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How Rubber Percentage and Size Affect Water Stability and Resistance in Hot Asphalt Pavements

Yvan Huaricallo[1*], Richards Segundo Gutiérrez Rivero[2], José Espinoza Eche[1],
Félix Santiago Sánchez Benites[1], Luis Alberto Mamani Mamani[3], Yamilet L. Condori Choque[4],
Samuel Laura Huanca[5]

[1] Academic Department of Civil Engineering, Universidad Nacional Mayor de San Marcos, Lima 07011, Peru
[2] Faculty of Engineering, Universidad Privada del Norte, Lima 07011, Peru
[3] Design Department, Airports of Peru, Lima 07011, Peru
[4] Professional Law School, Universidad Nacional del altiplano, Puno 07011, Peru
[5] Faculty of Civil Engineering, Universidad Nacional de Barranca, Lima 07011, Peru

Corresponding Author Email: yhuaricallov@unmsm.edu.pe

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ABSTRACT

The premature deterioration of asphalt pavements in urban areas, especially in contexts of an arid coastal climate such as that of Trujillo (Peru), raises the need for sustainable and technically feasible solutions. This research aimed to evaluate the effect of the percentage and granulometry of recycled rubber from end-of-life tires (ELT) on the mechanical performance of hot-dense asphalt mixtures. A two-factor experimental design was applied with three levels of granulometry (75 µm, 150 µm and 300 µm) and four percentages of addition (0%, 1%, 2%, 3%), analyzing the stability and Marshall flow, and the tensile strength ratio (TSR) as an indicator of resistance to moisture damage. The mixtures were molded and compacted in the laboratory under modified ASTM and AASHTO standards, using local aggregates and asphalt cement. The results showed that the combination of 2% recycled rubber with a grain size of 75 µm offered the best performance: stability of 13.43 kN, flow of 12.57 mm and TSR of 86.4%—values that exceed the MTC standards and international references. This combination did not affect the workability or compactness of the mix and represents a viable technical and environmental improvement. It is concluded that the use of thin rubber in moderate proportions significantly improves structural behavior and durability against moisture, with potential for practical implementation in similar urban contexts. It is recommended to evaluate its long-term behavior in real conditions and complement this evaluation with life cycle analysis to validate its integral sustainability.

1. INTRODUCTION

Globally, flexible pavements make up the majority of road surfaces, especially in developing countries, where they account for more than 90% of the road network [1-4]. However, its durability is compromised by factors such as increased heavy traffic, adverse weather conditions, and premature aging of materials, resulting in plastic deformations, fatigue cracking, and loss of adhesion [5-9]. These deteriorations significantly increase maintenance costs and affect road safety. In Latin America, and particularly in Peru, these problems are aggravated by the variability in the quality of materials and the limited application of regulatory controls in construction processes [10, 11]. In cities such as Trujillo, the situation is complicated by deficiencies in urban drainage and the infiltration of water in the lower layers of the pavement, increasing their susceptibility to moisture damage [12-15].

An emerging strategy to improve the durability of pavements and address the environmental issues associated with end-of-life tires (ELTs) is the incorporation of recycled rubber into asphalt mixtures. This practice not only improves properties such as stability and moisture resistance, but also contributes to environmental sustainability [16-18]. Several studies have explored the benefits of rubber-modified asphalt. For example, some researchers [19-21] conducted a comprehensive review on the potential of granular rubber-modified asphalt for flexible pavements, highlighting improvements in performance and longer service life, although they noted the need for further research on its environmental and economic impact during recycling. Aguila et al. [22] investigated the use of granulated rubber obtained from waste tires as a sustainable additive, observing a decrease in penetration depth with a higher rubber content, indicating an increase in the rigidity of the modified binder. At the national level, research such as that of Moreno et al. [23] evaluated the influence of recycled rubber as a modifying agent on the design parameters of asphalt mixtures, concluding that its use is safe and reliable, and that rubber particles interact with asphalt cement at temperatures higher than conventional ones, partially replicating the wet process. Ma et al. [24] studied the incorporation of recycled rubber powder in hot asphalt mixtures, determining that the addition of 10% rubber powder did not allow the desired compaction to be achieved, while the mixture with 1.5% rubber presented the best results in the Marshall parameters. Despite these advances, knowledge gaps persist, especially in relation to the combined effect of rubber percentage and particle size on key parameters such as Marshall stability, flow, and susceptibility to water, particularly in tropical and coastal contexts such as that of northern Peru. In this context, the objective of this research is to determine the influence of the percentage and particle size of rubber on the stability, flow and susceptibility to water in hot asphalt pavements, considering environmental conditions of Trujillo. To this end, a two-factor experimental design was developed, manipulating three levels of particle size (300 µm, 150 µm and 75 µm) and four levels of addition percentage (0%, 1%, 2% and 3%), keeping the optimal dosage of asphalt cement constant. Standardized methods such as the Marshall test and the moisture resistance test (AASHTO T 283), with statistical analysis of variance (ANOVA) were applied to validate the results. This research contributes to closing the scientific gap on the combined effect of granulometry and proportion of recycled rubber in asphalt mixtures, providing replicable technical evidence that allows optimizing the design of modified mixtures for similar urban contexts in coastal areas. It is also aligned with the UN's Sustainable Development Goals (SDGs), particularly SDG 9: Industry, Innovation and Infrastructure, by promoting more sustainable and resilient construction technologies, and SDG 12: responsible consumption and production, by promoting the recycling of solid waste with a high environmental impact such as ELTs.

2. METHODOLOGY

2.1 Type and focus of research

This research was developed under a quantitative approach, with explanatory and applied scope. It is classified as applied because it uses technical-scientific knowledge to solve a specific problem of road infrastructure through the use of recycled waste rubber from ELT. It is also explanatory, since it seeks to determine the causal effect of two independent variables: percentage and particle size of rubber, on three fundamental dependent variables in the performance of asphalt mixtures: Marshall stability, flow and moisture resistance.

2.2 Research design

A fully randomized, two-factor experimental design was used, in which three levels of rubber particle size (300 µm, 150 µm, and 75 µm) and four levels of rubber percentage to aggregate weight (0%, 1%, 2%, 3%) were manipulated. These sizes were selected for their commercial availability and because they represent critical ranges identified in recent literature [20, 21]. In total, 12 experimental treatments were generated, for which three briquettes were developed for Marshall testing and three duplicates for moisture resistance testing, adding up to a total of 72 cylindrical specimens.

2.3 Population and sample

The target population was hot asphalt mixtures used in urban paving in the city of Trujillo, a region characterized by an arid coastal climate, moderate-high traffic and thermal conditions that influence the behavior of asphalt.

The experimental sample consisted of cylindrical specimens of 101.6 mm in diameter and 63.5 mm in height, molded under controlled conditions according to ASTM D6926. Stone aggregates from a certified quarry were used, selected based on their granulometry, hardness and absorption.

2.4 Preparation of materials

PG 64-22 asphalt cement, with 60/70 penetration, was previously characterized in the laboratory. Its optimal content was experimentally determined at 4.7%, evaluating stability, void, flow and density curves. The aggregates were designed according to the Fuller curve.

The recycled rubber came from locally harvested ELTs. It was processed by mechanical crushing and sieved with ASTM meshes to obtain the desired fractions (300 µm, 150 µm and 75 µm). It was stored in dry conditions and weighed with a 0.01 g precision digital scale before being incorporated into the mixture.

2.5 Laboratory procedures

The modified Marshall procedure was applied. The mixture of asphalt cement with aggregates and rubber was carried out at 145-160°C, controlled by a digital infrared thermometer (maximum variation ±3°C). Compaction was carried out with 75 blows per face [25]. The evaluations included:

Marshall Stability and Flow [26].

TSR moisture resistance [27]: samples were saturated to 70% in water for 24 hours at room temperature, without the application of freeze-thaw cycles, using three conditioned and three non-conditioned briquettes per treatment, in accordance with the modified method adapted to the laboratory conditions.

Physical characterization of aggregates: absorption, specific gravity, fineness modulus, Los Angeles abrasion, magnesium sulfate, particle geometry.

2.6 Quality control and repeatability

All procedures were executed in a laboratory accredited by the National Quality Institute of Peru, under protocols of periodic calibration of equipment, temperature control and data traceability. Coded record sheets were used for each treatment, and weighing was repeated twice per sample. The tests were carried out by trained operators and supervised by a certified senior engineer.

2.7 Statistical analysis

The data obtained were subjected to a two-factor ANOVA to determine the individual and combined effect of the percentage and granulometry of rubber on the response variables. The Minitab 19 software was used, adopting a significance level of 5% ($\alpha = 0.05$). Statistical validation allowed us to identify significant differences between treatments and confirm the influence of the manipulated variables.

2.8 Ethical considerations and sustainability

The research respected the principles of scientific integrity, transparency and ethical use of resources. The reuse of hazardous waste (tires) was promoted under a circular economy approach. The experimental design avoided the waste of materials and applied safety practices in thermal and solid waste management. In addition, the possibility of replicability in similar urban regions is contemplated, aligning research with SDG 9 (resilient infrastructure) and SDG 12 (responsible production).

3. RESULTS

3.1 Characterization of aggregates

The aggregates used in the asphalt mix were evaluated according to studies [4, 7, 8]. The coarse aggregate presented a low water absorption (0.48%), good resistance to Los Angeles abrasion (20.35%) and durability to magnesium sulfate (5.47%), all within the established limits, which guarantees adequate mechanical resistance against dynamic loads. In the case of fine aggregate, a fineness modulus of 2.99 and a sand equivalent of 90.34% were obtained, indicating cleanliness and adequate granulometry for internal cohesion of the mixture.

These parameters ensure a compact internal structure that is resistant to thermal and water variations, in line with the findings of reference [1].

3.2 Determination of the optimal percentage of asphalt cement

Using the Asphalt Institute method and Fuller's particle size curve, a theoretical asphalt cement content of 4.0% was calculated. This value was experimentally adjusted in the range of 3.5% to 5.0% with increments of 0.5%, observing an inverse relationship between the binder content and the percentage of air voids. Finally, an optimal percentage of 4.7% asphalt cement was determined, which provides the best combination of stability, density and void content.

3.3 Marshall stability and flow

The results of the Marshall assay revealed that the addition of 2% rubber with a grain size of 75 µm produced the highest stability, reaching a value of 13.43 kN, compared to 10.60 kN in the control group. Similarly, the optimal flow was observed in this same configuration, with a value of 12.57 mm, higher than that of other combinations evaluated.

The ANOVA analysis showed significance values $p < 0.05$ for both variables, indicating that both particle size and rubber percentage have a statistically significant effect on the stability and flow of the mixture.

3.4 Water susceptibility (TSR)

The AASHTO T 283 method was used to evaluate moisture resistance. The best tensile strength ratio was achieved with the modified mixture with 2% 75 µm rubber, reaching a TSR of 86.4%, far exceeding the minimum of 80% established as acceptable. This result validates the hypothesis that a fine granulometry improves the integration of the rubber with the binder, sealing microvoids and reducing moisture entry pathways.

To determine the optimal percentage of asphalt cement according to the method established by the Asphalt Institute", we began with the estimation of the theoretical percentage of asphalt cement. This process involved the mixing of coarse and fine aggregates using Fuller's method, obtaining 49.62% of fine aggregate and 50.38% of coarse aggregate, essential values for the theoretical calculation of asphalt cement.

The method suggested by the Asphalt Institute to calculate the optimal percentage of asphalt cement in asphalt mixtures is based on the particle size analysis of the aggregates, which are combined according to the Fuller method. These parameters are used in a particular equation, which takes into account the relevant variables.

The formula used to determine the optimal asphalt cement content is as follows:

$$CA = 0.035 \times a + 0.045 \times b + k \times c \quad (1)$$

where:

•CA: Represents the estimated percentage of asphalt cement in relation to the total weight of the mixture.

•a: Corresponds to the percentage of coarse material.

•b: Indicates the percentage of sand aggregate.

•k: It is a value that varies according to the percentage of material that passes through sieve No. 200:

0.15 if between 11% and 15% of the material passes through the sieve.

0.18 if between 6% and 10% of the material passes through the sieve.

0.20 if less than 5% of the material passes through the sieve.

•c: It is the percentage of aggregate that passes through sieve No. 200.

Substituting the values obtained in this equation, a theoretical percentage of asphalt cement of 4% was calculated. Subsequently, laboratory tests were carried out to determine the practical or real percentage of asphalt cement, using a range of variation of ±1% with respect to the theoretical value, with increments of 0.5% in each case. The results obtained are presented in Figure 1.

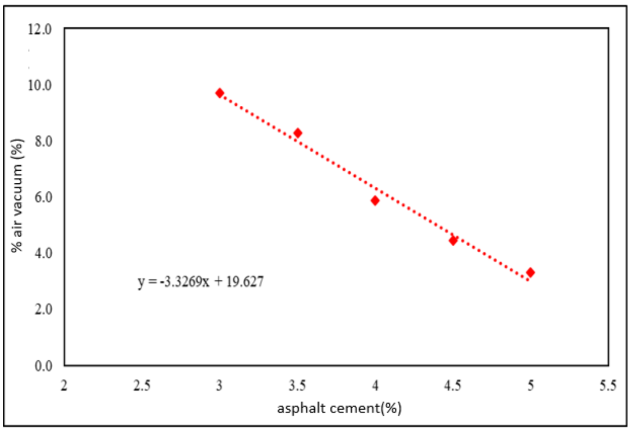

Figure 1. Percentage of air vacuums Va

Figure 2 shows an inverse correlation between the percentage of asphalt cement (%) and the percentage of air voids (%). As the asphalt cement content increases, a decrease in the percentage of air voids is observed. The linear regression model that describes this relationship is given by the equation y=−3.3269x+19.627, which suggests that, for every 1% increase in asphalt cement, air voids decrease by about 3.33%. In addition, the figure illustrates the results corresponding to the percentage of voids in briquettes made with different proportions of asphalt cement: 3%, 3.5%, 4%, 4.5%, and 5%, according to the guidelines of the Asphalt Cement Institute, it is recommended to work with 4% of voids, applying this value in the equation derived from the graph, it was determined that the optimal percentage of asphalt cement is 4.7%. This value, considered to be the most appropriate and accurate, was established as the standard for the manufacture of all the briquettes evaluated in this research.

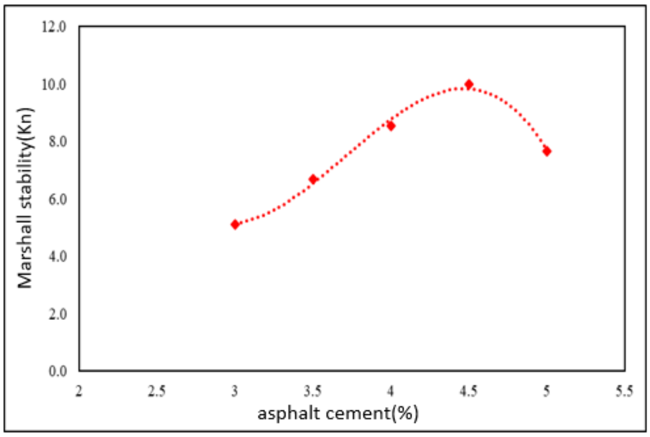

Figure 2. Marshall stability

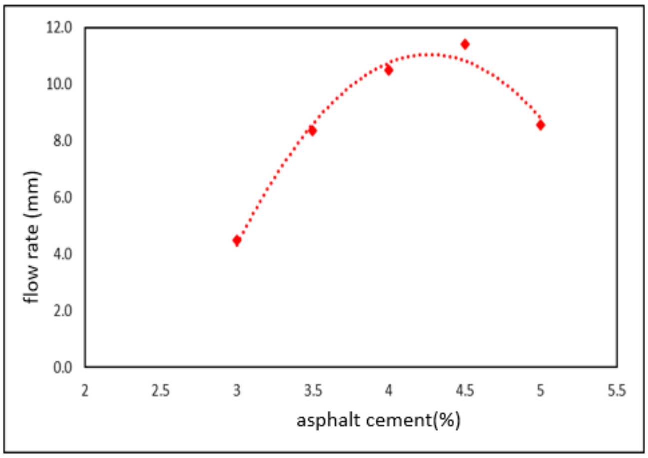

Figure 3. Marshall flow

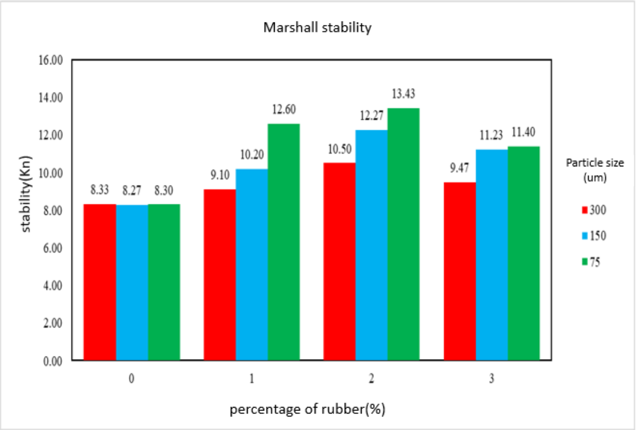

Figure 4. Marshall stability

Figure 3 shows the relationship between the percentage of asphalt cement (%) and Marshall stability (kN). As the percentage of asphalt cement increases, the Marshall stability increases until it reaches a maximum, and then decreases, this behavior suggests an optimal percentage of asphalt cement around 4.5%, where maximum stability is achieved. It is relevant to mention that the optimal percentage of asphalt cement calculated above, which was 4.7%, is among the highest stability values in this graph, which reinforces its suitability to maximize the stability of the briquettes analyzed. In addition, it is important to note that the Ministry of Transport and Communications (MTC) establishes a stability requirement of 8.15 kN for class A mixtures, in Figure 3, it can be seen that this level of stability is reached and exceeded for the percentages of asphalt cement close to 4.5%.

Figure 4 shows the relationship between the percentage of asphalt cement (%) and the flow index (mm). The observed trend is not linear. The flow index increases with the increase in the percentage of asphalt cement, reaching a maximum value of around 4%, and then decreases, this behavior suggests that there is an optimal percentage of asphalt cement that maximizes the flow in the mixture, the optimal percentage of asphalt cement, previously determined at 4.7%, is at one of the highest flow points recorded in the graph, which confirms its effectiveness in achieving a high flow rate. In addition, according to the guidelines of the MTC, the flow index for class A mixtures must be between 8 mm and 14 mm, as can be seen in the graph, the flow corresponding to 4.7% of asphalt cement is within this specified range, which validates the adequacy of this percentage to comply with the mixing standards established by the MTC.

To evaluate the effect of the percentage and particle size of rubber on the properties of the asphalt mixture, specifically on stability, flow and susceptibility to water, the figures showing the results of the stability, flow and susceptibility tests to water obtained in the laboratory are presented. Each combination of percentage and rubber size was evaluated with three replications to ensure the accuracy and reliability of the data.

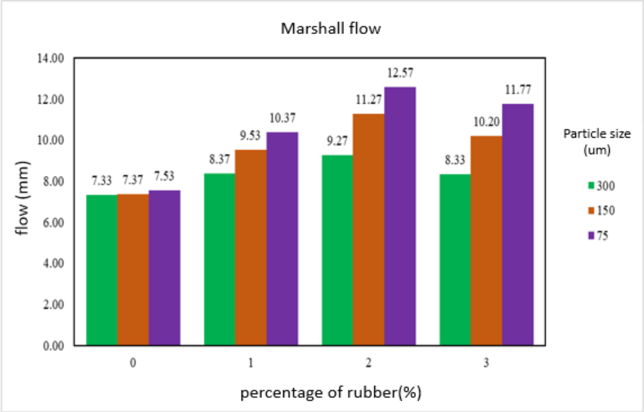

Figure 5. Marshall flow

Figure 5 shows how Marshall stability varies by incorporating different percentages and sizes of recycled rubber particles. Three sizes of rubber particles (300 µm, 150 µm, and 75 µm) were evaluated in increasing percentages of rubber (0%, 1%, 2%, and 3%), observing that without rubber (0%), the initial stability is similar with values close to 8.3 kN, which suggests a relatively uniform asphalt base in resistance, with 1% rubber, an increase in stability is observed, especially for the smallest particles (75 µm), reaching 12.60 kN, indicating that a small addition of finely crushed rubber reinforces the mixture, with 2% rubber, stability reaches its peak, with the maximum resistance observed in the smallest particle size (75 µm), reaching 13.43 kN, suggesting that this percentage and particle size are optimal to maximize the strength of the asphalt mixture. However, with 3% rubber, a reduction in stability is noted for all particle sizes, indicating that too much rubber can negatively affect the cohesion and therefore the strength of the mixture.

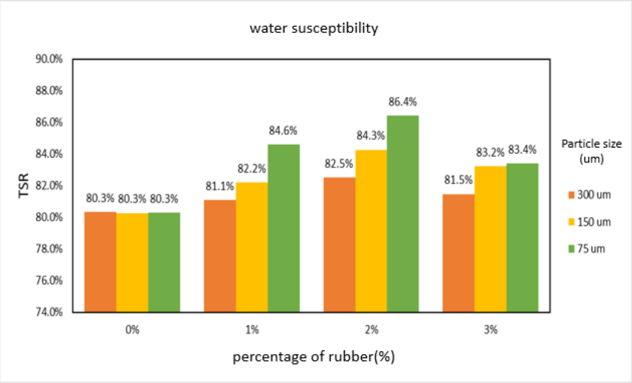

Figure 6. Susceptibility to water

Figure 6 of the Marshall flow shows how the deformability of asphalt mixtures varies when incorporating different percentages and sizes of recycled rubber particles (300 µm, 150 µm, and 75 µm). Without rubber (0%), the flow is similar, with values between 7.33 mm and 7.53 mm, indicating a consistency in the deformability of the base mix, with 1% rubber, the flow increases, reaching 10.37 mm with 75 µm particles, suggesting that the addition of finely crushed rubber increases the deformability of the mixture. This effect is intensified with 2% rubber, where the flux reaches its maximum of 12.57 mm with 75 µm particles, indicating a greater tendency to deformation under load, however, with 3% rubber, the flux decreases slightly, especially with 300 µm (8.33 mm) particles, although it remains elevated for the 150 µm and 75 µm sizes. These results indicate that both the percentage of rubber and the size of the particles affect the ability of the mixture to deform, with the smallest particles and a rubber content of 2% being the most effective in maximizing flow.

In Figure 6, the variation in susceptibility to water, measured by the tensile strength ratio (TSR), is observed by incorporating different percentages and sizes of recycled rubber particles (300 µm, 150 µm and 75 µm) in asphalt mixtures. In the mixture without added rubber (0%), the TSR remains constant at 80.3%, which suggests that the asphalt base presents a homogeneous susceptibility to water damage. By adding 1% rubber, an increase in TSR is detected, reaching a maximum value of 84.6% for 75 µm particles, which indicates an improvement in the water resistance of the mixture, this trend is intensified by incorporating 2% rubber, where the TSR reaches a peak of 86.4% for 75 µm particles, suggesting that this percentage and particle size optimize resistance to water damage, however, by increasing the proportion of rubber to 3%, the TSR decreases slightly for 300 µm particles (81.5%), although it remains relatively high for 150 µm and 75 µm particles, with values of 83.2% and 83.4% respectively. These results indicate that the addition of rubber improves water resistance in asphalt mixtures, being more effective when 2% rubber with fine particles (75 µm) is used. However, higher amounts of rubber or the use of larger particles diminish this positive effect, suggesting the need for a balance in the design of the mixture to optimize its properties.

To determine the optimal percentage of rubber addition and size over the asphalt mix to achieve an adequate balance between stability, flow, and susceptibility to water," Figure 7 is presented below, illustrating the results of the stability, flow, and water susceptibility tests, indicating that the particle size of 75 µm and a percentage of 2% recycled rubber achieved the highest values compared to the established pattern.

Figure 7 compares the different parameters measured for two types of asphalt mixtures: a mixture without added rubber (0%) and a mixture with 2% recycled rubber and particles of size 75 µm, which in the previous graphs obtained the highest values for stability, flow and susceptibility to water.

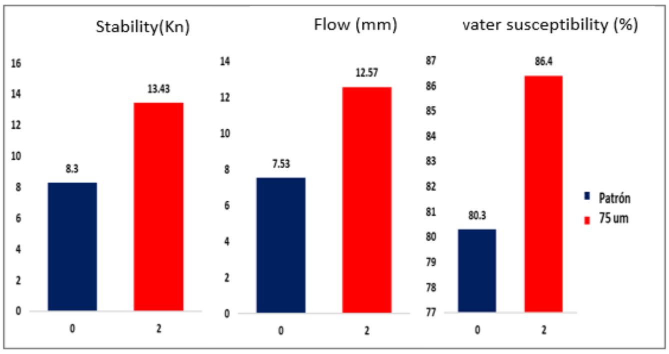

Figure 7. Stability, flow, and water susceptibility of the optimal percentage and size compared to the standard

Stability (KN): The graph on the left shows that the mixture with 2% rubber and 75 µm particles has a stability of 13.43 KN, significantly higher than the mixture without rubber, which has 8.3 KN. This represents a 61.75% improvement in mix stability with 2% rubber compared to the non-rubber mix.

Flow (mm): The graph in the center indicates that the mixture with 2% rubber and 75 µm particles has a flow of 12.57 mm, which is higher compared to the 7.53 mm flow of the mixture without rubber. Here, the improvement in flow is 67.00% in the mix with 2% rubber compared to the mix without rubber.

Water susceptibility (%): The graph on the right shows that the mixture with 2% rubber and 75 µm particles has a water susceptibility of 86.4%, while the mixture without rubber has a lower susceptibility of 80.3%. This implies an improvement of approximately 7.66% in the water susceptibility of the mixture with 2% rubber compared to the mixture without rubber.

In general, it is observed that the mixture with 2% rubber and 75 µm particles shows higher values in all the parameters measured (stability, flow and susceptibility to water) compared to the mixture without rubber, with significant improvements in each of them.

3.4.1 Statistical data analysis

The statistical analysis was carried out in order to evaluate the influence of both the percentage and size of rubber particles on the stability, flow and susceptibility to water in hot asphalt pavements. To determine whether parametric or non-parametric statistical tests were appropriate, the normality of the data obtained was checked. In this context, it was decided to use ANOVA.

For the processing of the data collected in the research, the Minitab software was used, this tool facilitates both the evaluation of the normality of the data and the execution of the ANOVA analysis, through this analysis, it was possible to identify if there were significant differences in the aforementioned variables based on the percentage and size of the rubber particles incorporated in the pavements.

Before proceeding with ANOVA, the data was checked for normality using the tools available in Minitab, such as the Q-Q chart. After confirming that the data followed a normal distribution since the p-value is greater than 0.05, the use of parametric tests was justified, thus guaranteeing the validity of the results obtained.

When going from 300 µm to 75 µm, stability increased by an average of 25.8% (from 10.67 kN to 13.43 kN), while TSR rose from 81.4% to 86.4%, evidencing a significant effect beyond the p-value.

3.4.2 ANOVA

ANOVA is a statistical methodology that allows comparing the means of several groups, identifying whether there are significant differences between them. In the present study, ANOVA was used to analyze the impact of different percentages and sizes of rubber particles, which allowed to determine which of these factors significantly influence pavement properties.

A statistical test was carried out to verify whether the percentage and size of rubber particles have a significant or equivalent effect on stability, flow and susceptibility to water in hot asphalt pavements.

For this test, two hypotheses were raised:

- Null hypothesis (H0): This hypothesis holds if variations in the percentage and size of rubber particles do not show significant differences in their effect on the stability, flow, and water susceptibility of the asphalt mixture. The null hypothesis is accepted when the p-value is greater than or equal to 0.05.
- Alternate Hypothesis (H1): This hypothesis is accepted if some combination of percentage and size of rubber particles is found to exert a significantly different effect on the stability, flow, or water susceptibility of the asphalt mixture. To accept this hypothesis, the p-value must be less than or equal to 0.05.

The results obtained from the analysis of variance tables in Tables 1-3 (ANOVA) for the properties of stability, Marshall flow and susceptibility to water revealed values below 0.05. This finding supports the acceptance of the alternative hypothesis (H1), suggesting that variations in the percentage and size of rubber particles have a significant and differentiable impact on the stability, flow, and water susceptibility of the asphalt mix.

Table 1. ANOVA for stability

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	Fo	Fα	p-value
Factor A	3	65.99	22.00	570.4	3.01	0.000
Factor B	2	26.06	13.03	337.8	3.4	0.000
Inter A × B	6	13.07	2.18	56.5	2.51	0.000
Error	24	0.93	0.04			
Total	35	106.05				

Note: The table shows the "F" value and the significance of the values of the stability.

Table 2. ANOVA for flow

Source of Variation	Degrees of Freedom	Sum of squares	Mean Squares	Fo	Fα	p-value
Factor A	3	63.72	21.24	583.7	3.01	0.000
Factor B	2	30.11	15.05	413.7	3.4	0.000
Inter A × B	6	10.32	1.72	47.3	2.51	0.000
Error	24	0.87	0.04			
Total	35	105.03				

Note: The table shows the "F" value and the significance of the flow values.

Table 3 ANOVA for water susceptibility

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	Fo	Fα	p-value
Factor A	3	76.56	25.52	666.5	3.01	0.000
Factor B	2	32.58	16.29	425.4	3.4	0.000
Inter A × B	6	16.72	2.79	72.8	2.51	0.000
Error	24	0.92	0.04			
Total	35	126.78				

Note: The table shows the "F" value and the significance of the values of the stability.

4. DISCUSSION

4.1 Characterization of the aggregates

The analysis of the coarse and fine aggregates used in hot asphalt mixtures has shown satisfactory results according to the standards of the Highway Manual and the Asphalt Institute. In terms of water absorption, the values obtained were 0.48% for coarse aggregate and 0.41% for fine aggregate. These values are significantly low, implying minimal moisture retention and therefore lower susceptibility to volumetric expansion that could compromise the structural integrity of the pavement under wet conditions [1]. This behavior is consistent with the study of Akisetty et al. [2], who also observed that aggregates with low absorption (below 1%) contribute to greater stability and durability of asphalt mixtures.

Regarding abrasion resistance (Los Angeles), coarse aggregate presented a value of 20.35%, indicating good wear resistance. This value is an indicator of the ability of the aggregates to resist the action of traffic and the movements of loads on the pavement, coinciding with the study of Akisetty et al. [2], who highlighted those aggregates with an abrasion resistance of less than 30% contribute to pavements with a longer useful life and less plastic deformation.

On the other hand, the resistance to magnesium sulfate was 5.47%, which is within the recommended values to guarantee the durability of the material in aggressive environments. In addition, 6.4% of flat and elongated particles and 24/17 of fractured faces in the coarse aggregate favor compaction and adhesion in the mixture, improving its performance under load [3].

4.2 Optimal percentage of asphalt cement

The theoretical content of asphalt cement was 4%, based on Fuller's methodology, and experimentally adjusted to an optimal value of 4.7%. A 1% increase in binder content was found to reduce air vacuums by approximately 3.33%, which is in accordance with the principles of the Marshall method. This behavior was also reported by Wen et al. [4], who identified improvements in stability as the binder content increased to an optimal point. In this case, 4.7% meet MTC requirements for class A mixtures (stability ≥ 8.15 kN).

4.3 Stability and Marshall flow

The mixture with 2% rubber and 75 µm particles reached a stability of 13.43 kN, 62% higher than the control mixture (8.3 kN). This result indicates a significant improvement in the structural cohesion of the mixture, making it more resistant to deformation. It coincides with what was reported [6], who observed structural improvements with the inclusion of recycled rubber. The Marshall flow was 12.57 mm, within the range allowed by the ASTM and MTC standards, and slightly higher than that of Fontes et al. [8], who obtained 11.5 mm with 1.5% rubber. This flow indicates good deformation capacity without loss of stability. It was observed that contents above 3% rubber, especially with particles of 300 µm, decrease the flow, reducing efficiency under load.

4.4 Water susceptibility (TSR)

The TSR value achieved was 86.4% for the mixture with 2% rubber and 75 µm particles, exceeding the minimum of 80% required by the MTC. This result shows excellent resistance to moisture, in accordance with the findings in references [5, 9], who reported improvements of up to 6% in TSR with thin rubber. Comparatively, Yang et al. [11] obtained a TSR of 83.5% with 1.5% rubber, while our result represents an improvement of 3.5%. By increasing the rubber content to 3% and using coarser particles, the TSR decreased, which could be due to internal segregation that affects cohesion and water resistance, as these authors also point out.

4.5 Balance between stability, flow and susceptibility to water

Comprehensive analysis indicates that the mixture with 2% recycled rubber and 75 µm particles achieves the best balance between stability (13.43 kN), flow (12.57 mm) and moisture resistance (86.4% TSR). This sweet spot ensures a structurally robust, flexible and water-resistant mixture. Compared to international specifications, the results achieved far exceed the minimum recommended standards. For example, the Asphalt Institute Manual (MS-2) and ASTM D6927 establish a minimum stability of 8.0 kN for mixtures subjected to medium-high traffic, a flow range between 8 mm and 14 mm, and a minimum TSR of 80%, all of which are exceeded by the optimal mixture in this study.

In addition, the TSR of 86.4% obtained is higher than that reported by Macedo and Ureta (83.5% with 1.5% rubber), Ayala (values close to 84%) and consistent with the findings [5], who observed increases of 4% to 6% when using rubber particles smaller than 150 µm. Our mixture, by using 75 µm particles, achieved an increase of 6.1% compared to the TSR of the control mixture (80.3%), empirically validating the effectiveness of the adopted design. This combination of properties allows us to conclude that the use of recycled rubber in moderate proportions and fine granulometry not only meets the technical criteria, but also offers an effective and quantifiable improvement compared to traditional mixtures and similar studies in similar climatic contexts.

4.6 Practicalities, limitations and plant operability

From a practical point of view, the mixture with 2% fine rubber (75 µm) presents an estimated 5-8% increase in production cost, mainly associated with the grinding process. However, this increase can be offset by the reduction in maintenance and greater durability of the pavement. Regarding workability, no significant difficulties were identified during mixing or compaction in the laboratory. It is noted that fine grain rubber can generate dust, so it is recommended to consider control measures in silos and hoppers of industrial plants. This size was chosen due to its commercial availability and support in the literature according to the reference [6].

Regarding limitations, this study focuses on short-term mechanical properties under laboratory conditions (Marshall, TSR), so future research should evaluate long-term behavior (aging, cracking, fingerprinting), as well as environmental impacts such as emissions and leaching. In addition, a compaction with 75 strokes was used according to the Marshall method, which, although standardized, does not completely replicate the field conditions.

5. CONCLUSIONS

The present research demonstrates that the incorporation of recycled rubber from ELT in hot-dense asphalt mixtures can significantly improve their technical performance, while contributing to an environmentally responsible solution. 2% rubber with a grain size of 75 µm was identified as the optimal combination, as it offers the best balance between structural stability, deformation capacity and resistance to moisture damage, within the limits established by technical regulations.

From a practical perspective, this alternative is feasible, as the materials used are commercially accessible and the incorporation process does not significantly alter workability or require substantial modifications to conventional blending operations. Although it implies a slight increase in costs associated with fine grinding, these can be offset by the increase in the durability of the pavement and the reduction in maintenance.

The findings obtained reinforce the potential of mixtures modified with ELT as a sustainable solution for road infrastructure in urban areas with an arid coastal climate such as Trujillo. It is recommended, as a future line of research, the evaluation of long-term behavior in real traffic and climate conditions, as well as the incorporation of life cycle analysis to quantify its integral economic and environmental benefits.

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