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Article

Enhancing Pavement Performance Through Organosilane Nanotechnology: Improved Roughness Index and Load-Bearing Capacity

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Abstract: The growing demand for sustainable road infrastructure requires innovative materials that enhance soil stabilization while minimizing environmental impact. This study explores the application of organosilane-based nanotechnology to improve the structural performance and durability of road corridors in Peru, offering an alternative to conventional stabilization methods. Laboratory evaluations show that the modified soil exhibits a more than 100% increase in the California Bearing Ratio (CBR), while expansion remains below 0.5%, significantly reducing moisture susceptibility. Asphalt mixtures incorporating nanotechnology-based adhesion enhancers achieved a Tensile Strength Ratio (TSR) above 80%, ensuring resistance to moisture-induced damage. Non-destructive evaluations, including the Dynamic Cone Penetrometer (DCP) and Pavement Condition Index (PCI) tests, confirm long-term durability and enhanced load-bearing capacity. Additionally, statistical analysis of the International Roughness Index (IRI) shows a mean value of 2.449 m/km, well below the technical threshold of 3.5 m/km established by Peruvian regulations. Furthermore, IRI values from other countries are also referenced. This research highlights the potential of nanotechnology to enhance pavement resilience, optimize resource utilization, and promote greener construction practices..

Keywords: nanotechnology; soil stabilization; bituminous coatings; road corridors; organosilane-based nanomaterials

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1. Introduction

The design and construction of cost-effective pavements are critical for infrastructure development, particularly in developing countries like Peru, where economic constraints and varied geographical conditions present significant challenges. Traditional methods of pavement construction, which rely heavily on specific soil characteristics and conventional materials, often lead to high costs and limited material availability [1]. Consequently, there is an urgent need for innovative approaches that can utilize locally available materials while maintaining or enhancing pavement performance [2,3]. Even though effective pavements can be constructed with current materials and methods, the strategic use of nanotechnology can enhance the durability and performance of pavements over their service life [4].

Nanotechnology offers a promising solution to these challenges [5,6]. By incorporating nanomaterials [7], such as organosilanes, into pavement construction, it is possible to significantly improve the properties of both soil and asphalt . This technology enhances the chemical bonding within the soil and between the soil and asphalt, leading to improved stabilization and durability [8]. The use of nanotechnology in pavements has the potential to revolutionize road construction, making it more sustainable and cost-effective [9].

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This paper focuses on the application of nanotechnology for stabilizing bases and bituminous layers in road corridors in Peru, specifically targeting both low and high traffic volumes. The primary objectives are to evaluate the effectiveness of nanotechnology in enhancing pavement performance and to provide a comprehensive comparison with conventional methods. By leveraging the latest advancements in nanotechnology, this study aims to propose a viable alternative that addresses the economic and material constraints in the Peruvian context.

In Peru, the construction and maintenance of road corridors spanning over 150 km are essential for regional connectivity and economic development. However, the diverse soil types and climatic conditions pose significant challenges to traditional pavement methods. The limitations of conventional materials, coupled with the high costs of importation, necessitate the exploration of innovative technologies.

Nanotechnology, through the use of organosilane compounds, offers a unique approach to soil stabilization and asphalt enhancement. These compounds create chemical bonds that significantly improve the strength, flexibility, and moisture resistance of the pavement materials [10]. The integration of nanotechnology into road construction practices can lead to longer-lasting pavements with reduced maintenance needs and lower overall costs [11,12]. Also, Nanotechnology offers advantages for improving durability and sustainability, as some cases in U.S. road infrastructure [13].

Some previous studies show that the use of nano-fly ash in flexible pavement mixes increased the rutting factor by up to 61% at 10% content, while in rigid concrete pavement, it enhanced compressive strength by 14.8% and reduced absorption by 20.1% at the same 10% content [14,15]. Other studies have shown that the asphalt binder modification by High-Density Polyethylene and Nano Clay can greatly improve the creep resistance of the asphalt mixture. Under the axial loading, asphalt mixtures of 8% HDPE and 3% NC have permanent strains two times lower than the mixture of the virgin binder [16].

The primary objectives of this study are to evaluate the use of nanotechnology for stabilizing soil bases and enhancing bituminous layers in road construction, particularly in Peruvian road corridors. The research investigates the application of organosilane compounds to improve soil stabilization and adhesion enhancers to enhance the performance of asphalt mixtures. The study compares the mechanical performance, moisture resistance, and durability of nanotechnology-enhanced pavements with conventional methods. Additionally, it assesses the impact of these technologies on pavement lifespan, maintenance needs, and cost-effectiveness. A comprehensive statistical analysis, including both descriptive and inferential methods, is conducted on the International Roughness Index (IRI) data to evaluate road smoothness and performance improvements. The results aim to provide insights into the potential of nanotechnology to offer sustainable and economically viable solutions for road construction in diverse environmental conditions.

This study poses several key research questions: First, how does the incorporation of organosilane compounds in soil stabilization affect the load-bearing capacity and moisture resistance of pavement materials? Second, to what extent do asphalt mixtures enhanced with nanotechnology-based adhesion compounds outperform conventional mixes in terms of moisture-induced damage resistance and overall durability? Finally, what impact does the application of nanotechnology have on the International Roughness Index (IRI) values of pavements, and how do these values compare with accepted quality standards? These questions will guide the research toward evaluating the effectiveness of nanotechnology in enhancing road construction materials, providing a foundation for advancing more sustainable and efficient road construction practices.

By addressing the outlined objectives, this study aims to contribute to the advancement of sustainable and cost-effective road construction practices in Peru and other regions facing similar challenges.

2. Materials and Methods

2.1. Background

In the field of civil engineering, soil stabilization is primarily used to optimize its mechanical properties, increase its load-bearing capacity, and enhance its structural stability. Additionally, this process helps regulate permeability, reduce plasticity, and extend the soil's durability. Moreover, the application of stabilizers involves a chemical modification of the material, significantly improving its physical and functional characteristics [17].

Various studies have shown that the chemical stabilization of soils, especially in expansive clays, significantly improves their properties, allowing their use as a structural layer in pavements [18]. Among the many techniques employed, the addition of lime and Portland cement has been the most commonly used for this purpose [19–21]. However, its production impacts the carbon footprint, representing a limitation for these traditional materials. This limitation, combined with the construction sector's interest in identifying improvements for optimal environmental management, drives the search for more sustainable alternatives [22], leads to the search for alternative solutions.

Other studies have explored the use of fly ash [23], biomass bottom ash [24–26] and phosphogypsum [27,28]. Likewise, various investigations have examined the use of slag, particularly that from the steel industry [29].

In recent years, nanomaterials have gained increasing interest in the field of soil stabilization due to their ability to effectively interact with expansive clay particles, primarily attributed to their high specific surface area [30,31]. Among the most commonly used nanomaterials in cementitious compounds are silicon dioxide (SiO_2), titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), and carbon nanotubes [32] .

In soil stabilization, there are several common chemical agents. In addition to lime and cement, numerous previous studies have examined the application of sodium silicate, considering this stabilization method as non-traditional. Soil stabilized with sodium silicate improves soil strength. [33]. However, when applied in powder form, it is difficult to penetrate the soil pores and even more challenging to apply in situ. [34]. For this reason, the use of nanomaterials is more effective. Among all nanomaterials, nano-SiO_2 has a high pozzolanic capacity due to its pure amorphous SiO_2 composition, which characterizes it as a high-potential material for soil stabilization [17]. The use of nano-SiO_2 particles in combination with a reduced percentage of lime or cement leads to the modification of the soil's expansive properties, as these particles result from a chemical reaction between SiO_2 and $Ca(OH)_2$ during the hydration of cement or lime [35]. The use of nano-SiO_2 for soil stabilization has a significant influence on the microstructure and the physical and chemical properties of soils [36], in addition to improving its compaction density [37,38]. When combined with cement, it significantly enhances the geotechnical properties of soils. According to various studies [39] the use of nano-SiO_2 shows an increase in the unconfined compressive strength of the soil compared to other traditional stabilizers, such as lime or cement. The use of a commercial nanomaterial, such as the Sodium Silicate-Based Admixture (SSBA), mixed with lime and soil calcium, was proposed in [40], and works as a soil stabilizer. When applied to clayey soils, it increases the CBR index by 50% and allows a reduction of 0.30 m in pavement layer thickness.

2.2. Materials

The soils used for stabilization were sourced from Loreto and Madre de Dios, regions known for their diverse soil types. Detailed characteristics of these soils, including grain size distribution, liquid limit, and plasticity index for Loreto in Peru are documented in Table 1. These soils include fine sands, silts, and clays, often considered unsuitable for conventional pavement structures.

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Table 1. Soil Classification and Properties for Selected Road and Quarry Locations in Loreto, Peru.

Identification	(% passing) No. 40	(% passing) No. 200	Liquid Limit (%)	Plasticity index (%)	SUCS Classification	AASHTO Classification
Road: Zungarococha, Km 02+000	100	93	48	21	CL	A-7-6 (23)
Road: Zungarococha, Km 09+500	100	83	50	21	MH	A-7-6 (19)
Road: El Paujil, Km 00+300	100	87	53	24	CH	A-7-6 (31)
Road: Palo Seco, Km 00+100	94	23	15	N.P.	SM	A-2-4 (0)
Road: Santa Clara, Km 04+500	100	96	67	33	MH	A-7-5 (39)
Quarry: El Varillal, Km 14+050	78	10	-.-	N.P.	SP-SM	A-3 (0)

[1] The table presents the soil classification and physical properties for various road and quarry locations in Loreto (Peru) detailing the percentage passing through sieves No. 40 and No. 200, liquid limit, plasticity index, and classifications according to the SUCS and AASHTO systems.

Table 2 further explores the soil properties found in the region of Madre de Dios. This table presents detailed information on the soil's physical properties, including grain size distribution, liquid limit, and plasticity index. The data helps in determining the specific requirements for stabilization using nanotechnology and provides a basis for comparison with conventional methods. This comparison is essential for analyzing the effectiveness of nanotechnology-based solutions in improving soil stability and enhancing the overall durability of pavements in diverse environmental conditions.

Table 2. Soil Classification and Properties for Selected Road and Quarry Locations in Madre de Dios, Peru.

Identification	(% passing) No. 40	(% passing) No. 200	Liquid Limit (%)	Plasticity index (%)	SUCS Classification	AASHTO Classification
Road: La Joya – Infierno, Km 15+800	100	89	40	20	CL	A-6 (18)
Carretera Interoceánica Sur, Km 423+750, Cantera Río Madre de Dios	16	1	N.P.	N.P.	GP	A-1-a (0)
Carretera Interoceánica Sur, Km 598+000, Savoy Quarry	100	2	N.P.	N.P.	SP	A-3 (0)
Road: Dv 166 – Tropezón, Km 06+800	100	67	32	15	CL	A-6 (8)
Road: Dv 166 – Tropezón, Km 08+800	97	69	45	18	ML	A-7-6 (12)
Road: Iñapari – Belgica, Km 00+800	100	5	-.-	N.P.	SP-SM	A-3 (0)
Road: Iñapari – Belgica, Km 01+500	98	73	30	12	CL	A-6 (7)

[1] The table presents the soil classification and physical properties for various road and quarry locations in Madre de Dios (Peru) detailing the percentage passing through sieves No. 40 and No. 200, liquid limit, plasticity index, and classifications according to the SUCS and AASHTO systems.

The stabilizing agent employed is an organosilane-based nanotechnology compound. This compound enhances the chemical bonding within the soil matrix and between the soil and asphalt, significantly improving the soil's physical properties.

For the bituminous coatings, conventional asphalt was used in conjunction with a nanotechnology-based adhesion enhancer. This additive, applied at 0.075% by weight of the asphalt, aims to improve the bonding between the asphalt and aggregate, enhancing durability and moisture resistance.

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2.3. Methods

2.3.1. Soil Stabilization

The preparation of soil samples began with air-drying and sieving to remove debris and large particles. This step was crucial to ensure that the soil samples were uniform and free of any extraneous materials that might affect the subsequent testing. Standard testing methods were employed to determine the physical properties of the soils, including grain size distribution, liquid limit, and plasticity index. These properties are essential for understanding the baseline characteristics of the soils before any stabilization measures are applied.

Following the initial preparation, the organosilane compound was added to the soil samples in varying dosages to determine the optimal concentration needed for effective stabilization. The addition of this compound required careful mixing to ensure a homogeneous distribution throughout the soil. This uniformity was vital to ensure that the additive would effectively interact with the soil particles and enhance their properties consistently across all samples.

Once the additive was thoroughly mixed, the soil samples were compacted using the Marshall method. This involved applying 75 blows per side to achieve the desired density and structural integrity of the samples. After compaction, the samples were cured at ambient temperature for seven days, allowing the stabilization processes to take full effect and achieve the necessary stability for further evaluation.

The stabilized soil samples then underwent a series of tests to evaluate their performance. These included testing for the California Bearing Ratio (CBR), expansion, and moisture sensitivity. The CBR tests were conducted after a four-day soaking period, which helped assess the load-bearing capacity and swelling characteristics of the stabilized soils. These tests provided crucial data on how well the soil would perform under real-world conditions and the effectiveness of the nanotechnology-based stabilization. In the Figure 1, the B-1 sample represents a clay that is not suitable for stabilization, while the B-2 sample represents a clay that is favorable for stabilization.

(a) (b)

Figure 1. Stabilization Suitability of Clay Samples (a) Comparison of clay samples B-1 and B-2 after immersion in water, highlighting differences in stabilization suitability. Sample B-1, labeled in red, shows characteristics unsuitable for stabilization. (b) Detailed view of the clay samples post-immersion, with sample B-2, labeled in white, demonstrating favorable characteristics for stabilization.

2.3.2. Bituminous Coating Enhancement

The preparation of the asphalt mixture began with the incorporation of a nanotechnology-based adhesion enhancer into conventional asphalt. The additive was applied at a concentration of 0.075% by weight. To ensure the additive was evenly distributed throughout the asphalt, the mixture was heated and thoroughly mixed. This process was essential to achieve a uniform consistency and optimize the interaction between the asphalt and the nanotechnology additive.

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Once the asphalt mixture was prepared, it underwent compaction and curing according to standard procedures. This step involved forming the mixture into test specimens by compacting it to the desired density, which is critical for ensuring the mechanical properties needed for performance evaluation. The specimens were then cured to allow the mixture to stabilize and set properly, providing a reliable basis for further testing.

The performance of the enhanced asphalt mixture was assessed using several tests to determine its resistance to moisture-induced damage. The primary test used was the AASHTO T-283 method, commonly known as the Lottman test. This test evaluates the asphalt's ability to resist damage caused by moisture, which is crucial for maintaining the pavement's structural integrity over time. In addition to the Lottman test, other performance tests were conducted, including measuring the tensile strength ratio (TSR) and performing visual inspections for signs of aggregate fracture and moisture damage. These evaluations provided comprehensive insights into the durability and effectiveness of the nanotechnology-enhanced asphalt mixture in real-world conditions.

2.3.3. Non-Destructive Evaluations

Eight days after the construction of the stabilized base, the Dynamic Cone Penetrometer (DCP) test was conducted to measure the in-situ resistance of the pavement. This test provided crucial data regarding the strength and stiffness of the stabilized layer. By penetrating the pavement with a cone-tipped instrument, the DCP test assessed the structural integrity of the base, offering insights into its ability to withstand loads and its overall durability.

Over a three-year period, the pavement's condition was systematically evaluated using the Pavement Condition Index (PCI) in accordance with ASTM D 6433 standards. This evaluation involved a detailed assessment of the pavement surface, examining parameters such as surface roughness, cracking, and other forms of deterioration. The PCI assessments provided a comprehensive overview of the pavement's health and performance, allowing for the identification of any degradation that may have occurred over time.

To further assess the pavement's performance, measurements of the International Roughness Index (IRI) were conducted to evaluate ride quality and comfort. These measurements were taken after three years of service to determine the long-term impact of nanotechnology on the pavement's smoothness. The IRI data offered valuable information on the road's ability to provide a comfortable driving experience and maintained surface quality, reflecting the effectiveness of the nanotechnology in preserving pavement conditions [41].

3. Results

The results of this study demonstrate the significant impact of nanotechnology on the stabilization of bases and enhancement of bituminous layers in road corridors in Peru. This section presents the findings from the laboratory tests and field evaluations, highlighting improvements in soil and asphalt properties, as well as the long-term performance of nanotechnology-enhanced pavements.

3.1. Soil Stabilization Results

3.1.1. California Bearing Ratio (CBR) and Expansion

The application of the organosilane-based nanotechnology compound significantly improved the CBR values of the stabilized soils. Table 3 summarizes the CBR and expansion results for various soil mixtures with different additive dosages. The CBR values of stabilized soils exceeded 100%, indicating a substantial increase in load-bearing capacity. Additionally, the expansion values were generally below 0.5%, demonstrating reduced susceptibility to moisture-induced swelling. For example, the mixture of 65% clay and 35% fine sand with additive F showed a CBR value of 167.7%

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and zero expansion, highlighting the effectiveness of the nanotechnology compound in enhancing soil stability.

Table 3. Effect of Additives on the CBR and Expansion of Various Soil Mixtures.

Mixture Type	Additive	CBR (0.1", 100% MDS) (%)	Expansion (%)
Mix II: Clay (65%) - Fine Sand (35%)	A	156.2	0.53
	B	102.2	0.80
Mix III: Clay (65%) - Fine Sand (35%)	F	149.9	0.28
	B	141.4	0.54
Mix II: Clay (65%) - Gravel (35%)	F	167.7	0.00
	B	90.4	0.11
Mix I: Clay (70%) - Fine Sand (30%)	C	90.9	0.00
	F	193.6	0.00
	B	136.2	0.00
Mix II: Clay (65%) - Fine Sand (35%)	C	82.9	0.00
	F	162.8	0.00
	B	103.5	0.00

[1] Table 3 presents the California Bearing Ratio (CBR) and expansion values for different soil mixtures enhanced with various additives. The mixtures consist of varying proportions of clay, fine sand, and gravel. The CBR values indicate the load-bearing capacity, while the expansion percentages reflect the moisture-induced swelling of each mixture.

3.1.2. Flexibility and Rigidity

The Marshall compaction method revealed notable differences in the flexibility and rigidity of stabilized soil samples. Figure 2 illustrates the results of the CBR test, showing that sample M-1 (flexible) recovered its shape post-penetration, while sample M-2 (rigid) exhibited deformation and cracks. These findings confirm that nanotechnology-stabilized soils can achieve the desired balance between flexibility and rigidity, essential for durable pavement bases.

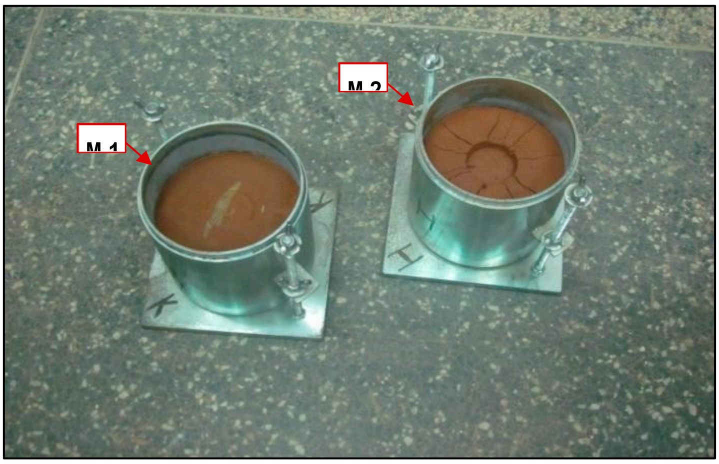

Figure 2. Samples Verification of the flexibility or rigidity of the stabilized base. The M-1 sample, after penetration, recovers its initial shape, leaving a mark due to the flexibility of the stabilized material. The M-2 sample shows deformation and cracks, which are due to the rigidity of the material.

3.2. Bituminous Coating Enhancement Results

3.2.1. Moisture-Induced Damage Resistance

The enhanced asphalt mixtures were evaluated for resistance to moisture-induced damage using the AASHTO T-283 method. Table 4 presents the results of the tensile strength ratio (TSR) tests. The

TSR values for the nanotechnology-enhanced mixtures were above the specified minimum of 80%, indicating superior resistance to moisture damage. For instance, the mixture with the adhesion enhancer exhibited a TSR value of 86.3%, confirming its enhanced durability.

Table 4. Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage.

Sample Conditioning	Dry	Wet
Average Air Voids (%)	7.0	7.2
Degree of Saturation (%)	-.-	73.6
Tensile Strength (psi)	70.34	60.68
Moisture Damage (visual)	1	2
Fractured Aggregates (visual)	Not present	Not present
Tensile Stress Ratio – TSR	86.3	

[1] This table presents a comparison of various properties of asphalt samples conditioned in dry and wet environments. The parameters include average air voids, degree of saturation, tensile strength, visual assessments of moisture damage and fractured aggregates, and the tensile stress ratio (TSR). These results highlight the impact of moisture on the structural integrity and performance of asphalt mixtures.

3.2.2. Adhesion and Cohesion

The adhesion of the bituminous layers was further assessed using the Riedel Weber method and the ASTM D 3625 boiling water test. Tables 5 and 6 present the results of these tests, showing improved adhesion between the asphalt and aggregates. The nanotechnology-enhanced asphalt demonstrated nearly complete coating of the aggregates, with adhesion values reaching up to 99% in some cases. These results indicate that the nanotechnology additive significantly enhances the bonding and overall performance of the asphalt mixture.

Table 5. Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage.

Sample Identification	Additive (% by weight of asphalt)	Result (Degree) Partial - total detachment
25% Crushed Sand 35% Natural Sand	0.066	6 - 10

[1] This table shows the effectiveness of different additives in resisting moisture-induced damage in asphalt mixtures. The table includes the percentage by weight of the additive, the resulting degree of resistance, and the observed range of partial to total detachment of aggregates in the mixtures.

Table 6. Adhesion of Bituminous Binders to Fine Aggregates.

Description	Coating (%)	Observation
Natural sample	50	
Additive (nanotechnology) at 0.1% dose	99	
Additive (nanotechnology) at 0.1% dose	98	Seawater was used
Additive (nanotechnology) at 0.05% dose	85	The liquid asphalt used for the test was
Additive (nanotechnology) at 0.1% dose	96	MC-30

[1] Table 6 presents the adhesion performance of bituminous binders to fine aggregates with various additives. The table indicates the percentage of coating achieved and includes observations such as the use of seawater or specific types of liquid asphalt, highlighting the influence of different conditions on adhesion quality.

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3.3. Non-Destructive Evaluation Results

3.3.1. Dynamic Cone Penetrometer (DCP)

The DCP tests conducted eight days post-construction revealed high in-situ resistance values for the stabilized bases. The data indicated that the nanotechnology-stabilized layers maintained their strength and stiffness over time, contributing to the overall durability of the pavement structure.

3.3.2. Pavement Condition Index (PCI)

The PCI assessments conducted over a three-year period demonstrated that pavements with nanotechnology-enhanced bases and bituminous layers maintained a "Very Good" condition rating, as shown in Figure 3. This evaluation included measurements of surface roughness, cracking, and other forms of deterioration. The sustained high PCI ratings suggest that the application of nanotechnology can significantly extend the lifespan of pavements.

Figure 3. Surface condition of pavement applying nanotechnology. This image shows a section of road that has been improved using nanotechnology in the bituminous layers and stabilized bases. The results of the Pavement Condition Index (PCI) assessments over a three-year period demonstrate that these improvements maintain a "Very Good" condition.

3.3.3. International Roughness Index (IRI)

The IRI measurements taken after three years of service showed that the pavement surfaces remained smooth, with IRI values below the project specification of 3.5 m/km. This finding indicates that the nanotechnology-enhanced pavements provided superior ride quality and comfort throughout their service life, as shown in Figure 4. The python code to generate the Figure 4 is shown in Appendix A.

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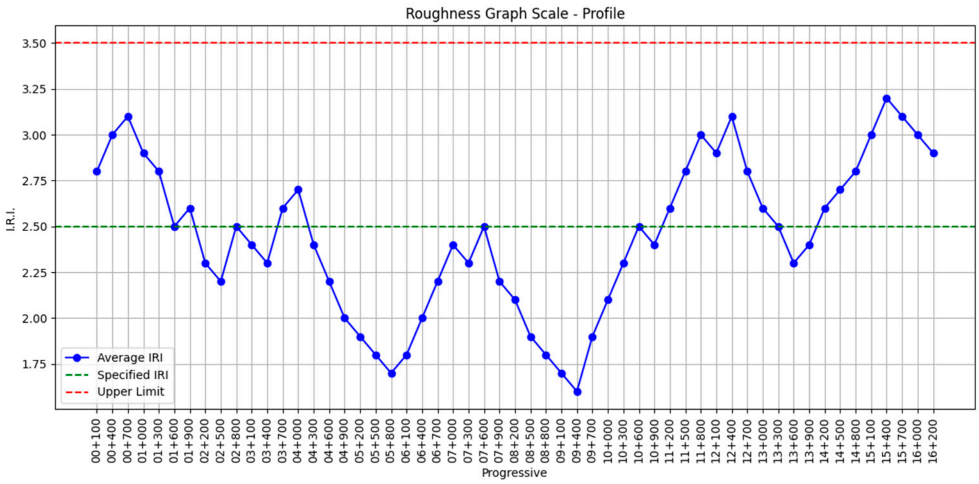

Figure 4. Roughness Graph Scale - Profile. This graph illustrates the variation of the International Roughness Index (IRI) along the road section.

The statistical analysis of the International Roughness Index (IRI) data provides insights into the road surface quality across various sections. The mean IRI value of 2.45 indicates that, on average, the road sections maintain a satisfactory level of smoothness, falling below the specified threshold. The median value of 2.5 suggests a balanced distribution of roughness, with the majority of sections offering a consistent ride quality. The standard deviation of 0.42 reflects moderate variability, indicating some differences in surface conditions, likely due to varying construction or environmental factors. Control limits are established with an Upper Control Limit (UCL) of 3.71 and a Lower Control Limit (LCL) of 1.19. All measured IRI values fall within these limits, indicating that the road sections meet acceptable standards of roughness.

Table 7. Statistical analysis of the International Roughness Index (IRI).

Statistic	Value
Mean IRI	2.449
Median IRI	2.5
Standard Deviation	0.421
Range	1.6
Upper Control Limit (UCL)	3.711
Lower Control Limit (LCL)	1.187

[1] Table 7 presents the main values of the statistical analysis of IRI in the road corridor. These statistics suggest that the road surface is generally well-maintained, with room for improvement in reducing variability to ensure uniform ride quality across all sections.

Then, to perform an inferential analysis on the International Roughness Index (IRI) data, it was necessary to conduct hypothesis testing and confidence interval estimation to draw conclusions about the overall road surface quality beyond the sample data. First, it is necessary to make a Hypothesis Testing. The objective is: Test whether the mean IRI of the road sections is significantly different from a specified standard (e.g., an IRI of 2.5, which is often used as a benchmark for acceptable road smoothness).

Null Hypothesis (H0). *The mean IRI is equal to 2.5 (H0: $\mu = 2.5$).*

Alternativa Hypothesis (H1). *The mean IRI is not equal to 2.5 (H1: $\mu \neq 2.5$).*

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To perform a hypothesis test using a t-test, you first calculate the test statistic because the sample size is small and the population standard deviation is unknown. Typically, a 5% significance level (α=0.05) is used. Next, you calculate the p-value by comparing the test statistic to a t-distribution. Finally, according to the decision rule, if the p-value is less than α, it is posible to reject the null hypothesis. The formula for the t-test statistic is given by:

$$t = \frac{\bar{x}-u_0}{s/\sqrt{n}} \approx -0.898 \quad (1)$$

where $\bar{x}$ = 2.449 is the mean IRI, $\mu0$ = 2.5 is the hypothesized mean IRI, s = 0.421 is the standard deviation, and n=55 is the sample size. Substituting the values into the formula, we get that t = -0.898, . Next, we calculate the p-value. With 54 degrees of freedom (n-1), we look up the critical t-value. The p-value associated with t = −0.898 is greater than 0.05, indicating that we fail to reject the null hypothesis. This suggests that there is no significant difference between the mean IRI and the hypothesized value of 2.5.

To construct a 95% confidence interval for the mean IRI, we use the formula:

$$Confidence\ Interval = \bar{x} \pm t\left(\frac{S}{\sqrt{n}}\right) = (2.335; 2.563) \quad (2)$$

In terms of interpretation, the hypothesis testing shows that since the p-value is greater than 0.05, we fail to reject the null hypothesis. This indicates that there is no significant difference between the mean IRI and the hypothesized value of 2.5. The 95% confidence interval for the mean IRI is (2.335, 2.563). This interval includes the standard value of 2.5, indicating that the mean IRI likely aligns with the expected smoothness standard. Based on the statistical analysis, the International Roughness Index (IRI) data suggests that the road surface is generally within acceptable smoothness standards. The mean IRI is 2.449, and the confidence interval (2.335, 2.563) indicates that the true mean IRI is likely close to these values. All the statistical data is shown in the Figure

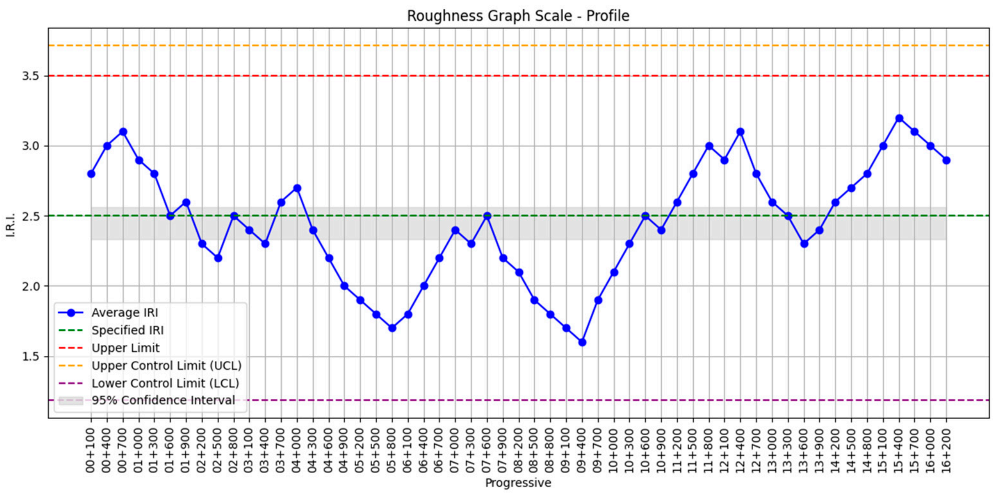

Figure 5. Enhanced Roughness Graph Scale - Profile. This graph illustrates the variation of the International Roughness Index (IRI) along the road section including.

These numbers are well below the specified maximum threshold of 3.5, suggesting that the road surface is smoother than the upper limit typically considered acceptable for ride quality.

4. Discussion

This study demonstrates the impact of organosilane-based nanotechnology compounds in increasing the California Bearing Ratio (CBR) and reducing moisture-induced expansion in stabilized soils. The results show enhanced CBR values, exceeding 100%, which suggest an improved load-bearing capacity, making these stabilized soils suitable for both low and high traffic volumes.

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The reduction in expansion values, generally below 0.5%, indicates decreased susceptibility to swelling and shrinkage caused by moisture variations. This characteristic is particularly relevant for regions experiencing high rainfall, where conventional stabilization methods often struggle to maintain pavement integrity. The ability to provide both strength and flexibility contributes to long-term pavement stability and durability.

The inclusion of nanotechnology-based adhesion enhancers in conventional asphalt mixtures improved resistance to moisture-induced damage, as demonstrated by tensile strength ratio (TSR) values consistently above the specified minimum of 80%. The Riedel Weber and ASTM D 3625 tests confirmed enhanced adhesion and cohesion between asphalt and aggregates, suggesting a reduction in issues such as stripping and aggregate loss, which are common in conventional asphalt pavements. These findings indicate potential for reduced maintenance requirements and extended pavement life.

Non-destructive evaluations, including Dynamic Cone Penetrometer (DCP) tests, Pavement Condition Index (PCI) assessments, and International Roughness Index (IRI) measurements, provided insights into the long-term performance of nanotechnology-enhanced pavements. The high in-situ resistance values observed in DCP tests confirmed the strength and stiffness of the stabilized bases, critical for supporting traffic loads over time.

PCI assessments over three years indicated that pavements incorporating nanotechnology maintained a "Very Good" condition rating, with minimal deterioration observed. Low IRI values further indicated that these pavements offered superior ride quality and comfort, which are important factors for user satisfaction.

However, it is important to mention that there is limited regulation on this aspect in Latin American countries. The average IRI value of 2.449 is below the Peruvian standard threshold of 3.0 m/km, which coincides with the Chilean standard; however, there is limited regulatory framework in other countries. In Spain, the IRI is measured in decimeters per hectometer (dm/hm), whose values numerically align with m/km. Technical Document 17.2 PG4 establishes that the IRI must meet the following thresholds: ≤ 1.5 m/km in at least 50% of the project segments, ≤ 2.0 m/km in at least 80%, and ≤ 2.5 m/km across 100% of the segments [42]. Other IRI thresholds or normative limits in other countries are presented in Appendix A.

Considering the limited investment in developing countries, there is a knowledge gap regarding the outcomes that can be achieved in terms of IRI on road corridors, especially when the evaluation is conducted by pavement segments. Additionally, the extended lifespan and reduced maintenance needs of these pavements could contribute to economic and environmental benefits [43], such as fewer disruptions for road users and lower carbon emissions associated with construction activities. The comprehensive analysis of existing studies highlights the advantages of nanotechnology in pavement construction. However, incorporating nanomaterials into asphalt mixtures presents challenges due to the limited practical application and insufficient understanding of their use [44].

Future research should focus on optimizing nanotechnology formulations and exploring their applications under different climatic and geological conditions. Long-term field studies are needed to validate laboratory findings and assess real-world performance over extended periods. Moreover, economic impacts and cost-benefit analyses of nanotechnology applications in road construction should be investigated to better understand the potential savings and efficiencies offered by this technology.

Integrating nanotechnology with emerging technologies, such as smart sensors for real-time pavement monitoring, could further enhance the durability and efficiency of road infrastructure. Collaboration among academia, industry, and government agencies is crucial for advancing these research directions and implementing innovative solutions in road construction practices. This is particularly important in developing countries like Peru, where previous studies have highlighted the need for strong policies in innovation and technology development to conduct research in nanotechnology [45]

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5. Conclusions

This study evaluated the use of nanotechnology to stabilize bases and enhance bituminous layers in Peruvian road corridors. The application of organosilane compounds resulted in a significant increase in the California Bearing Ratio (CBR) of soils, exceeding 100%, which indicates a substantial enhancement in load-bearing capacity. Additionally, expansion values were consistently below 0.5%, reducing the susceptibility to moisture-induced swelling and shrinkage. These findings highlight the effectiveness of nanotechnology in improving soil stability, making it suitable for both low and high traffic volumes.

In the asphalt mixtures, nanotechnology-based adhesion enhancers improved resistance to moisture-induced damage, with tensile strength ratios consistently above 80%. This enhancement suggests a reduction in issues such as stripping and aggregate loss. The evaluation of adhesion and cohesion, using methods like the Riedel Weber and ASTM D 3625 boiling water test, showed adhesion values reaching up to 99%, indicating superior bonding between asphalt and aggregates.

Non-destructive evaluations, including Dynamic Cone Penetrometer (DCP) tests and Pavement Condition Index (PCI) assessments, confirmed the long-term durability and strength of nanotechnology-enhanced pavements. The PCI assessments over three years demonstrated that pavements with nanotechnology enhancements maintained a "Very Good" condition rating, indicating minimal deterioration.

Statistical analysis of the International Roughness Index (IRI) further supports the benefits of nanotechnology in pavement performance. The mean IRI was 2.449, with a 95% confidence interval of (2.335, 2.563), suggesting that the road surface quality was well within acceptable standards. The hypothesis testing indicated no significant difference from the standard IRI value of 2.5, confirming that the nanotechnology-enhanced pavements provided superior ride quality and comfort throughout their service life.

These findings suggest that nanotechnology offers a viable alternative to traditional pavement methods by utilizing local materials and potentially reducing reliance on imported resources. Additional studies are recommended to optimize the formulations of organosilane compounds and adhesion additives to adapt to different soil types and climatic conditions. Customizing formulations can maximize the effectiveness and efficiency of nanotechnology solutions.

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Appendix A

The table provides a comparative overview of International Roughness Index (IRI) standards across various countries and institutions. It highlights specific procedures for measuring IRI and the established thresholds for different pavement types. The data includes limits for asphalt, hydraulic surfaces, and surface treatments, with regional variations in methodology and acceptable values. This comparison underscores the diversity in pavement evaluation criteria globally.

<table>
<tr><th>Public Institution</th><th>General Procedure</th><th>Asphalt</th><th>Hydraulic</th><th>Surface Treatments</th></tr>
<tr><td rowspan="3">Ministerio de Transportes y Comunicaciones (Peru) [46,47]</td><td rowspan="3">IRI obtained in segments of 100 m</td><td>Asphalt Concrete Pavement IRI < 2.0 m / km (Section 425 - EG 2013)</td><td rowspan="3">IRI ≤ 3.0 m/km (Section 438 - EG 2013)</td><td>Gravel Paved Surface IRI <5m /km (Section 301 - EG 2013)</td></tr>
<tr><td>Micro surfacing IRI < 2.0 m / km (Section 425 - EG 2013)</td><td>Chemically stabilized soils or with sodium chloride/magnesium chloride < 6m /km (Section 301C - EG 2013)</td></tr>
<tr><td>Asphalt Mortar IRI < 2.5 m / km (Section 420 - EG 2013)</td><td></td></tr>
<tr><td rowspan="2">Ministerio de Obras Públicas de Chile [48]</td><td rowspan="2">IRI obtained in 5 segments of 20 m in homogeneous sections</td><td colspan="2">Average of 5 segments ≤ 2.0 m/km</td><td>Average of 5 segments ≤ 3.0 m/km</td></tr>
<tr><td colspan="2">Individual Average ≤ 2.5 m/km</td><td>Individual Average ≤ 4.0 m/km</td></tr>
<tr><td rowspan="3">Ministerio de Fomento de España [42]</td><td rowspan="3">IRI obtained in segments of 100 m</td><td colspan="3">IRI ≤ 1.5 m/km in 50% of project segments</td></tr>
<tr><td colspan="3">IRI ≤ 2.0 m/km in 80% of project segments</td></tr>
<tr><td colspan="3">IRI ≤ 2.5 m/km in 100% of project segments</td></tr>
<tr><td>United States (Wisconsin Department of Transportation, WisDOT)*</td><td>IRI obtained in segments of 1.609 m (1 mile)</td><td><table><tr><th>IRI m/km</th><th>Time</th></tr><tr><td><1.1</td><td>Nev Pavement</td></tr><tr><td><1.17</td><td>1 Year</td></tr><tr><td><1.29</td><td>2 Year</td></tr><tr><td><1.33</td><td>3 Year</td></tr><tr><td><1.37</td><td>4 Year</td></tr><tr><td><1.45</td><td>5 Year</td></tr></table></td><td>-----</td><td>-----</td></tr>
<tr><td rowspan="2">Canada (Québec)</td><td rowspan="2">IRI obtained in segments of 100 m</td><td colspan="2">IRI ≤ 1.2 m/km, in 70% data</td><td rowspan="2">-----</td></tr>
<tr><td colspan="2">IRI ≤ 1.4 m/km, in 100% data</td></tr>
<tr><td rowspan="2">Sweden*</td><td>IRI in 20 m segments</td><td colspan="2">≤ 1.4 m/km</td><td></td></tr>
<tr><td>IRI in 200 m segments</td><td colspan="2">≤ 2.4 m/km</td><td>-----</td></tr>
</table>

Note: The values for the United States, Canada, and Sweden are referential and may vary depending on local specifications.

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