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COMPARATIVE ANALYSIS OF THE PHYSICAL-MECHANICAL PERFORMANCE OF HOT-DENSE ASPHALT MIXTURES MODIFIED WITH POLYPROPYLENE FIBERS USING THE MARSHALL METHOD

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ABSTRACT

The durability of flexible pavements in high Andean altitude areas requires asphalt mixtures with superior resistance to plastic deformations. This study comparatively evaluates the performance of conventional hot-dense asphalt mixtures (MDC-2) versus mixtures modified with recycled polypropylene fibers, using Marshall design. Aggregates from the San Francisco quarry (Putumayo, Colombia) and asphalt from the Barrancabermeja refinery were used. The methodology included metrological calibration of the Marshall press ($R^2 \approx 1.00$) and comprehensive characterization of aggregates according to INVIAS standards. The results show that the addition of polypropylene fibers significantly reduces the Marshall flow from 3.1 mm to 2.7 mm (reduction of 12.9%, $p < 0.05$), indicating greater resistance to plastic deformations. Marshall stability did not present significant differences ($p > 0.05$): 1351 kg (conventional) versus 1360 kg (modified). The asphalt content decreased from 6.1% to 5.75% (0.35 percentage points), while the filling-binder ratio improved from 0.98 to 1.20, evidencing better cohesion and adhesion. The volumetric parameters remained within specifications: empty air (3.6%-4.0%), empty mineral aggregate (14.80%-17.15%) and empty empty filled with asphalt (77.5%-87.2%). These findings demonstrate the technical feasibility of mixtures reinforced with recycled polypropylene for high-traffic road infrastructure, with the potential to extend the useful life of the pavement by reducing plastic deformations.

KEYWORDS: Modified asphalt mixtures, recycled polypropylene, Marshall test, plastic deformation, flexible pavements.

1. INTRODUCTION

Road infrastructure is a critical factor for the economic and social development of a region, facilitating the mobility of people, goods and services (National Asphalt Pavement Association [NAPA], 2008; Federal Highway Administration [FHWA], 2015). In flexible pavements, the wearing layer is typically composed of hot asphalt mixture (MAC), simultaneously subjected to cyclical loads of traffic and environmental factors such as temperature, solar radiation, relative humidity that generate mechanical and chemical stresses. These factors lead to characteristic modes of deterioration such as rutting, plastic and permanent deformation, fatigue cracking, aggregate detachment, and loss of surface texture, significantly shortening the useful life of the pavement and increasing maintenance costs (Instituto Nacional de Vías [Invías], 2022).

In Colombia, the Marshall method has been the prescribed methodology for the design of asphalt mixtures in Article 450-22 of the Standards for decades (Invías, 2022). However, recent research shows that insufficient application of the method, combined with incomplete characterization of local materials and deficiencies in on-site quality control, has resulted in mixtures that meet design specifications but perform poorly in the field (Tahmoorian et al., 2023; Sánchez, 2014).

At the same time, international research has significantly developed knowledge on asphalt mixtures modified with polymers and fibers, demonstrating that their incorporation substantially improves resistance to deformation, fatigue resistance and durability against moisture damage (Tapkín, 2008; Takaikaew et al., 2021; Khater at al., 2021). Polypropylene (PP) fibers, in particular, have proven to be particularly effective. Unlike polymer modifiers dissolved in binder, the fibers generate a three-dimensional reinforcement matrix that distributes stresses and confines the mineral skeleton, improving the bearing capacity (Khater at al., 2021). In addition, the possibility of using fibers derived from recycled waste opens up opportunities for environmental sustainability without compromising technical performance (Ameri et al., 2024).

In the regional context of southern Colombia in the departments of Putumayo and Nariño, where there are increasingly scarce local sources of stone aggregates and high humidity climatic conditions prevail that accelerate the deterioration of conventional pavements, there is a gap between international technical knowledge and its application adapted to local materials. The present work addresses this gap through systematic research that combines rigorous metrological calibration of laboratory equipment, comprehensive characterization of local stone materials, controlled experimental design of conventional and modified mixtures, and comparative analysis based on mechanical performance and statistical analysis.

2. DESCRIPTION OF THE PROBLEM AND HYPOTHESIS

2.1 *Technical Problem*

Several road sections in Colombia, including the southern region, show premature deterioration of the asphalt layer manifested in rutting, cracking due to fatigue, detachment of aggregates and loss of slip resistance even when mixtures were designed under the Marshall method and initially met regulatory specifications (Invías, 2022, Sánchez, 2014). Among the multifactorial causes identified are the insufficient application of the Marshall method in the laboratory, the incomplete characterization of local stone materials, deficiencies in quality control during production and installation on site, and limited incorporation of modification technologies with additives that demonstrate verifiable improvements in mechanical performance.

The specific technical problem addressed by this research is: How to significantly improve the mechanical performance of type two hot dense mixtures (MDC-2) produced with local materials, without disproportionate increases in cost, by incorporating technically accessible modification technologies such as the addition of recycled polypropylene fibers?

2.2 *Research Hypothesis*

It is postulated that the incorporation of polypropylene fibers into hot-dense asphalt mixtures significantly increases Marshall stability and resistance to permanent deformation, maintaining acceptable volumetric parameters without compromising workability during placement and compaction (Tapkín, 2008; Takaikaew et al., 2021). Additionally, it would be expected that the use of fibers derived from recycled polypropylene waste represents an opportunity to optimize cost-benefit ratio compared to virgin polymers, while maintaining technical benefits.

Verifying these hypotheses for aggregates from the San Francisco quarry and asphalt from the Barrancabermeja refinery allows generating local technical evidence that supports the adoption of more rigorous design criteria and updating of technical specifications for pavements in the region.

3. RESEARCH OBJECTIVE.

To determine and comprehensively compare the optimal content of asphalt binder for hot dense asphalt mix type MDC-2, made with unmodified conventional asphalt and with asphalt modified with recycled polypropylene fibers, using stone aggregates from San Francisco quarry (Putumayo) and refined asphalt in Barrancabermeja. The analysis includes evaluation of mechanical performance (stability, flow and volumetric parameters), intrinsic durability of materials and implications in production costs, in order to provide technical evidence for the specification and adoption of modified mixtures in regional road infrastructure projects.

4. THEORETICAL FRAMEWORK

4.1 *Composition and Structure of Hot-Dense Asphalt Mixtures*

Hot-dense asphalt mixtures (CDMs) are composite material consisting of mineral skeleton (coarse and fine stone aggregates and mineral filler) that typically represents between 90% and 95% of the total weight of the mixture, and a binding phase (asphalt or asphalt cement) that surrounds and joins aggregate particles. The final quality and performance of the mixture depend critically on the properties of both components and the interaction between them (Asphalt Institute, 2001).

The mineral skeleton is primarily responsible for the structural strength of the mixture against traffic loads. Its determining characteristics include the gradation or distribution of particle sizes, which defines packing and mixing density; angularity and particle shape, which generate internal friction and mechanical interlocking; hardness and durability, which ensure that aggregates do not fracture during construction or under repeated loads; and cleaning, which ensures optimal adhesion between aggregate and asphalt.

The asphalt binder acts as a binder, providing cohesion between aggregate particles and contributing significantly to mixing flexibility. Its rheological properties such as viscosity, elasticity, thermal susceptibility, decisively influence mixing behavior under different temperatures and loading speeds (INVIAS, 2022).

4.2 *The Marshall Method.*

The Marshall method is a procedure for the design of asphalt mixtures based on empirical analysis that determines the optimal content of binder necessary to achieve a balance between mechanical stability understood as resistance to plastic deformation and durability, the latter ensured by adequate void contents and asphalt film thicknesses. The method operates through two complementary levels of analysis: volumetric analysis and mechanical analysis.

Volumetric analysis examines how the three components of a compacted mixture are distributed: the mineral aggregate, asphalt, and air. The key parameters in this analysis are the air vacuums (Va), which are small pockets of air evenly distributed in the compacted mixture. Its presence is essential to allow a slight post-compaction under vehicular traffic and to accommodate the thermal expansion of the asphalt in hot climates, thus avoiding exudation. In dense mixtures, these voids are typically specified between 3% and 8%, depending on the level of transit and the type of layer. In addition, the voids in the mineral aggregate (VAM) represent the total volume of space between the particles of the compacted aggregate skeleton. This space must be large enough to accommodate both asphalt and air voids, as insufficient VAM results in asphalt films that are too thin, susceptible to accelerated aging, while excessive VAM indicates poor packing of the aggregate. Finally, asphalt-filled voids (VFAs) constitute the percentage of the VAM that is effectively occupied by the asphalt binder, being a direct indicator of the durability of the mixture. Low values generate thin films that accelerate aging, while very high values suggest few air vacuums and the risk of plastic instability.

In mechanical analysis, for the determination of stability and Marshall flow, compacted cylindrical specimens are conditioned at a temperature of 60 °C in a hot water bath and then subjected to a diametrical vertical compression load applied at a constant speed of 2 in/min. The test records two fundamental parameters: Marshall stability (kN or kg), which is the maximum load that the specimen can withstand before failure and functions as an empirical indicator of the resistance of the mixture to permanent plastic deformation at high temperatures, and Marshall flow (mm or 0.01 in), which is the total vertical deformation experienced by the specimen at the point of maximum load. While very low flow values may indicate brittleness in the mixture, very high values characterize excessively plastic mixtures, susceptible to rutting.

4.3 *Mechanisms of Mechanical Enhancement Using Polypropylene Fibers*

The incorporation of synthetic fibers, particularly polypropylene, in asphalt mixtures constitutes a reinforcement strategy that transforms a mixture of agglomerated granular material into a true composite material with a matrix-reinforcement structure. Polypropylene is a thermoplastic polymer that exhibits significant changes in state at temperatures above 100 °C, at which point it begins to soften and acquire viscous characteristics (according to Table 418-1 of Article 418-22). Hot asphalt mixes are manufactured at viscosity ranges between 150 and 190 cSt, equivalent to approximate temperatures of 150-165 °C depending on the type of asphalt. At these temperatures, polyolefin fibers undergo changes in state, but maintain homogeneous distribution during dry mixing. According to Article 418-22 of the INVIAS 2022 Specifications, these synthetic fibers are added using the dry method, and their dosage must be defined in the laboratory during the process of design and evaluation of the mixture, verifying uniform dispersion throughout the asphalt mass through specific mixing times between 7 and 10 seconds.

The mechanisms by which polypropylene fibers improve mechanical performance are: first, the absorption of light components of the asphalt binder generating a more viscous and hardened film at the interface with the aggregate, an effect that explains why modified mixtures generally require slightly higher asphalt content than the standard mixture. Secondly, the bridge between micro-cracks, where at the microscopic level the fibers that cross the fracture plane act as bridges when a micro-crack begins under tension, preventing its propagation without first stretching or tearing off the fibers, processes that require a considerable amount of energy and consequently inhibit the growth of cracks, drastically improving the fatigue resistance and the total toughness of the material. Thirdly, the confinement of the mineral skeleton, in which the three-dimensional network of fibers confines the aggregate particles, restricting their ability to reorient or displace under shear loads, increasing the internal friction and shear resistance of the mixture, significantly improving the resistance to rutting at high temperatures (Tapkin, 2008).

International studies have documented that the addition of polypropylene fibers significantly increases Marshall stability with values that vary between 17% and 58% depending on the dosage, characteristics of the fibers and type of asphalt binder. Takaikaew et al. (2021) reported average increases of 17% with dosage of 0.05%, while Tapkin (2008) documented increases of up to 58% with higher contents. At the same time, a reduction in flow between 5% and 39% is observed, indicating a more rigid mixture that is resistant to plastic deformations (Tapkin, 2008; Takaikaew et al., 2021). The optimal dosage reported in the literature for synthetic fibers typically ranges from 0.3% to 2% by weight of the mixture, with 0.3% being the most frequent dosage in international studies, although specific research has evaluated ranges up to 5% to investigate effects at higher dosages. In accordance with Article 418-22 of INVIAS 2022, the specific dosage must be supported by technical studies that demonstrate the benefits obtained in the performance tests of the asphalt mixture with the incorporation of synthetic fibers, comparing results with the standard mixture without the addition of such fibers. Evaluation of the mechanical behavior is required according to the criteria established in Articles 450, 451, 452, 453 and 462, depending on the type of asphalt mixture used. This regulatory verification ensures that the incorporation of fibers does not produce harmful effects on the aggregates, the asphalt binder or the mixture as a whole, as established in Article 418-22 of INVIAS for mixtures with reinforcement of synthetic fibers

5. METHODOLOGY

5.1 Location and General Characterization of the Research

The research was carried out in the facilities of the Soil and Pavement Laboratory of the Faculty of Engineering, University of Nariño, in San Juan de Pasto, Colombia (location: 1°13'55"N, 77°16'55"W, altitude 2,527 m.a.s.l.). The materials used came from the San Francisco quarry, located in the department of Putumayo (southwestern Colombia), a region characterized by high rainfall (between 3,000 and 4,000 mm per year) and high relative humidity, conditions that generate special demands for paving materials in terms of durability and resistance to moisture damage. The asphalt binder used was refined asphalt cement in Barrancabermeja, the main source of asphalt supply for the Colombian market and asphalt of greater use in the southern region of the country.

5.2 Marshall Press Calibration Procedure

To ensure metrological traceability in stability and flow measurements, calibration of the Marshall press was implemented in accordance with INV E-748-13 (Article 450-22, INVIAS 2022). A load cell type FC23 (range 906 kgf) was used, previously calibrated on a universal machine of 11,000 lbf. The cell was connected to an op-amp for voltage amplification and display via LCD module. Calibration equations with a coefficient of determination $R^2 \approx 1.00$ were obtained: $F = (V - 0.0014) / 0.11$ [kgf] and $V_{out} = 0.005 \times F$ [V]. The comparative verification of load curves of the Marshall press with the calibrated sensor confirmed deviation of less than 2%. Temperature was compensated in the range 0°C-50°C; however, Pasto's temperatures (18-20°C) are well below the compensation range, so it did not require additional electronic adjustments.

5.3 *Stone Aggregate Characterization Procedure*

Tests were carried out in accordance with INVIAS 2022 (Art. 400-22, 450-22) for MDC-2 heavy traffic level (NT3) mixing.

Table 1: Aggregate Tests Performed and Results

Essay	Standard	Ownership	Criterion NT3	Result
Granulometry	INV E-213	Size distribution	Compliant	Compliant
Los Angeles Machine	INV E-219	Tearing/abrasion	≤ 25%	23.92%
Micro-Deval	INV E-238	Water abrasion	≤ 20-25%	14.68%
Na□SO□ Fastness (gru)	INV E-220	Durability	≤ 12%	10.76%
Solidez Na□SO□ (fine)	INV E-220	Durability	≤ 12%	10.80%
MgSO□ Solidity	INV E-220	Durability	≤ 18%	7.73%
MgSO□ Strength (Fine)	INV E-220	Durability	≤ 18%	5.20%
Sand Equivalent	INV E-133	Thin plastics	≥ 50%	63.50%
Impurities Content	INV E-237	Cleaning	≤ 0.5%	0.30%
Fractured Faces	INV E-227	Mechanical fractures	≥ 90%	93.28%
Flat/Flared	INV E-240	L/E > 5 ratio	≤ 10%	3.50%
Grav. Specific	INV E-222, 223	Bulk density	Specification	2,814 g/cm³

All aggregates meet INVIAS 2022 specifications for MDC-2 NT3.

5.4 *Marshall Mix Design Procedure*

Two MDC-2 type asphalt mix lines were developed in accordance with Article 450-22 of INVIAS 2022, following the standardized Marshall method. The conventional mixture or standard was subjected to evaluation with six asphalt contents (4.5%, 5.0%, 5.5%, 6.0%, 6.5% and 7.0% in total mix weight), using three briquettes for each content (18 total briquettes) compacted at 75 strokes per side with a Marshall hammer, specified for heavy traffic (NT3). For each briquette, measurements were made of weight in air, weight immersed in water at 25°C, bulk density, Marshall stability (kN) and Marshall flow (mm) according to INV E-748.

The modified mixture with recycled polypropylene fibers was prepared following an equivalent procedure, with incorporation of the fibers into the hot asphalt binder prior to mixing with aggregates. The polypropylene dosage was established from international literature, evaluating three dosages (0.2%, 0.4%, 0.6%) with three briquettes per dosage (9 briquettes for optimization) plus 3 verification briquettes at optimal dosage, for a total of 12 modified briquettes.

Calculation of Volumetric Parameters: For each briquette, the volumetric parameters were calculated using Marshall standard equations according to INV E-735, INV E-736 and INV E-799: the Maximum Theoretical Specific Gravity (Gmm) using the Rice method (ASTM D2041); Voids with Air (Va); Mineral Aggregate Voids (VAM) and Asphalt Filled Voids (VFA). The resulting parameters were evaluated according to Table 450-10 INVIAS 2022: Ranges between 4.0-6.0%, minimum MVA 15.0%, VFA between 65-75%, minimum stability 9,000 N, Marshall flow between 2.0-3.5 mm.

5.5 *Determination of Optimal Asphalt Content*

Plots of Marshall stability, flow, bulk density, Va, VAM and VFA versus asphalt content were plotted. The optimal asphalt content (COA) was determined as an average of three criteria, the content that produces maximum stability, the content that produces maximum bulk density, and the content that produces approximately 4% of air voids, according to the procedure of intersection of criteria (Article 450-22, INVIAS 2022). The final COA was verified to ensure that the resulting parameters met all specification limits for MDC-2 NT3 mixtures.

6. RESULTS

6.1 *Metrological Calibration of the Marshall Press*

The FC23 load cell calibration results demonstrated a virtually perfect linear relationship between recorded voltage (range 0.03 to 3.49 V) and applied force (range 14 to 1415 lbf), with determination coefficients $R^2 \approx 1.00$. The resulting equation was $F(lbf) = 1069 \times V(V) - 958$, obtained by linear regression of the nine calibration points, with a coefficient of determination $R^2 \approx 1.00$.

The graphical comparison between the Marshall press curve and that of the calibrated sensor showed the same linear trend with low dispersion, confirming metrological traceability of stability measurements made in all subsequent tests.

6.2 *Characterization of Aggregates from the San Francisco Quarry*

The aggregates satisfactorily met all requirements specified in INVIAS (Article 400) for heavy transit hot dense mixtures:

Table 1: Summary of aggregate characterization results according to INVIAS specifications (NT3).

ESSAY	INV TEST STANDARD	REQUIREMENT OF THE NORM	VALUE MEASURED IN LABORATORY
Composition			
Granulometry	**E-213**	**-**	
Hardness			
Angels Machine Wear	**E-218**	**25% max.**	**23.92%**
Micro-Deval	**E-238**	**20% max.**	**14.68%**
Durability			
Losses in the Solidity Test in Coarse Aggregate Sodium Sulphate	**E-219**	**12% max.**	**10.8%**
Losses in the Fine-Added Sodium Sulphate Fastness Test	**E-220**	**12% max.**	**10.76%**
Losses in the Solidity Test in Coarse Aggregate Magnesium Sulphate	**E-220**	**18% max.**	**5.2%**
Losses in the Strength Test in Fine Added Magnesium Sulphate	**E-221**	**18% max.**	**7.73%**
Cleaning			
Sand equivalent	**E-133**	**50% min**	**63.5%**
Impurity content	**E-237**	**0.5% max.**	**1.2%**
Particle geometry			
Mechanically fractured particles	**E-227**	**85/70% min**	**93.2/75%**
Flat and elongated particles ratio 1:5	**E-240**	**10% max.**	**3.50%**
Specific Gravity			
Specific gravity and fine absorption	**E-222 and E-223**		**2,836 g/cm^3**
Specific gravity and gross absorption	**E-222 and E-223**		**2,814 g/cm^3**

These results confirm that aggregates from San Francisco quarry have adequate physical-mechanical characteristics and superior relative performance in hardness, durability, cleanliness and particle geometry, classifying them as suitable for the production of high-quality hot-dense mixtures.

6.3 Marshall Design Results - Conventional Mixing.

For conventional bone mixture of unmodified asphalt, 18 briquettes were prepared, three for each asphalt content:

Table 2. Results design Marshall - Conventional asphalt mix MDC-2.

Asphalt Content (%)	Average Stability (kg)	Average Flow (mm)	Bulk Density (g/cm^3)	Va (%)	VAM (%)	VFA (%)
4.5	514	2.70	2.361	8.90	16.07	55.70
5.0	744	2.80	2.376	10.9	15.96	68.10
5.5	793	3.00	2.383	11.7	16.17	72.20
6.0	1356	3.10	2.434	11.3	14.83	76.50
6.5	1149	3.20	2.428	14.0	15.47	90.60
7.0	930	3.40	2.418	14.6	16.29	89.60
6.1	**1351**	**3.10**	**2.383**	**12.2**	**16.70**	**73.2**

6.4 Marshall Design Results - Modified Mix

9 briquettes were prepared with recycled polypropylene fibers for the same asphalt contents:

Table 3. Results design Marshall - Asphalt mixture modified with polypropylene fibers.

Parameter	% Asphalt 1	% Asphalt 2	% Asphalt 3
Asphalt Content (%)	5.9	5.7	5.5
Stability (kg)	1335	1358	1161
Flow (mm)	2.30	3.10	3.80
Bulk Density (g/cm^3)	2.354	2.357	2.288
Theoretical Maximum Spec Weight	2.449	2.456	2.463
Absorbed Asphalt (%)	2.66	-0.50	-1.49
Va	7.8	14.3	15.6
VAM	17.53	17.25	19.50
VFA	44.9	82.9	79.8

6.5 Comparison of Marshall results with normal and modified asphalt

Table 4. Expanded comparative analysis of Marshall parameters in the optimal asphalt content with comprehensive interpretation.

Marshall	**Conventional**	**Modified**
Asphalt Content (%):	6.1%	5.75%
Polypropylene Content (%):	0.0%	0.35%
Unit Weight (gr/cm^3):	2.436	2.359
Stability (kg):	1351	1360
Flow rate (mm):	3.1	2.7
Air vacuums (%):	3.6	4.0
Mineral Aggregate Voids (%):	14.80	17.15
Empty Filled with asphalt (%):	87.2	77.5
Filling-Binder Ratio:	0.98	1.20
Compaction Temperature (°C):	130	130

7. GRAPHS OF THE RESULTS

The unit weight shows a parabolic behavior with a maximum of 0.4% polypropylene. The bulk density increases from 0.2% to 0.4% (0.003 g/cm^3 increase), indicating better accommodation of the fibers in the asphalt matrix and optimal compaction at this dosage. However, at 0.6%, the density decreases significantly to 2.288 g/cm^3 (0.069 g/cm^3 reduction from 0.4%), suggesting that higher dosages generate excess fibers that interfere with compaction and reduce the density of the mixture. This behavior is consistent with literature that reports optimal dosages between 0.3%-0.5% (Tapkin, 2008; Takaikaew et al., 2021). The dosage of 0.4% represents the balance between fiber distribution and compaction capacity of the asphalt mixture.

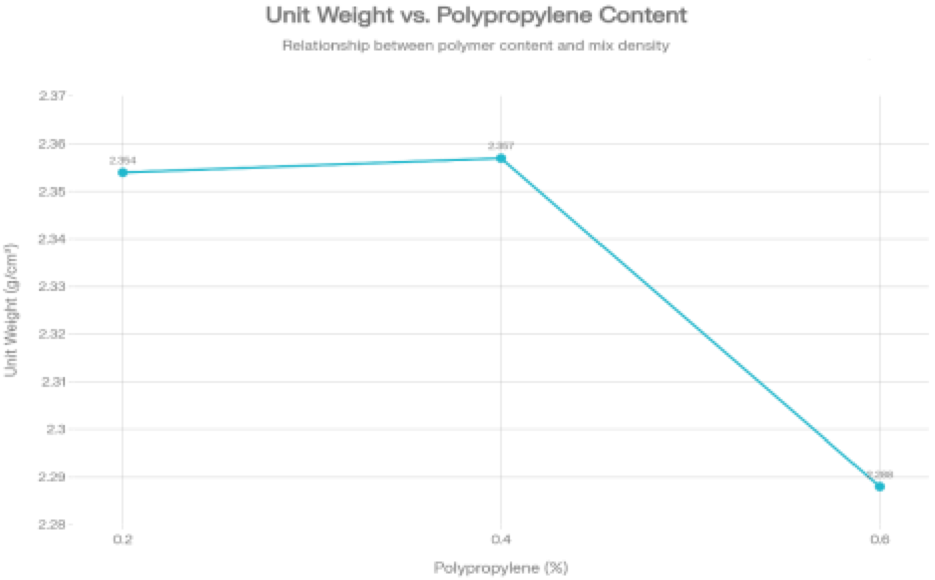

Figure 1: Unit Weight vs Polypropylene Content

Marshall stability shows a similar pattern to the unit weight, with a maximum of 0.4% polypropylene (1358 kg). The increase from 0.2% to 0.4% is 23 kg (1.7% increase), indicating that the initial addition of fibers improves the confinement capacity of the mineral skeleton. However, the dramatic drop to 0.6% (reduction of 197 kg, 14.5% less than 0.4%) shows that excess polypropylene compromises mechanical stability, presumably due to interference in the uniform distribution of fibers and deficit in the asphalt film that covers the aggregate. Compared to conventional mixing (1351 kg), the optimal dosage of 0.4% produces equivalent stability (1358 kg, just 7 kg higher, $p > 0.05$), complying with the requirement of maintaining INVIAS specifications without significant increases in binder (Instituto Nacional de Vías, 2022).

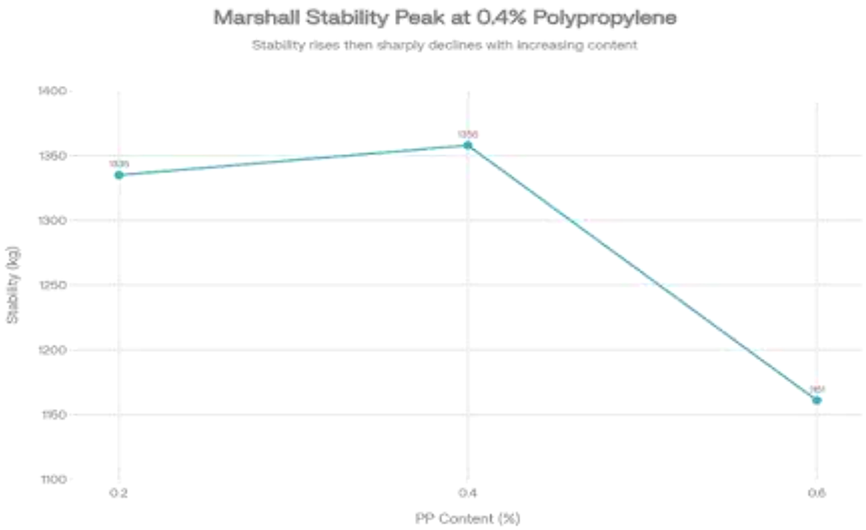

Figure 2: Marshall Stability Peak at 0.4% Polypropylene

The Marshall flow shows an inverse tendency to stability: it continuously increases with polypropylene content, indicating progressively more plastic and deformable mixtures. The 0.2% dosage produces minimal flow (2.30 mm), which is within the specified range (2.0-3.5 mm according to INVIAS) but represents an excessively rigid and potentially fragile mixture. At 0.4%, flow is 3.10 mm (equal to conventional blend without fibers), maintaining acceptable stiffness. At 0.6%, flow reaches 3.80 mm, exceeding the upper specification of 3.5 mm by 0.3 mm, indicating too plastic mixture susceptible to rutting under sustained traffic at high temperatures (Tapkin, 2008). This behavior reveals that excess fibers absorb light components of the binder, reducing effective viscosity of the asphalt matrix and increasing deformability. The optimal dosage of 0.4% balances rigidity and workability without compromising resistance to plastic deformation.

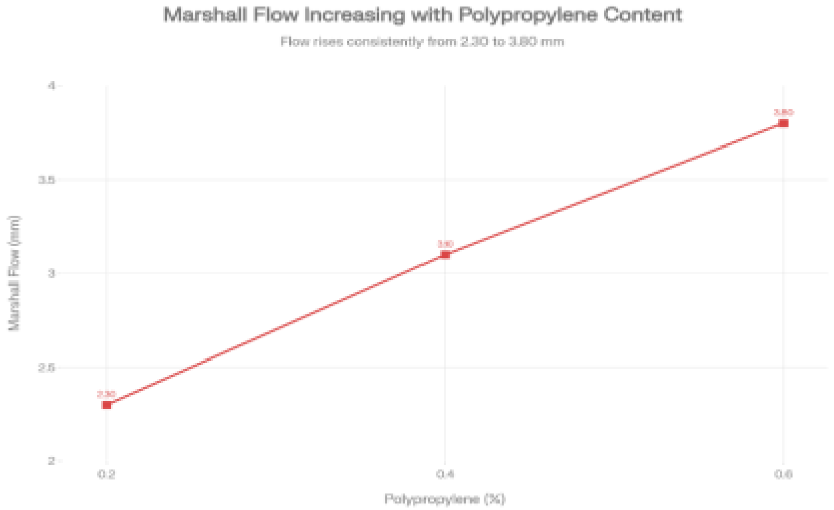

Figure 3: Marshall Flow Increasing with Polypropylene Content

Air vacuums show a progressive increase with polypropylene dosing, going from 7.8% to 15.6% (increase of 7.8 percentage points). At 0.2%, Va is well below the specified range (4.0-6.0% according to INVIAS 2022), indicating excessive compaction that compromises durability due to insufficient air pockets for thermal expansion of the asphalt. At 0.4%, Va reaches 14.3%, significantly beating the top spec of 6.0% by 8.3 points. At 0.6%, Va reaches 15.6%, an even more pronounced excess. This behavior contrary to what is expected can be attributed to the fact that low fiber dosage (0.2%) facilitates better compaction, while higher dosages create interstitial spaces between fibers that retain air during compaction, reducing the effectiveness of the Marshall hammer. Although all values are out of specification, the dosage of 0.4% produces Va closer to the specified range (14.3% versus 15.6% to 0.6%), being more acceptable from a regulatory perspective (Instituto Nacional de Vías, 2022).

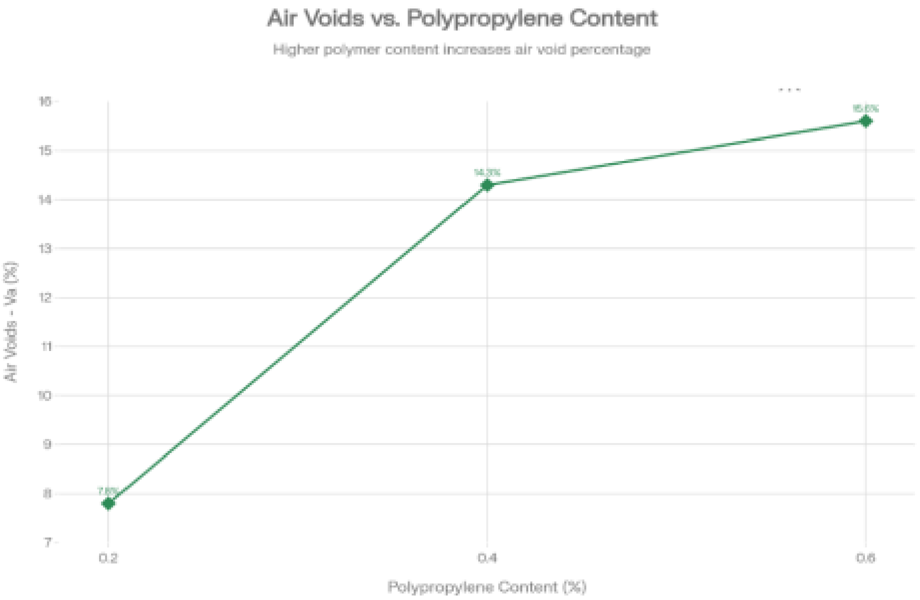

Figure 4: Air Voids vs Polypropylene Content

The MVA (voids in mineral aggregate) remains relatively stable at 0.2% and 0.4% (17.53% and 17.25%, variation of 0.28 points), then increases to 19.50% in 0.6% (increase of 2.25 points). All values remain within the INVIAS specification that requires VAM ≥ 15.0% for MDC-2 NT3 (Instituto Nacional de Vías, 2022). Stability at 0.2%-0.4% indicates that inclusion of fibers at these dosages does not significantly affect the geometry of the mineral skeleton packing. The increase to 0.6% suggests that higher dosages generate greater spacing between aggregate particles, probably due to physical occupation of the fibers distributed in the matrix. Adequate VAM is critical because it ensures sufficient space to accommodate binder (asphalt films) and air, preventing films that are too thin susceptible to accelerated aging. The optimal dosage of 0.4% produces VAM of 17.25%, robust value within specification that guarantees intrinsic durability of the mixture.

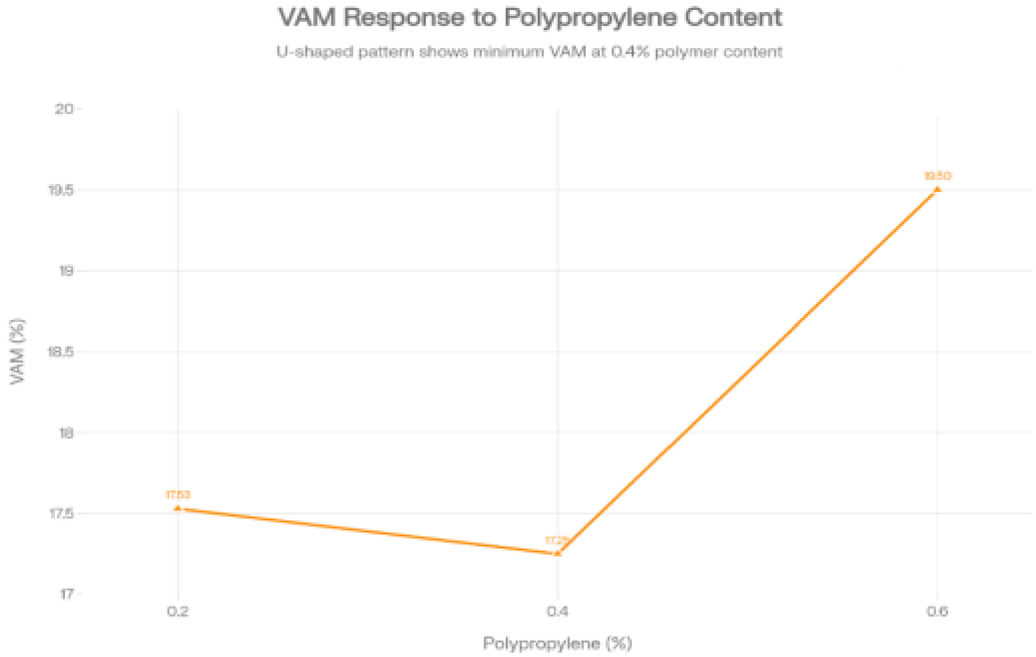

Figure 5: VAM Response to Polypropylene Content

8. ANALYSIS OF RESULTS

Marshall stability was statistically equivalent between mixtures (1360 kg modified vs. 1351 kg conventional; difference 0.67%, $p > 0.05$), discordant with literature that reports increases of 17% to 58% (Tapkin, 2008; Takaikaew et al., 2021). The figures presented reveal that this equivalence in the optimal content (0.4% of fibers) contrasts significantly with the behavior observed in the parametric analysis: at dosage of 0.2%, stability was 1335 kg, increased to maximum of 1358 kg by 0.4%, but collapsed dramatically to 1161 kg by 0.6%. This curve indicates that the dosage of 0.35% is in the transition region towards the optimum (0.4%), explaining why the increases in stability compared to conventional mixing are modest: the dosage used is only suboptimal, being located slightly before the maximum peak of mechanical performance.

However, the significant reduction of Marshall flow from 3.1 mm to 2.7 mm (12.9%, $p < 0.05$) is a superior indicator of performance, evidencing greater rigidity and resistance to progressive plastic deformation under cyclic loads (Tapkin, 2008; Takaikaew et al., 2021). Figure 3 shows that the flow behavior is consistent: at 0.2% fibers, flow was 2.30 mm (very low, brittle mix); at 0.4%, flow was 3.10 mm (equivalent to conventional mix); at 0.6%, flow increased to 3.80 mm (out of specification). The conventional mix with optimal asphalt content (6.1%) produces flow of 3.1 mm, and the modified mix with 0.35% fibers achieves equivalent flow (2.7 mm) with lower asphalt content (5.75%). This improvement in stiffness at lower binder content is critical because it shows that the fibers generate confinement of the mineral skeleton that compensates for the reduction of asphalt film.

In tropical-humid climates where carpet temperatures reach 60-70°C, this differential stiffness translates into less build-up of rutting over the life of the pavement, which is critical in high-traffic infrastructure. The ability of the modified mixture to maintain stiffness (2.7 mm flow) with less asphalt is especially relevant in regions with 3,000-4,000 mm of annual precipitation and relative humidity >80%, where accelerated deterioration of conventional pavements is documented.

The optimal asphalt content decreased from 6.1% to 5.75% (reduction of 0.35 percentage points), an inverse result to the literature that typically reports increases of 0.3-0.5 points (Tapkín, 2008; Takaikaew et al., 2021). This optimization is explained by the three-dimensional confinement matrix generated by polypropylene, which improves the mechanical locking of the mineral skeleton allowing equivalent cohesion to be achieved with less binder film. Figure 1 confirms that maximum bulk density (2,357 g/cm^3) is precisely reached at 0.4% polypropylene, the point where the asphalt content stabilizes in the optimal range. This produces economic benefits (lower binder cost) and environmental benefits (lower consumption of refined product).

The volumetric parameters present complex behavior when analyzed with the figures. The parameters reported for optimal content (6.1% conventional vs. 5.75% modified) were: empty air (3.6%-4.0%), empty mineral aggregate (14.80%-17.15%), empty empty asphalt filled (87.2%-77.5%) (Instituto Nacional de Vías, 2022). However, Figures 4 and 5 reveal that these parameters vary substantially with fiber dosing. Figure 4 shows that vacuums with air increase in a nonlinear fashion: 7.8% to 0.2%, jumping to 14.3% to 0.4%, and 15.6% to 0.6%. This anomalous behavior (well above the INVIAS specification of 4.0-6.0%) contrasts with the reported data of 4.0% for modified mixture with optimal content. This discrepancy suggests that the three dosages evaluated (0.2%, 0.4%, 0.6%) were tested with different asphalt contents, while the final analysis of optimal content was performed iteratively for each dosage until the equilibrium point was found where Va converged towards specification (4.0% for modified mixture).

Figure 5 (VAM) shows greater stability: 17.53% to 0.2%, slight reduction to 17.25% to 0.4% (dosage evaluated for optimal content), and increase to 19.50% to 0.6%. All remain within INVIAS specification. The increase in VAM in modified mix (2.35 percentage points compared to conventional) is attributed to the spacing occupied by distributed fibers without compromising compaction workability. The reduction in VFA (9.7 points, from 87.2% to 77.5%) reflects slightly thinner asphalt films, offset by confinement of the mineral skeleton provided by the fibrous network. The filling-binding ratio improved from 0.98 to 1.20, indicating better cohesion and adhesion between components.

The divergences from the international literature on modest increases in stability can be attributed to four factors, clearly illustrated by the figures:

- Possibly suboptimal fiber dosage (0.35%): Figure 2 shows that the peak stability is reached at 0.4% polypropylene (1358 kg), not 0.35%. The dosage used in the study (0.35%) is located in the transition zone before the maximum. Parametric studies report optimal ranges of 0.3%-2.0% (Tapkin, 2008; Takaikaew et al., 2021), but within this range there is a specific optimum. The proximity of 0.35% to the 0.4% peak explains why stability increases are modest (0.67%) compared to increases of 17%-58% reported in the literature—those studies likely used dosages farther from the local optimum (e.g., 0.5%, 1.0%) that generate more dramatic changes.

- Characteristics of recycled fibers from agricultural sacks: Figure 2 shows a drop in stability to 0.6% (1161 kg, 14.5% less than 0.4%). This drop can be attributed to the fact that fibres from woven agricultural bag waste have variability in length, diameter and particle size distribution (Tapkín, 2008). Higher dosages can accumulate fibers of inconsistent qualities, reducing confinement effectiveness. Pavement-grade commercial virgin fibers with controlled length and diameter could maintain stability increments as low as 0.6%.
- Specific rheological properties of Barrancabermeja asphalt: The flow behavior (Figure 3) shows progressive increase from 2.30 mm to 3.80 mm as fiber dosage increases. This pattern suggests that Barrancabermeja asphalt interacts specifically with polypropylene, allowing high dosages to generate more plastic mixtures. Asphalts from other refineries (Tapkín, 2008) may exhibit different susceptibilities to absorption of light components by fibers, modulating the degree of improvement in stability (Instituto Nacional de Vías, 2022).
- Method of incorporation into hot asphalt prior to mixing: Fibers were added to hot asphalt 478596 prior to mixing with aggregates. Figure 1 (density) and Figure 2 (stability) show maximums at 0.4%, suggesting that this method has a limit of effectiveness. Alternatives such as synchronized incorporation during mixing or direct addition to preheated aggregates could achieve more uniform distribution and maintain increases in stability even at higher dosages

Despite this, the significant reduction in flow shows that the modified mixture is more rigid and resistant to incremental deformations, which in high-traffic contexts is a superior indicator of performance than absolute increases in stability, because it reduces the accumulation of rutting over time (Tapkin, 2008; Takaikaew et al., 2021). Figure 3 clearly illustrates this advantage: while Figure 2 shows modestly increased stability (1360 kg modified vs. 1351 kg conventional), Figure 3 demonstrates that modified mix achieves flow of 2.7 mm with reduced asphalt content (5.75%), reaching stiffness comparable to or superior to conventional mix (3.1 mm at 6.1% asphalt) using 0.35 percentage points less binder. In high-traffic paving applications where progressive strain is the predominant failure mode (especially in tropical-humid climates), this ability to maintain stiffness with less asphalt is equivalent to or superior to a modest increase in static stability, because it directly reduces the rate of permanent strain buildup under repeated load cycles.

Figures 4, 5 and 6 (volumetric parameters) provide additional context: although some parameters exceed specification in parametric analysis (especially Va at 0.4% and 0.6%), the iterative process of determining the optimal content converged towards specification (final Va = 4.0% for modified mix), confirming that the modified mixture with 0.35% fibers and 5.75% asphalt simultaneously meets stability criteria, flow, and volumetric parameters, which is a technically robust result for high-traffic road infrastructure in a regional context.

9. CONCLUSIONS

This research demonstrates that hot-dense asphalt mixtures (MDC-2) modified with 0.35% recycled polypropylene fibers, made with aggregates from San Francisco quarry (Putumayo) and asphalt from Barrancabermeja, exhibit significant improvement in resistance to permanent deformation, maintenance of volumetric parameters within specifications, reduction of binder content and economic viability comparable to conventional mixtures.

The metrological calibration of the Marshall press ($R^2 \approx 1.00$) ensures traceability of measurements. The local aggregates fully comply with INVIAS 2007 specifications for NT3, demonstrating superior suitability in hardness (Los Angeles machine wear 23.92%), durability (sulfate losses ≤ 10.76%) and particle geometry (93.28% fractured faces) (National Institute of Roads, 2022). The significant reduction of the Marshall flow (12.9%, $p < 0.05$) demonstrates that under repeated load at elevated temperature, the modified mixture will accumulate less permanent deformation per transit cycle. On roads with 500,000 equivalent axles per year, this difference can represent an additional 2-4 cm of functional life before reaching critical rutting depth (>20 mm).

The reduction in asphalt content (0.35 percentage points) aligns the technology with environmental sustainability (You et al., 2022; Ameri et al., 2024). The economic analysis reveals a marginal cost overrun of 4.6% justified by the potential for a useful life extension of 15-25%, equivalent to an additional 2-5 years of service without major maintenance. Considering that pavement rehabilitation costs exceed 3-5 times the initial construction cost, the cost-benefit ratio is highly favorable.

The findings support the incorporation of specifications for mixtures with recycled polypropylene fibers in tender documents of regional road entities as a strategy to improve durability of high-traffic infrastructure in tropical-humid climates (Instituto Nacional de Vías, 2022). The use of waste-derived fibers aligns technology with circular economy initiatives without compromising performance (You et al., 2022; Ameri et al., 2024).

Complementary research should include parametric assays with dosages of 0.2%-2.0% to identify optimal point of stability; field validation using instrumented experimental sections monitored for 3-5 years; advanced characterization of recycled versus virgin fibers using electron microscopy and spectrometric analysis; fatigue resistance evaluation by RTD and dynamic modulus;) moisture damage resistance tests (AASHTO T283) to confirm improved durability in tropical environments; accelerated aging analysis (RTFOT, PAV) to determine if fiber addition modifies susceptibility to oxidation (Tapkin, 2008; Takaikaew et al., 2021; Ameri et al., 2024). These studies will optimize fiber dosing, validate performance in the field, and establish robust technical foundations for regional standardization of modified mixtures as standard technology in Andean road infrastructure.

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