DOI: https://doi.org/10.46296/ig.v8i16.0302

ANÁLISIS DE LA MACROTEXTURA Y LA RESISTENCIA AL DESLIZAMIENTO EN PAVIMENTOS FLEXIBLES MEDIANTE MÉTODOS ESTANDARIZADOS

ANALYSIS OF MACROTEXTURE AND SKID RESISTANCE IN FLEXIBLE PAVEMENTS USING STANDARDISED METHODS

Moreno-Ponce Luis Alfonso [1]; Solórzano-Villegas Lucy Elizabeth [2]; Peralta-Delgado Jaime Adrián [3]; Guillén-Morales Freddy Humberto [4]

[1] Universidad Estatal del Sur de Manabí. Jipijapa, Ecuador.
Correo: luis.moreno@unesum.edu.ec. ORCID ID: https://orcid.org/0009-0000-9026-1009

[2] Universidad Estatal del Sur de Manabí. Jipijapa, Ecuador.
Correo: lucy.solorzano@unesum.edu.ec. ORCID ID: https://orcid.org/0000-0002-9903-5304

[3] Universidad Estatal del Sur de Manabí. Jipijapa, Ecuador.
Correo: jaime.peralta@unesum.edu.ec. ORCID ID: https://orcid.org/0000-0003-3830-9719

[4] Universidad Estatal del Sur de Manabí. Jipijapa, Ecuador.
Correo: freddy.guillen@unesum.edu.ec. ORCID ID: https://orcid.org/0000-0002-6240-2377

Resumen

El estudio evaluó la relación entre la macrotextura del pavimento y la fricción en condiciones húmedas en una sección flexible de la carretera El Venado (El Carmen, Manabí, Ecuador). El objetivo fue establecer una correlación cuantitativa entre la Profundidad Media de Textura (MTD) y el Número de Péndulo Británico (BPN). Se aplicaron métodos estandarizados: ASTM E965 (parche de arena) para MTD y ASTM E303 (British Pendulum Tester) para BPN. Se definieron cinco secciones de 50 m con cinco puntos por sección (n = 25), con control ambiental y calibración del instrumento. El análisis estadístico (Pearson y MCO) indicó una asociación positiva y significativa ($r = 0,91$; $R^2 = 0,83$) y un modelo lineal $BPN = 28,54 + 51,04 \cdot MTD$. Un aumento de 0,1 mm en MTD elevó BPN en aproximadamente 5,1 unidades. Los residuos exhibieron normalidad y homocedasticidad, confirmando la validez del modelo. Se concluyó que la macrotextura actuó como un predictor sólido de la fricción en pavimentos flexibles y proporciona una herramienta operativa para priorizar el mantenimiento y las auditorías de seguridad vial, y se recomienda una recalibración para diferentes gradaciones de agregados, climas y niveles de tráfico.

Palabras clave: Macrotextura; Resistencia al deslizamiento; Pavimentos flexibles; ASTM E965; ASTM E303.

Abstract

The study assessed the relationship between pavement macrotexture and wet-condition friction on a flexible section of El Venado Road (El Carmen, Manabí, Ecuador). The objective was to establish a quantitative correlation between Mean Texture Depth (MTD) and the British Pendulum Number (BPN). Standardised methods were applied: ASTM E965 (sand patch) for MTD and ASTM E303 (British Pendulum Tester) for BPN. Five 50 m sections were defined with five points per section (n = 25), with environmental control and instrument calibration. Statistical analysis (Pearson and OLS) indicated a positive, significant association ($r = 0.91$; $R^2 = 0.83$) and a linear model $BPN = 28.54 + 51.04 \cdot MTD$. A 0.1 mm increase in MTD raised BPN by approximately 5.1 units. Residuals exhibited normality and homoscedasticity, confirming model validity. It was concluded that macrotexture acted as a robust predictor of friction on flexible pavements and provides an operational tool to prioritise maintenance and road safety audits, with recalibration advised for different aggregate gradations, climates, and traffic levels.

Información del manuscrito:
Fecha de recepción: 08 de julio de 2025.
Fecha de aceptación: 18 de septiembre de 2025.
Fecha de publicación: 27 de octubre de 2025.

Keywords: Macrotexture; Skid resistance; Flexible pavements; ASTM E965; ASTM E303.

1. Introduction

Tyre–pavement friction is a determining factor in road safety, as it defines the ability of vehicles to maintain control, brake effectively, and avoid crashes, especially under adverse conditions such as wet surfaces or sharp curves (Liu et al., 2022; Xu et al., 2022). This interaction, which represents the only physical link between the vehicle and the road, directly influences stability, manoeuvrability, and braking distance (Khaleghian et al., 2017).

Various investigations have shown that a reduction in the coefficient of friction, caused by pavement wear, the presence of water, or deficient surface texture, significantly increases both the likelihood and severity of crashes. It has been evidenced, for example, that crashes on wet pavements can double the frequency of those occurring in dry conditions, and that improving skid resistance can reduce the incidence of crashes under wet conditions by up to 68% (Khaleghian et al., 2017; Pardillo Mayora & Jurado Piña, 2009).

Consequently, maintaining adequate tyre–pavement friction levels has become a priority within road infrastructure management programmes. This objective has driven the implementation of monitoring systems and the development of advanced technologies, such as smart tyres and predictive models, which enable the anticipation of risk situations and the optimisation of road design and maintenance (Chen et al., 2023; Liu et al., 2022; Zhao et al., 2024). Ensuring optimal friction is therefore recognised as an essential strategy to reduce crash rates and preserve road users' lives.

In this regard, pavement surface texture assumes a fundamental role, being composed of two complementary components: microtexture, related to microscopic surface irregularities, and macrotexture, associated with undulations perceptible to the naked eye. Both influence tyre–pavement adhesion, water drainage, and crash prevention, particularly during intense rainfall events (Costa et al., 2022; Jia et al., 2024; Luo et al., 2014).

Macrotexture promotes the evacuation of water on the pavement surface, preventing the formation of films that generate hydroplaning and loss of vehicular control. Recent studies confirm that adequate macrotexture channels water away from the contact patch, significantly reducing crash risk under wet conditions (Costa et al., 2022; Mataei et al., 2023). Microtexture, for its part, provides the initial grip between the tyre and the surface, while macrotexture maintains adhesion in the presence of water or contaminants. Both determine the coefficient of friction, whose relationship has been precisely characterised using three-dimensional laser technologie (Luo et al., 2014; Su et al., 2023).

Effective management of surface texture contributes to a proven reduction in skid-related crashes, especially on wet pavements. The progressive loss of texture increases crash risk, whereas its restoration leads to measurable decreases in crash rates (Espinoza-Molina et al., 2021; Martinez et al., 2019).

However, despite the available technical evidence, Ecuador and much of Latin America face a lack of standardised regulations and methodologies for evaluating texture and friction on pavements. This lack of harmonisation generates inconsistencies in the application of preventive measures, hinders the comparison of results, and limits the effectiveness of road safety policies (Gaibor & Carvajal, 2024; Izurieta et al., 2024; Martinez et al., 2019). In the Ecuadorian case, the transfer of competences to local governments has resulted in decentralised management but without unified national guidelines, producing disparities in the protection of road users (Izurieta et al., 2024).

At the regional level, legislative differences and the uneven application of standards have created institutional gaps that hinder road safety education and compliance with safety standards. In addition, the lack of integrated systems for collecting data on crashes and infrastructure conditions limits scientific research and evidence-based decision-making

(Espinoza-Molina et al., 2021; Martinez et al., 2019).

International experience shows that regulatory standardisation and the creation of integrated information systems are essential to strengthening road safety. Legislative harmonisation and the consolidation of unified databases constitute strategic actions to improve public policies and ensure more efficient safety management in Ecuador and the region (Gaibor & Carvajal, 2024; Izurieta et al., 2024).

From a technical perspective, organisations such as the World Road Association (PIARC), the Transport Research Laboratory (TRRL), and the American Society for Testing and Materials (ASTM) have established standardised methodologies and parameters to evaluate friction and surface texture. Among them, the International Friction Index (IFI) stands out, as it correlates measurements obtained with different devices and methods, facilitating international comparison and road safety management (Vicencio et al., 2022). These standards emphasise the joint analysis of micro- and macrotexture, since each influences anti-skid behaviour in different ways depending on climatic and operational conditions (Gao et al., 2025; Kováč et al., 2023; Vicencio et al., 2022).

Recent research has deepened the correlation between surface texture parameters and friction values on flexible pavements. Field and laboratory studies demonstrate significant correlations, especially under wet conditions (Gao et al., 2025; Kogbara et al., 2018). Parameters such as peak density, crest material volume, and effective texture depth achieve coefficients of determination (R^2) greater than 0.75. Regression models and multiscale analyses allow the prediction of anti-skid behaviour, improving the design and maintenance of safe and sustainable roads (Ding et al., 2021; Gao et al., 2025; Kogbara et al., 2018).

The study aimed to analyse the relationship between surface macrotexture and the skid resistance coefficient on flexible pavements using internationally standardised methods. Standards ASTM E965 and ASTM E303 were applied to determine mean texture depth and friction values through the sand patch and British Pendulum tests. The research was carried out on a road section in the canton of El Carmen, Manabí Province (Ecuador), in order to establish correlations between both variables and provide a replicable technical methodology that strengthens the evaluation, maintenance, and safety of flexible pavements in Latin American contexts.

The article is structured into four main sections. The Materials and Methods section describe the study area, the experimental procedures, and the technical standards used to measure macrotexture and skid resistance. The Results section presents the values obtained in the tests, the statistical analysis, and the correlation between the variables studied. In the Discussion section, the findings are interpreted in the light of previous research and international standards. Finally, the Conclusions section synthesises the study's technical contributions and proposes recommendations for the management and evaluation of pavements in Latin American contexts.

2. Materials and Methods

2.1 Research Design

The research was conducted under a quantitative, experimental, and correlational approach, aimed at analysing the relationship between surface macrotexture and the skid resistance coefficient on flexible pavements. The study was based on internationally standardised methods that ensure the reproducibility of results and their comparability with technical references from recognised organisations such as the World Road Association (PIARC), the Transport Research Laboratory (TRRL), and the American Society for Testing and Materials (ASTM).

The experimental design was structured in two complementary phases: the first consisted of field data collection, through direct tests on the pavement surface to determine mean texture depth and the friction coefficient; the second corresponded to statistical analysis and modelling of the correlation between both variables. The purpose was to establish a model that describes anti-skid behaviour as a function of texture, based on standards ASTM E965-15 and ASTM E303-22.

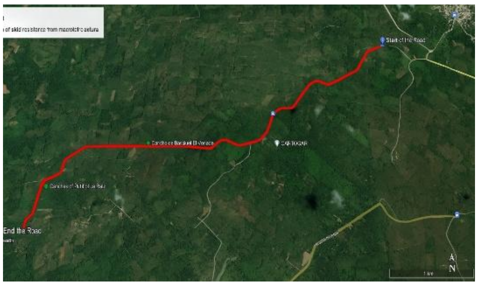
The research was carried out in accordance with principles of validity, reliability, and measurement traceability, prioritising homogeneous conditions on the analysed surface and safety criteria during testing. This methodological approach enabled the obtaining of representative results that contribute to assessing the surface performance of flexible pavements and to improving road safety management programmes at the national level.

2.2 Study Area

The study was conducted on a section of flexible pavement located on El Venado Road, part of the road network of the canton of El Carmen, in Manabí Province (Ecuador). This sector lies in a humid tropical transition zone, characterised by a mean annual temperature of 24–27 °C and an average precipitation close to 2,000 mm. These conditions create an environment prone to progressive pavement degradation, especially due to the combined action of moisture, solar radiation, and traffic loads (Figure 1).

The analysed section is approximately 250 linear metres in length and serves local connectivity and rural access functions, with mixed traffic composed mainly of light and medium vehicles. The surface has a hot-mix asphalt wearing course placed over a stabilised granular base. This segment was selected for its structural homogeneity, its representativeness within the area's secondary roads, and the feasibility of conducting tests under safe and controlled conditions. Measurements were taken on a dry, clean surface, avoiding areas with potholes, recent repairs, or surface contamination that could affect test accuracy.

Figure 1. *Location map of the study area – El Venado Road, El Carmen, Manabí, Ecuador.*



Note. The red line indicates the evaluated section of the El Venado Road.

2.3 Selection of Sections and Sampling Points

The selection of test points was carried out according to criteria of uniformity, representativeness, and operational safety, in accordance with the recommendations of ASTM E965-15 for determining surface texture and ASTM E303-22 for measuring friction. The study section was divided into five 50-metre sections, with the aim of representing variations in texture and ageing within the pavement.

In each section, five independent measurement points were established, distributed transversely between the wheelpaths and the carriageway centreline, with an average longitudinal spacing of 10 metres between consecutive points. This scheme yielded a total of 25 observations, sufficient for the statistical correlation analysis between Mean Texture Depth (MTD) and the British Pendulum Number (BPN). Before each test, the surface was cleaned and the absence of contaminants, dust, or visible moisture that could affect the results was verified.

2.4 Equipment and Measurement Procedures

Two complementary standardised measurement methods were used to characterise the pavement surface: the sand patch test (ASTM E965-15) to determine macrotexture, and the British Pendulum Test (ASTM E303-22) to measure skid resistance or friction under wet conditions.

The sand patch test was carried out using calibrated silica sand of uniform gradation, with a fixed volume of 25 ± 0.1 cm^3. The sand was poured onto the clean, dry surface and gently spread in circular motions until the pavement surface irregularities were filled. The diameter of the formed circle was then measured, averaging four orthogonal readings to calculate MTD using the relationship:

$$MTD = \frac{4V}{\pi D^2}$$

where V represents the volume of sand and D the average diameter of the circle. This parameter, expressed in millimetres, reflects the pavement's capacity to evacuate water and maintain tyre–surface adhesion.

The British Pendulum Tester (BPT) was applied in accordance with ASTM E303-22, using equipment duly calibrated before each testing day. The procedure consisted of releasing the pendulum from a constant height so that its rubber slider travelled over the wetted pavement surface. Five consecutive readings were taken per point, discarding the highest and lowest, and averaging the remaining three to obtain the BPN. This value represents a relative friction index, whose magnitude decreases with wear or the presence of contaminants.

A standard rubber slider (IRHD 55–60) was used, conditioned with 10 preliminary swings per point; the surface was wetted at ambient temperature (~25 °C) in accordance with ASTM E303-22. Five readings were taken, discarding the highest and lowest, and averaging the central three to obtain the BPN. Both tests were performed under controlled environmental conditions, avoiding direct sun exposure or excessive moisture, in order to ensure measurement repeatability and result reliability.

2.5 Data Processing and Analysis

The data obtained from the field tests were organised in a structured digital database, using Microsoft Excel for initial recording and Python (NumPy, Pandas, and Matplotlib libraries) for statistical and graphical analysis. Mean, maximum, minimum, and standard deviation values were calculated for both MTD and BPN.

Subsequently, the relationship between the two parameters was evaluated using Pearson's linear correlation (r), with the aim of identifying the degree of dependence between texture and friction. Likewise, a simple linear regression model was applied, taking MTD as the independent variable and BPN as the dependent variable, in order to obtain the predictive equation of friction as a function of texture.

Goodness of fit was verified using the coefficient of determination (R^2), and statistical validity was checked with a significance level of $\alpha = 0.05$. For the visual representation of results, scatter plots, trend lines, and residual analyses were generated, which allowed confirmation of model coherence and detection of possible outliers.

2.6 Validation and Quality Control

Measurements were carried out under controlled environmental conditions, following ASTM E965-15 and ASTM E303-22, to ensure the reliability of results. Tests were performed at temperatures between 25 °C and 30 °C and an average relative humidity of 70%, avoiding direct sun exposure or the presence of surface moisture. Each point was evaluated three times consecutively, averaging valid values and discarding anomalous readings. Before each testing session, calibration of the British Pendulum and the volumetric accuracy of the sand patch apparatus were verified, ensuring pavement cleanliness and uniform testing conditions.

Quality control included metrological traceability of measurements and cross-comparison between operators to verify reproducibility. Data were statistically reviewed using the coefficient of variation (CV) and outlier detection, eliminating those that exceeded 10% variation with respect to the mean. This procedure ensured the validity, consistency, and reliability of the experimental results, strengthening the methodological robustness of the study.

3. Results and discussion

3.1 Descriptive analysis of texture and friction

he descriptive analysis made it possible to characterise the pavement surface behaviour based on the measured values of Mean Texture Depth (MTD) and British Pendulum Number (BPN) in the five sections of the studied stretch. n = 25 observations were analysed (5 sections × 5 points), with three repetitions per point and averaging of valid readings. The results show moderate variability between sections, attributed mainly to the degree of binder ageing and to local differences in aggregate gradation. Table 1 summarises the mean values and their standard deviations; Figure 2 illustrates the joint trend between MTD and BPN.

Table 1. *Mean values of texture and friction by test section.*

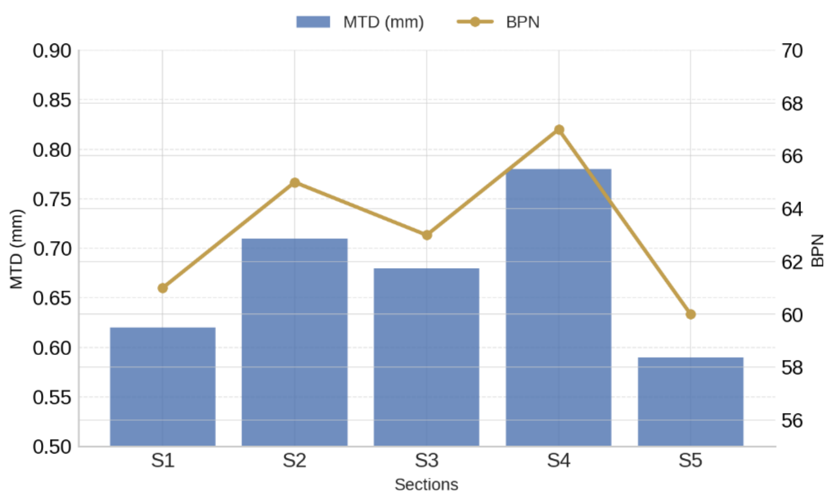
Section	Mean Texture Depth (MTD, mm)	Standard deviation MTD (mm)	British Pendulum Number (BPN)	Standard deviation BPN
S1	0,62	0,05	61	2,4
S2	0,71	0,06	65	2,1
S3	0,68	0,07	63	1,9
S4	0,78	0,08	67	2,3
S5	0,59	0,05	60	2,0
Overall mean	**0,68**	—	**63,2**	—

*Note***.** Data obtained through ASTM E965-15 (sand patch) and ASTM E303-22 (British Pendulum). The values reflect dry surface conditions, free of contaminants and representative of the pavement's service state.

The results show that MTD ranges between 0,59 mm and 0,78 mm, with an average value of 0,68 mm, which classifies the surface within the medium texture range, suitable for urban roads with mixed traffic according to the criteria of the World Road Association (PIARC, 2011). Regarding friction, BPN values vary between 60 and 67, with an overall average of 63,2, which indicates good skid resistance under wet conditions, in accordance with the classification of ASTM E303-22.

Figure 2 shows the general trend between both parameters, evidencing that sections with higher macrotexture values also tend to present an increase in friction. This preliminary relationship suggests a positive correlation between MTD and BPN, which will be analysed in greater detail in the following subsection.

Figure 2. *Average relationship between macrotexture (MTD) and friction (BPN)*



Note. The figure illustrates the average relationship between surface macrotexture (MTD) and skid resistance (BPN) across pavement test sections.

The observed values confirm a homogeneous surface condition in the analysed stretch, with no critical sections compromising user safety. The small differences detected between sections are associated with compaction level, environmental exposure, and traffic type. These results constitute the basis for the correlational analysis developed in the next subsection, aimed at quantifying the degree of dependence between surface texture and pavement skid resistance.

3.2 Correlation between macrotexture and skid resistance

The correlation analysis enabled the statistical relationship to be established between MTD and BPN obtained in the five sections of the studied stretch. The results show a positive linear correlation between both variables, indicating that an increase in macrotexture tends to improve pavement surface friction.

Table 2 presents the values of the Pearson correlation coefficient (r) and the coefficient of determination (R^2), obtained through simple linear regression, taking MTD as the independent variable and BPN as the dependent variable.

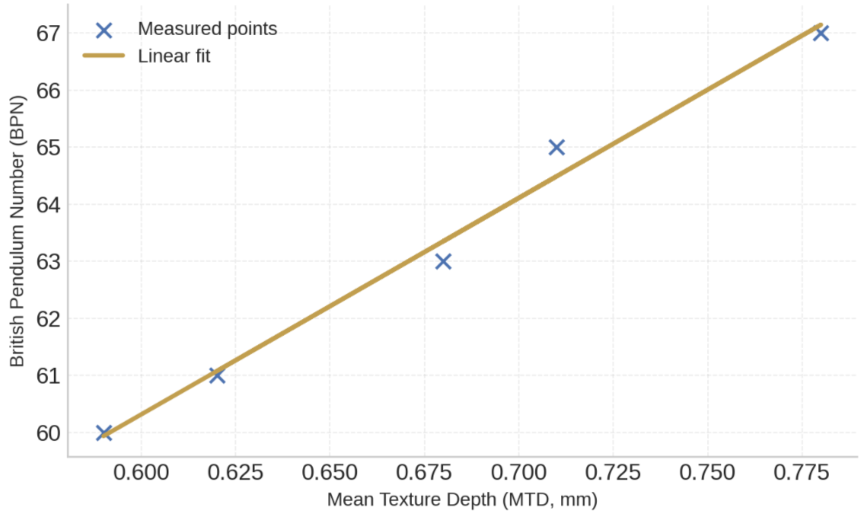
Table 2. *Results of the correlation analysis and linear fit between MTD and BPN.*

Statistical parameter	Symbol	Obtained value
Pearson correlation coefficient	r	0,91
Coefficient of determination	R^2	0,83
Linear regression equation	—	BPN = 28,54 + 51,04·MTD
Significance level	α	0,05
Sample size	n	25

Note. The analysis was performed with Python (NumPy, Pandas, SciPy), considering MTD as the predictor of friction (BPN) under wet conditions.

The graphical representation of the linear fit (Figure 3) shows the upward trend between texture and friction values, where sections with MTD greater than 0,70 mm reach BPN values above 65. This behaviour is consistent with studies by Gao et al. (2025) and Kogbara et al. (2018), which report direct relationships between macrotexture and anti-skid capacity, especially in flexible pavements exposed to tropical climates.

Figure 3. *Scatter between Mean Texture Depth (MTD) and British Pendulum Number (BPN).*



Note. A positive linear trend confirms the dependence between surface texture and skid resistance.

The results indicate that variation in macrotexture explains approximately 83% of the variability of the friction coefficient, which demonstrates that surface texture is a determining factor in the anti-skid behaviour of the pavement. The values obtained for r and R^2 fall within the range considered high correlation ($r > 0,8$) according to the technical literature (PIARC, 2011; Vicencio et al., 2022). This evidence validates the use of the MTD parameter as an indirect road safety indicator, applicable in conservation and routine monitoring programmes for flexible pavements.

3.3 Linear regression model and statistical fit

For the purpose of quantifying the relationship between macrotexture and surface friction, a simple linear regression model was fitted, considering MTD as the independent variable and BPN as the dependent variable. The analysis was performed by ordinary least squares (OLS), obtaining the equation represented in Equation 1.

$$\text{BPN} = 28{,}54 + 51{,}04 \times \text{MTD}$$

The model indicates that, for every 0,1 mm increase in MTD, BPN increases by approximately 5,1 units, which confirms a direct and significant relationship between both variables. The model coefficients were statistically significant ($p < 0{,}001$). Slope = 51,04 (95% CI: 37,8–64,3); intercept = 28,54 (95% CI: 18,9–38,2). Assumption checks showed residual normality (Shapiro–Wilk, $p > 0{,}05$) and homoscedasticity (Breusch–Pagan, $p > 0{,}05$), consistent with Figure 4. This trend agrees with the results reported by Ding et al. (2021) and Gao et al. (2025), who highlight the positive influence of macrotexture on skid resistance, especially in pavements exposed to wet conditions.

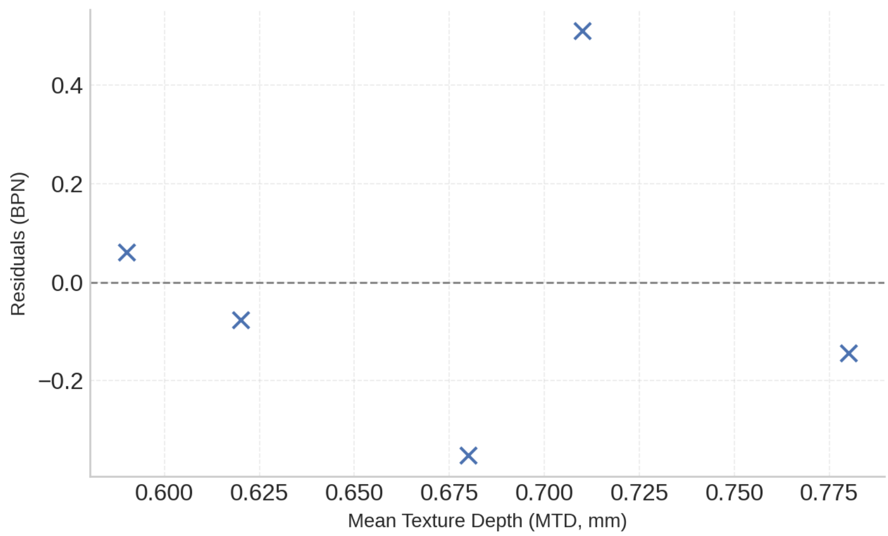
***Table 3**. OLS model coefficients and goodness-of-fit diagnostics.*

Parameter	Estimate	Standard error	*t*-statistic	*p*-value	95% CI lower	95% CI upper
Intercept	28,54	4,70	6,07	< 0,001	18,9	38,2
Slope (MTD)	51,04	6,61	7,72	< 0,001	37,8	64,3

Model diagnostics: $R^2 = 0,83$; Shapiro–Wilk (residuals) $p > 0,05$; Breusch–Pagan $p > 0,05$. Note. OLS with MTD as predictor of BPN. Values consistent with Figure 4 (residuals).

The statistical analysis yielded a coefficient of determination (R^2 = 0,83), which implies that the variability of BPN is 83% explained by MTD. The residual plot (Figure 4) shows a random distribution, without defined patterns, which supports the linearity of the model and the stability of variance. The coefficients were calibrated on a single stretch with a texture range of 0,59–0,78 mm; extrapolation to other gradations, traffic levels, or climates requires local recalibration.

***Figure 4.** Residual distribution of the MTD–BPN linear regression model.*



Note. Residuals show random dispersion, confirming model validity and absence of systematic bias.

The robustness of the model makes it a practical tool for estimating skid resistance from macrotexture measurements, optimising functional pavement evaluation. However, its validation is recommended on stretches with different traffic characteristics, gradations, and binder ageing, in order to adjust the model coefficients to broader local contexts.

3.4 Technical interpretation of the results

The results obtained confirm that pavement surface macrotexture exerts a determining influence on skid resistance, especially under wet conditions. The strong correlation (r = 0,91; R^2 = 0,83) shows that moderate increases in MTD generate significant improvements in BPN, which translates into a higher level of operational safety for users. This behaviour is consistent with international research that highlights the importance of texture in preventing hydroplaning and loss of adhesion (Gao et al., 2025; Kogbara et al., 2018; Vicencio et al., 2022).

From a functional standpoint, macrotexture acts as a natural surface drainage mechanism, reducing water accumulation and facilitating effective tyre contact. MTD values between 0,60 mm and 0,80 mm, as observed in this study, are considered optimal for flexible pavements with medium urban traffic, ensuring a balance between comfort, noise, and friction (PIARC, 2011). However, textures below 0,50 mm tend to generate loss of adhesion, while excessive values may increase tyre wear or the level of perceived roughness by the user.

The prediction of friction from macrotexture offers a practical tool for maintenance management, especially in networks where friction measurement equipment is limited or costly. The proposed linear model allows anti-skid performance to be estimated through rapid, low-cost measurements, contributing to the technical prioritisation of preventive interventions. In line with the guidelines of the American Society for Testing and Materials (ASTM) and the World Road Association (PIARC), these results support the integration of texture parameters into road safety audit systems and functional pavement maintenance (Ding et al., 2021; Espinoza-Molina et al., 2021).

Taken together, the findings reinforce the need to incorporate surface texture assessment into pavement management programmes, not only as an aesthetic or comfort parameter, but as a risk and performance indicator. Its periodic monitoring would allow early detection of critical areas with loss of adhesion, improvement of maintenance strategies, and reduction of crash rates associated with wet pavement conditions.

Discussion

The results confirm a positive and significant relationship between macrotexture (MTD) and friction (BPN), with r = 0,91 and R^2 = 0,83, which is consistent with evidence associating moderate texture increases with improved adhesion under wet conditions (Gao et al., 2025; Kogbara et al., 2018). The estimated slope (51,04 BPN units per mm of MTD) aligns with the effect sizes reported by linear and multiscale models that link peaks, volumes, and effective texture depths with anti-skid performance (Ding et al., 2021; Gao et al., 2025). This external coherence reinforces the validity of the proposed model and its applicability to flexible pavements in humid tropical climates.

From a functional perspective, the observed interval (0,59–0,78 mm of MTD) corresponds to the medium texture recommended for balancing comfort, noise, and safety, as it promotes surface drainage and mitigates hydroplaning in wet conditions (PIARC, 2011). Translating these MTD levels into average friction values (BPN ≈ 60–67) supports the use of macrotexture as an indirect risk indicator in networks where friction instrumentation is limited, consistent with functional assessment and safety audit guidelines (Vicencio et al., 2022; PIARC, 2011). In particular, local calibration of MTD–BPN thresholds would accelerate inspections, focus preventive maintenance, and prioritise sections with loss of adhesion due to binder ageing or aggregate polishing (Ding et al., 2021).

At the methodological level, the statistical consistency of the fit (significant coefficients, normal and homoscedastic residuals) is congruent with studies that incorporate standardised ASTM protocols and section-based sampling with replication to reduce experimental dispersion (Kogbara et al., 2018; Vicencio et al., 2022). The ASTM E965 + ASTM E303 combination is suitable as a basis for routine monitoring and can be scaled with 3D profiles to capture additional micro/macro parameters (peak density, crest volume, effective texture) when greater predictive power is required (Ding et al., 2021; Gao et al., 2025).

As limitations, the model was calibrated on a single section with a restricted MTD range; therefore, extrapolation to other gradations, traffic volumes, or climates should be accompanied by recalibration and external verification. In addition, potentially influential variables (surface temperature, traffic speed, aggregate composition, microtexture, and contaminants) were not explicitly modelled and could be incorporated into multivariate or non-linear approaches (Ding et al., 2021; Gao et al., 2025). Even so, the evidence obtained shows that macrotexture is a robust predictor of friction in the evaluated context, providing quantitative criteria for functional pavement management and road safety.

Finally, it is recommended as a future line of work to integrate the MTD–BPN model into a pavement management module that incorporates intervention thresholds, time series, and cross-validation with continuous measurement equipment. In parallel, the adoption of harmonised standards (PIARC, TRRL, ASTM) will facilitate inter-network comparability and the definition of evidence-based policies, in line with regional needs for systematisation and improvement of road safety (PIARC, 2011; Vicencio et al., 2022).

4. Conclusiones

1. Surface macrotexture (MTD) showed a positive and significant relationship with skid resistance (BPN) on flexible pavements, evidenced by $r = 0{,}91$ and $R^2 = 0{,}83$. This performance confirms that moderate increases in MTD translate into measurable friction improvements under wet conditions.

2. The calibrated linear model ($BPN = 28{,}54 + 51{,}04 \cdot MTD$) indicates that a 0,1 mm increase in MTD raises BPN by ≈5,1 units, providing a predictive and operational tool to estimate friction from texture measurements obtained with ASTM E965.

3. Statistical diagnostics (significant coefficients, normal and homoscedastic residuals) support the validity of the OLS fit and its usefulness for assessing the anti-

skid behaviour of the pavement, consistent with standardised ASTM E303/E965 practices.

4. The observed texture range (0,59–0,78 mm) corresponds to medium texture suitable for roads with mixed traffic, as it promotes surface drainage and mitigates hydroplaning risks, reinforcing the relevance of controlling macrotexture as an indirect road safety indicator.

5. The practical applicability of the MTD–BPN approach is high in functional maintenance programmes: it allows prioritising interventions, targeting surface restoration, and optimising resources when continuous friction equipment is unavailable, while maintaining reproducible and comparable criteria.

6. The main limitation lies in the local calibration carried out on a single section of El Venado Road (El Carmen, Manabí) and within a restricted MTD interval; therefore, extrapolation to other gradations, traffic levels, or climates requires recalibration and external validation.

7. It is recommended to integrate periodic MTD and BPN measurements into the pavement management system, with alert thresholds and temporal monitoring, and to evaluate the incorporation of 3D parameters (peak density, crest volume, effective texture) to enhance multivariate models on more heterogeneous networks.

8. As a future line of work, it is advisable to extend the sample to different mix types, binder ages, and climatic conditions, compare with continuous friction equipment, and explore non-linear or machine-learning models that capture interactions among texture, microtexture, and environmental conditions.

Bibliografía

Asociación Mundial de la Carretera (PIARC). (2011). *Experiencia internacional en la comparación y armonización de medidas de deslizamiento y textura*. 423. https://www.piarc.org/en/order-library/3826-en-International Experiment to Compare and Harmonize Skid Resistance and Texture Measurements

Chen, X., Sathyanarayan, H., Gong, Y., Yi, J., & Wang, H. (2023). Dynamic Tire/Road Friction Estimation with Embedded Flexible Force Sensors. *IEEE Sensors Journal*, *23*(21), 26608–26619. https://doi.org/10.1109/JSEN.2023.3313002

Costa, H. L., Schille, J., & Rosenkranz, A. (2022). Tailored surface textures to increase friction—A review. *Friction*, *10*(9), 1285–1304. https://doi.org/10.1007/S40544-021-0589-Y/METRICS

Ding, S., Wang, K. C. P., Yang, E., & Zhan, Y. (2021). Influence of effective texture depth on pavement friction based on 3D texture area. *Construction and Building Materials*, *287*, 123002. https://doi.org/10.1016/J.CONBUILDMAT.2021.123002

Espinoza-Molina, F. E., Ojeda-Romero, C. F., Zumba-Paucar, H. D., Pillajo-Quijia, G., Arenas-Ramírez, B., & Aparicio-Izquierdo, F. (2021). Road Safety as a Public Health Problem: Case of Ecuador in the Period 2000–2019. *Sustainability 2021, Vol. 13, Page 8033*, *13*(14), 8033. https://doi.org/10.3390/SU13148033

Gaibor, M., & Carvajal, P. (2024). 160 A triumph and a miracle: developing and applying sub national public policy for road safety in Ecuador. *Injury Prevention*, *30*(Suppl 1), A29–A29. https://doi.org/10.1136/INJURYPREV-2024-SAFETY.70

Gao, J., Fan, J., Gao, C., & Song, L. (2025). Friction Prediction in Asphalt Pavements: The Role of Separated Macro- and Micro-Texture Parameters Under Dry and Wet Conditions. *Lubricants 2025, Vol. 13, Page 138*, *13*(4), 138. https://doi.org/10.3390/LUBRICANTS13040138

Izurieta, P., Vega, S., Maldonado, S., & Delgado, M. (2024). Análisis de intervenciones de Seguridad Vial para reducir accidentes de tránsito en Ecuador. *Revista Tecnológica - ESPOL*, *36*(2), 112–134. https://doi.org/10.37815/RTE.V36N2.1182

Jia, J., Chen, Y., Yu, Y., Zheng, X., Liang, H., Pagano, R. G., Oddone, S., Cong, L., & De Blasiis, M. R. (2024). Analysis of Road Surface Texture for Asphalt Pavement Adhesion Assessment Using 3D Laser Technology. *Remote Sensing 2024, Vol. 16, Page 1943*, *16*(11), 1943. https://doi.org/10.3390/RS16111943

Khaleghian, S., Emami, A., & Taheri, S. (2017). A technical survey on tire-road friction estimation. *Friction*, *5*(2), 123–146. https://doi.org/10.1007/S40544-017-0151-0/METRICS

Kogbara, R. B., Masad, E. A., Woodward, D., & Millar, P. (2018). Relating surface texture parameters from close range photogrammetry to Grip-Tester pavement friction measurements. *Construction and Building Materials*, *166*, 227–240. https://doi.org/10.1016/J.CONBUILDMAT.2018.01.102

Kováč, M., Brna, M., Pisca, P., Jandačka, D., & Decký, M. (2023). The Influence of Road Pavement Materials on Surface Texture and Friction. *Sustainability 2023, Vol. 15, Page 12195*, *15*(16), 12195. https://doi.org/10.3390/SU151612195

Liu, Y., Chadli, M., & Pomoni, M. (2022). Exploring Smart Tires as a Tool to Assist Safe Driving and Monitor Tire–Road Friction. *Vehicles 2022, Vol. 4, Pages 744-765*, *4*(3), 744–765. https://doi.org/10.3390/VEHICLES4030042

Luo, W., Wang, K. C. R., Li, L., Li, Q. J., & Moravec, M. (2014). Surface Drainage Evaluation for Rigid Pavements Using an Inertial Measurement Unit and 1-mm Three-Dimensional Texture Data. *Transportation Research Record*, *2457*, 121–128. https://doi.org/10.3141/2457-13

Martinez, S., Sanchez, R., & Yañez-Pagans, P. (2019). Road safety: challenges and opportunities in Latin America and the Caribbean. *Latin American Economic Review*, *28*(1), 1–30. https://doi.org/10.1186/S40503-019-0078-0/TABLES/8

Mataei, B., Nejad, F. M., & Zakeri, H. (2023). An improved multiresolution technique for pavement texture image evaluating. *Multimedia Tools and Applications*, *82*(2), 3007–3031. https://doi.org/10.1007/S11042-022-13112-7/METRICS

Pardillo Mayora, J. M., & Jurado Piña, R. (2009). An assessment of the skid resistance effect on traffic safety under wet-pavement conditions. *Accident Analysis & Prevention*, *41*(4), 881–886. https://doi.org/10.1016/J.AAP.2009.05.004

Su, B., Ye, J., Zou, X., Huang, L., & Wang, X. (2023). Effect of bionic hexagonal texture on squeezing films inside soft contacts with high adhesion and high friction. *Soft Matter*, *19*(25), 4697–4705. https://doi.org/10.1039/D3SM00154G

Vicencio, A. N., Varveri, K., Yang, Z., Pranji´c, I. P., & Deluka-Tibljaš, A. (2022). Pavement Texture–Friction Relationship Establishment via Image Analysis Methods. *Materials 2022, Vol. 15, Page 846*, *15*(3), 846. https://doi.org/10.3390/MA15030846

Xu, G., Xu, J., Shan, H., Gao, C., Ran, J., Ma, Y., & Yao, Y. (2022). The influence of the pavement friction coefficient evolution caused by traffic flow on the risk of motorway horizontal curves. *PLOS ONE*, *17*(8), e0266519. https://doi.org/10.1371/JOURNAL.PONE.0266519

Zhao, L., Zhao, H., & Cai, J. (2024). Tire-pavement friction modeling considering pavement texture and water film. *International Journal of Transportation Science and Technology*, *14*, 99–109. https://doi.org/10.1016/J.IJTST.2023.04.001