used per 1,998.78 grams of mixture; (ii) The unit cost of PPF is approximately USD 3 per kilogram; (iii) Therefore, the cost per ton of PPF is USD 1.80; (iv) The cost of unmodified cold asphalt mixture is estimated at USD 40 per ton; (v)The total cost of the modified mixture with 0.20% PPF is USD 41.80 per ton. This modest cost increase is justified by the improved tensile strength and performance, considering that repairs due to early damage are typically much more expensive.

Future studies should expand this research line by evaluating the absorption behavior of both aggregates and polypropylene microfibers under varied environmental and loading conditions. It is also recommended to implement this methodology in pilot-scale field sections to verify the performance of the modified mixtures under real traffic and weather exposure. Moreover, exploring the use of different types of fibers with diverse origins and compositions could provide valuable comparative insights. One limitation of the present study is that it was conducted exclusively under laboratory conditions, which may not fully capture the complexities and variability of in-service pavements.

CONCLUSIONS

The incorporation of polypropylene microfibers (PPF) into cold asphalt mixtures proved to be a feasible and beneficial strategy for enhancing their mechanical properties. Overall, the use of PPF significantly increased stability, compaction, and indirect tensile strength, reduced absorption and air voids, and did not compromise general performance. However, it is recommended to limit the dosage to a maximum of 0.20% to ensure compliance with swelling requirements and to prevent excessive deformation.

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ETHICAL CONSIDERATIONS

This research was conducted in accordance with international standards of scientific integrity and laboratory safety. All experiments involving asphalt mixtures were performed under controlled conditions and in compliance with ASTM International standards, ensuring the protection of personnel and the environment. This work was approved in the minutes dated November 25, 2024 by a jury of fourth- and fifth-level training teachers and members of the Department of Roads of the School of Civil Engineering of the University of Los Andes, Venezuela.

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DECLARATION OF COMPETING INTEREST

The authors have declared no conflict of interest

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