Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 06, June, 2025

Influence of Emulsion Type and Moisture on the Stiffness of Stabilized Granular Soil

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Received 16 February 2025; Revised 21 May 2025; Accepted 26 May 2025; Published 01 June 2025

Abstract

The objective of this study is to investigate how moisture content affects the stiffness of a gravelly-sandy soil stabilized with asphalt emulsion, considering different types of emulsion (medium- and slow-setting) and modified compaction energy. Dynamic triaxial tests were carried out to determine the stiffness of specimens at different moisture contents, considering the dry and wet branches of the compaction curve, all stabilized with 2% asphalt emulsion. The influence of moisture content and emulsion type was assessed using robust analysis of variance (ANOVA), allowing the evaluation of statistical significance and the interaction between factors. The results showed that the stiffness of the stabilized soil is strongly influenced by moisture content, with a peak value observed near the optimum moisture (~8.2%). The slow-setting (SS) emulsion achieved the best performance, reaching 938.94 MPa, representing a 452.32% increase compared to the untreated soil. The medium-setting (MS) emulsion also produced a significant stiffness gain (375.29%). Statistical analysis indicated that emulsion type was the most influential factor (Q = 1747; p = 0.001). This study contributes to the literature by experimentally and statistically demonstrating how moisture content and emulsion type affect the stiffness of stabilized soils.

Keywords: Stabilization; Resilient Modulus; Asphalt Emulsion; Robust ANOVA.

1. Introduction

Although lime and cement are widely used in soil stabilization due to their effectiveness in improving mechanical strength and durability, their environmental externalities are significant, especially because of the high CO_2 emissions associated with their production. Cement production, for instance, can emit approximately 1 kg of carbon dioxide for every 1 kg of cement produced, accounting for about 5% to 8% of global CO_2 emissions [1, 2]. Furthermore, these materials can induce chemical alterations in the soil and groundwater, such as excessive alkalinization and mobilization of heavy metals [3, 4]. In this context, asphalt emulsion emerges as a viable and less environmentally aggressive alternative, especially when properly applied. Although it is petroleum-based, its stabilizing action is predominantly physical, resulting in low geochemical reactivity and reduced risk of groundwater contamination when compared to calcium-based stabilizers. According to Silva et al. [5], once cured and properly compacted, asphalt emulsion exhibits low leaching potential, making it a technically efficient and environmentally safer solution in certain geotechnical contexts.

Additionally, its cold application contributes to reduced energy consumption during the construction process, which is relevant within the framework of Life Cycle Assessment (LCA) approaches used to compare stabilization alternatives from an environmental standpoint [6, 7]. In this sense, although emulsion is not impact-free — such as the emission of volatile organic compounds — its lower carbon footprint and minimal chemical aggressiveness to soil and groundwater

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http://dx.doi.org/10.28991/CEJ-2025-011-06-07

constitute significant advantages over traditional lime- and cement-based stabilizers. These benefits position asphalt emulsion as a promising alternative for soil stabilization in road construction, offering improvements in mechanical performance, economic efficiency, environmental benefits, and flexibility of application.

The present study aims to experimentally evaluate the influence of moisture content and emulsion type on the stiffness of a gravelly-sandy soil stabilized with 2% asphalt emulsion under modified compaction energy. To this end, the soil was prepared with three different moisture contents, varying between 5%, 8.2%, and 11%, and stabilized with both medium-setting (MSE) and slow-setting (SSE) asphalt emulsions. The samples were then compacted using modified energy to ensure adequate density and granular structure. The tests were conducted in a cyclic triaxial apparatus, applying repeated loading cycles with confining stresses (σ3) ranging from 0.02 MPa to 0.14 MPa and deviatoric stresses (σd) from 0.02 MPa to 0.42 MPa, with stress ratios (σd/σ3) varying from 1 to 3. The Resilient Modulus (RM) was calculated based on the relationship between deviatoric stress and the recoverable elastic strain, thus allowing comparison of RM across different moisture conditions and stabilization types using Robust ANOVA. By integrating mechanical testing, image-based granulometry, and robust statistical analysis, this study provides a comprehensive framework for understanding and optimizing the stiffness of emulsion-stabilized soils, offering practical insights for pavement engineering applications.

Robust ANOVA is a reliable extension of traditional ANOVA, ideal for cases where normality and homogeneity of variance assumptions are violated. By employing trimmed means and robust variance estimators, it minimizes the influence of outliers and asymmetric distributions, thereby preserving the statistical reliability and validity of the results.

A detailed literature review (Section 2) reveals that most studies focus on evaluating the resilient modulus (RM) and permanent deformation of emulsion-stabilized mixtures, considering different emulsion contents and curing conditions. However, a few studies systematically investigate the impact of moisture, both in the dry and wet branches, on the final stiffness of mixtures, particularly when using modified compaction energy. This gap is significant, as the initial moisture content can substantially affect the dispersion and curing of the emulsion, directly influencing the mechanical performance of the mixture.

Given these gaps, this study contributes to filling the existing research void by expanding the scientific understanding of how moisture variation—particularly in the dry and wet branches of the compaction curve—affects the stiffness of soils stabilized with asphalt emulsion. Through a comparative evaluation of emulsion types (medium-setting and slow-setting) and moisture levels, combined with the application of modified compaction energy, the research advances the knowledge frontier in geotechnical engineering regarding bituminous stabilization. The use of Robust ANOVA further reinforces this contribution by enabling statistically reliable analyses even when classical assumptions of normality and homogeneity of variance are not met. Additionally, the study incorporates quantitative granulometric analysis through computer vision techniques, providing a detailed characterization of the material and its influence on mechanical behavior. The expected outcomes include the identification of optimal stabilization conditions and insights into the long-term performance of treated soil under repeated loading cycles, thereby contributing to the development of resilient, efficient, and sustainable pavement base layers.

Additionally, the study innovates by employing quantitative image analysis through computer vision techniques. The use of Python and specialized libraries (OpenCV, NumPy, and Matplotlib) enabled the extraction of fundamental soil granulometry metrics, such as grain count, occupied area, average diameter, variance, and standard deviation of the grains. This approach allowed for a more detailed characterization of the material and its relationship with mechanical properties. Computational methodology enhances precision in granulometric analysis, reducing human error and increasing result reproducibility.

It is important to emphasize that this experiment used two commercially available cationic emulsions (not special formulations). Additionally, the tests focused solely on their effects on material stiffness. Therefore, complementary tests are necessary to ensure the safe use of stabilized soil in pavement applications, considering other performance aspects such as durability, resistance to environmental conditions, and long-term behavior under traffic loads. Due to the heterogeneous nature of soils, achieving standardization is challenging, necessitating further research to make this goal attainable. This study contributes to the advancement of soil stabilization techniques for their application in pavement engineering.

The remainder of this paper is structured as follows: Section 2 reviews the relevant literature on soil stabilization and resilient modulus behavior; Section 3 details the materials, experimental setup, and statistical procedures; Section 4 presents and discusses the experimental results; and Section 5 concludes with the study's key findings and recommendations for future research.

2. Literature Review

The analyzed studies present relevant contributions to various areas of civil engineering, particularly concerning soil stabilization, recycled mixtures, sustainability, modeling, and material evaluation for roadway infrastructure.

One of the primary approaches identified is the use of asphalt emulsion and other stabilizers to enhance the mechanical properties of soils and recycled materials used in road infrastructure. Liu et al. [8] investigated the application of polymer emulsions in stabilizing expansive clay soils collected from a construction site in Victoria, Australia, at a depth of 1 to 2 meters. Before compaction, the soil was oven-dried at 105°C for three days. Following the AS 1289.6.1.1 [9] standard, the soil underwent a four-day pre-curing period inside a sealed plastic bag, ensuring uniform moisture distribution among soil particles. This procedure is recommended for highly plastic soils with a liquid limit exceeding 50%. After pre-curing, an ethylene-vinyl acetate (EVA) copolymer emulsion was mixed into the pre-moistened soil in five different proportions. The samples were compacted using the Standard Proctor compaction test, according to AS 1289.5.1.1 [10].

The inclusion of Ethylene-Vinyl Acetate (EVA) polymer emulsion in the expansive soil significantly increased its resilient modulus (RM). Specifically, adding 1% EVA resulted in the highest resilient modulus (79.02 MPa) compared to the untreated soil (58.17 MPa). This increase in resilient modulus is attributed to the EVA emulsion's ability to fill voids between soil particles, coat their surfaces, and increase the viscosity of pore fluid, promoting stronger interparticle interlocking. However, the study also highlighted that excessive emulsion content (above 1%) significantly reduced the resilient modulus (to 33.55 MPa with 2% EVA), as the excess emulsion acted more as a lubricant than a cementing stabilizer, reducing soil strength by facilitating clay particle slippage.

The study by de Medeiros et al. [11] analyzed the stabilization of a silty sand (SM) soil with a slow-setting cationic asphalt emulsion (SS-1C), evaluating its influence on stiffness and mechanical strength under cyclic loading. Stabilization demonstrated positive effects on soil cohesion, reducing its tendency to disaggregate and increasing its indirect tensile strength. However, excessive emulsion content compromised stiffness, leading to increased plastic deformation over repeated loading cycles. The optimal emulsion content was identified at 2%, ensuring a balance between strength and resilient deformation. For emulsion contents above 2%, greater deformability was observed, indicating that excessive emulsion acts more as a lubricant than a cementing stabilizer. Compaction was performed with intermediate energy, applying 27 blows per layer in 10 layers within a split mold, simulating low-traffic pavement conditions. Laboratory tests included diametral compression to determine the optimal emulsion content, repeated triaxial loading with multiple loading stages (50,000 cycles), and evaluation of permanent deformation and resilient modulus. This research contributes to the understanding of asphalt emulsion-stabilized soils, reinforcing the need for an appropriate emulsion content to avoid excessive stiffness loss. Furthermore, while stabilization improved soil stiffness and cohesion, permanent deformation remained high, suggesting that formulation adjustments, such as combining emulsion with other stabilizers, may be necessary to optimize mechanical performance.

Chilufya et al. [12] incorporated biochar (a porous, carbon-rich material obtained through the thermochemical conversion of biomass, plant, or organic waste, typically via a process called pyrolysis. Pyrolysis occurs when biomass is heated to temperatures between 350°C and 700°C in a low-oxygen environment, resulting in highly stable and porous carbon. This material is widely studied for its ability to sequester carbon, contributing to climate change mitigation by storing carbon stably in the soil for long periods. Additionally, its unique structural properties help improve the mechanical and environmental characteristics of stabilized materials.) into asphalt emulsion for stabilizing lateritic soils, demonstrating both structural and environmental benefits.

The lateritic soil was oven-dried at 105°C for three days. After cooling, it was mixed with its optimum moisture content. Biochar was added in three proportions: 3%, 5%, and 7%. The asphalt emulsion was applied in proportions of 3.6%, 4.2%, 4.8%, and 5.4% (biochar-to-emulsion ratios of 1:1.2, 1:1.4, 1:1.6, and 1:1.8). The samples were cured in an oven at 40°C for three days before testing. The resilient modulus (ITM - Indirect Tensile Method) test samples were compacted with 75 Marshall blows on each end of the specimen using a Marshall drop hammer. The sample diameter was 101 mm. Under dry conditions, the highest resilient modulus was achieved with a biochar-to-emulsion ratio of 1:1.6. Under wet conditions, the best ratio was 1:1.4, indicating that moisture reduces the stiffness of stabilized material. The study demonstrated that emulsion addition improved soil strength, but an optimal content exists—excessive emulsion can compromise stiffness.

Medeiros et al. [13] evaluated the stabilization of a silty sand soil (SM, A-2-4) with RL-1C asphalt emulsion, analyzing its impact on the resilient modulus (RM) and permanent deformation (PD). Results indicated that emulsion addition significantly improved soil stiffness, with average RM increases of 68.04% for 2% emulsion and 90.32% for 3% emulsion compared to the untreated soil. However, despite the initial strength gain, mixtures with higher emulsion contents exhibited a progressive increase in PD over repeated loading cycles, suggesting an optimal stabilization limit. The best mechanical performance was achieved with 2% emulsion, ensuring a balance between strength and accumulated deformation. Tests included resilient modulus (RM) and permanent deformation (PD), both subjected to multi-stage loading ranging from 70 to 280 kPa, totaling 40,000 cycles. Specimens were compacted with intermediate energy and cured in an oven at 40°C for three days, ensuring emulsifier evaporation and development of the residual asphalt binder. The curing time significantly increased initial stiffness, but PD continued to rise in the final cycles, indicating that emulsion improves stiffness but does not eliminate plastic deformation over time.

Another relevant aspect addressed in the studies was the influence of curing time on the strength of stabilized mixtures. Coelho et al. [14] evaluated the mechanical behavior of cold recycled asphalt mixtures (CRAM) stabilized with RL-1C asphalt emulsion, considering different curing times (0, 7, 14, and 28 days). Tests included resilient modulus (RM) and permanent deformation (PD) under repeated triaxial loading. Results demonstrated that initial curing significantly impacts material stiffness, with an average RM increase of 80% in the first 7 days. After this period, gains were smaller, ranging between 10.9% and 19.4%. However, even after 28 days of curing, the mixture still exhibited considerable permanent deformation, indicating that while emulsion improves stiffness, it does not eliminate plastic deformation issues. Compaction was performed in tripartite cylindrical molds (100 mm in diameter and 200 mm in height) following the Modified Proctor method. The study highlighted the importance of curing time, showing that 7 days is sufficient to reach acceptable RM levels for base layer applications. However, it also emphasized the need for formulation adjustments to mitigate permanent deformation, such as increasing cement content or introducing other stabilizers.

Additionally, Andrews et al. [15] developed a predictive model to evaluate the performance of emulsion-stabilized mixtures, using indirect tensile strength (ITS) and resilient modulus (RM) as key indicators. The study explored the relationship between ITS (90 to 220 kPa) and RM (1011 to 2950 MPa) to predict the durability and resistance to permanent deformation of Emulsion Treated Base (ETB) mixtures. The research concluded that ETB with 3–4% emulsion, 1–2% cement, and a minimum of 50 Marshall blows provides an optimal balance between cracking resistance and permanent deformation.

Husain et al. [16] identified that using 50% fractionated reclaimed asphalt pavement (FRAP) combined with 3% emulsion resulted in substantially higher resilient modulus values compared to the control material (virgin crushed limestone aggregate). The mixture with these percentages (50% FRAP and 3% emulsion) exhibited a resilient modulus approximately 2.5 times higher than the unbound crushed limestone aggregate. Additionally, this composition demonstrated excellent resistance to permanent deformation, indicating significant potential for practical application as a stabilized base in pavements. The samples were compacted using 75 gyrations in a Superpave Gyratory Compactor (SGC), producing specimens with dimensions of 150 mm in diameter and 150 mm in height. After compaction, the specimens were air-cured until reaching constant weight and moisture equilibrium, followed by testing at a temperature of 25°C. The optimum emulsion content for each mixture type was determined using the Illinois Department of Transportation (IDOT) [17] mix design methodology, as specified by Anderson and Thompson, which accounts for the aggregate gradation. The residual asphalt content in the mixture is calculated using the following Equation 1.

$$\text{ResAC}\ (\%) = 0.00138 \times (P{+}4) \times (P{-}4) + 6.358 \times \log(P200) - 4.655 \tag{1}$$

where:

- ResAC: The residual asphalt content in the mixture (expressed as a percentage of the dry aggregate weight);
- P+4: The percentage of aggregate retained on the No. 4 sieve (particle size greater than 4.76 mm);
- P-4: The percentage of aggregate passing through the No. 4 sieve but retained on the No. 200 sieve (0.075 mm);
- P200: The percentage of aggregate passing through the No. 200 sieve (particle size smaller than 0.075 mm).

Additionally, an extra 2% of water was added to the mixtures during preparation, following recommendations from the literature, aiming to improve workability and ensure greater homogeneity of the emulsion-stabilized mixtures.

The research led by Orosa et al. [18] analyzed the evolution of the resilient modulus (RM) and water loss in cold recycled asphalt mixtures (CRM) over the curing period. The asphalt emulsion used was a cationic slow-setting emulsion with a 60% binder content, commonly applied in cold recycling projects in Spain. The samples were prepared with 100% RAP (Reclaimed Asphalt Pavement) and varying emulsion contents (1.5% to 3.5%), compacted using a gyratory compactor (100 gyrations), following the EN 12697-31 [19] standard. The study employed cyclic triaxial dynamic tests to evaluate resilient behavior over nine curing periods (0 to 18 months), correlating mass loss due to evaporation with stiffness gain. The results demonstrated that the stiffness of the mixtures evolved significantly within the first 7 days, with an average increase of 21.74% in resilient modulus (RM), while subsequent gains were lower (9.6% between 7 and 30 days, and 4.75% between 2 and 6 months). The mixture of 2.5% emulsion showed the best short-term performance, with greater stability in water loss and faster RM increase. However, in the long term, the mixture of 3.0% emulsion outperformed the others, maintaining continuous stiffness growth without loss after 12 months. Additionally, the study confirmed that even after the completion of water evaporation, the resilient modulus continued evolving due to binder aging.

Dias et al. [20] conducted a laboratory and field study on the use of bitumen-stabilized materials as pavement surfacing. The objective was to evaluate the mechanical behavior and field performance of these materials in terms of permanent deformation. The methodology involved preparing mixtures of crushed aggregates and reclaimed asphalt pavement (RAP) stabilized with cationic slow-setting asphalt emulsion (CSS-1) and Portland cement (CP II-E-32) as stabilizing agents. The percentages of asphalt emulsion and cement used in the mixtures were 3% and 1%, respectively, based on the dry weight of the aggregates and RAP. The study included indirect tensile strength tests, monotonic and cyclic triaxial tests, and field evaluations to assess the mechanical properties and durability of the stabilized materials. The authors used RAP with different proportions of recycled crushed stone, ranging from 0% to 100%. Triaxial tests were conducted at 20°C, 30°C, and 40°C to determine the resilient modulus (RM) of the mixtures. The RM values ranged between 300 MPa and 1000 MPa for RAP mixtures containing recycled crushed stone, and 200 MPa to 600 MPa for RAP mixtures without recycled crushed stone. The study also observed that RM decreased with increasing temperature and RAP percentage.

Orosa et al. [21] evaluated the impact of emulsion content on the resilient modulus (RM) of cold recycled mixtures with bitumen emulsion, concluding that RM depends on the soil type, emulsion type, curing time, and applied stress state. The authors used 4% conventional asphalt emulsion (AE) and 4% sulfur-modified asphalt emulsion (ESA) to stabilize marginal soils such as marl, sabkha, and dune sand. RM values ranged from 100 MPa to 500 MPa for AE-stabilized mixtures and 200 MPa to 800 MPa for ESA-stabilized mixtures after 28 days of curing at 22°C. The study also found that RM was not significantly affected by the applied confining stress.

Al-Mansob et al. [22] investigated the effect of asphalt emulsion on improving the mechanical properties of stabilized clay soil. The researchers conducted laboratory tests to measure the resilient modulus, compressive strength, and indirect tensile strength of soil samples treated with different asphalt emulsion contents. They also analyzed the influence of curing time, moisture content, and dry density on the stabilized soil properties. The study concluded that asphalt emulsion positively affects the resilient modulus, compressive strength, and indirect tensile strength of the stabilized clay soil. The increase in these properties depends on the emulsion content, with the optimal content identified at 6%. Additionally, the results indicated that curing time, moisture content, and dry density also influenced the stabilized soil's performance, with the best results obtained after 7 days of curing, 12% moisture content, and 95% of the maximum dry density.

Another approach investigated was the use of geopolymers as eco-friendly stabilizers, with Yaowarat et al. [23] evaluating the stabilization of crushed rock with fly ash and asphalt emulsion, yielding promising results in terms of mechanical behavior. The research analyzed the use of asphalt emulsion (AE) in stabilizing marginal crushed rock (CR) with alkaline-activated fly ash (FA), aiming to provide a sustainable alternative to cement for pavement base layers. The tests included unconfined compressive strength (UCS), indirect tensile strength (ITS), flexural strength (FS), indirect tensile resilient modulus (ITRM), and indirect tensile fatigue life (ITFL). The slow-setting emulsion used in the study enhanced the mechanical properties of the material, particularly in tensile and flexural strength tests. However, the addition of AE had a mixed effect on UCS, increasing strength at low FA contents (<20%) but reducing it at higher contents, due to interference in the geopolymerization process. The results indicate that the combination of FA and AE produced a material with increased flexibility and fatigue resistance, desirable characteristics for durable pavements. The indirect tensile resilient modulus (ITRM) increased by up to 20% with AE, while tensile and flexural strength were also significantly improved. Specimen compaction followed the Modified Proctor method (ASTM D1557) [24], ensuring standardized density and moisture conditions.

Kamran et al. [25] evaluated the performance of a base layer stabilized with asphalt emulsion and asphaltenes derived from Alberta oil sands. The objective was to assess the effect of asphaltenes on indirect tensile strength, permanent deformation, and moisture sensitivity of the stabilized material. The methodology involved preparing granular aggregate mixtures stabilized with 3%, 4%, and 5% asphalt emulsion relative to the dry aggregate weight, and adding 1% to 3% asphaltenes relative to the total mixture weight. The mixtures were subjected to laboratory tests to evaluate their mechanical properties and fatigue behavior. The results showed that asphaltene addition increased indirect tensile strength and resistance to permanent deformation, while moisture sensitivity was slightly lower compared to the control mixture. The study concluded that asphaltenes can be used as a waste material to improve the performance of asphalt-emulsion-stabilized bases. Regarding pavement design, studies demonstrated the need for adjustments in conventional models to accommodate stabilized mixtures.

Beesam & Torres-Machi [26] analyzed mechanical properties and mechanistic-empirical (M-E) design parameters for full-depth reclamation (FDR) mixtures, including those stabilized with asphalt emulsion. The study emphasized that current design practices underestimate the actual performance of FDR materials due to the use of conservative resilient modulus values. Eleven FDR sections in Colorado (USA) were evaluated, considering both emulsion-stabilized and unstabilized sections. Results showed that emulsion-stabilized mixtures exhibited higher stiffness than unstabilized sections, with resilient modulus values ranging from 99.6 to 256.2 ksi, compared to 14.3 to 50.7 ksi for unstabilized sections. The study suggested adjusting input values in M-E software, recommending 37.3 ksi for unstabilized mixtures and 160 ksi for emulsion-stabilized mixtures. This research highlights the need for calibrating design models to better represent real-world performance of FDR-stabilized layers, particularly considering curing time effects on stiffness evolution.

Over the years, there has been a notable increase in the variety of materials studied for stabilization. More recent studies (2024–2025) explore not only traditional soils but also hybrid compositions, such as lateritic bases stabilized with biochar and granular mixtures containing RAP and asphalt emulsion. The stabilization of recycled materials has become an increasing research focus, indicating a growing concern with sustainability and circular economy practices in pavement engineering.

Furthermore, the relationship between material type and emulsion content suggests that more heterogeneous and recycled-origin materials require higher emulsion percentages to ensure adequate cohesion and mechanical resistance. These trends reflect advancements in research aimed at more sustainable and cost-effective solutions for pavement stabilization. A detailed literature review has revealed that most existing studies on soil stabilization with asphalt emulsion focus on emulsion content and curing time, without systematically addressing the impact of moisture on soil stiffness, both in the dry and wet states. This research gap is significant since the initial moisture content of the soil can directly influence the dispersion and adhesion of the emulsion, thereby affecting the final mechanical performance of the mixture. Another identified gap relates to the quantitative characterization of the particle size distribution of stabilized soils. Most studies rely on conventional methods without incorporating advanced computational techniques for particle distribution analysis. This limitation may compromise assessment accuracy and hinder the identification of granulometric patterns that influence soil stiffness and stability. Few studies employ robust statistical methods, such as Robust ANOVA, to evaluate the interaction between moisture, emulsion type, and loading cycles on soil stiffness. The application of this method in the present study allows for a more reliable statistical assessment, minimizing the effects of outliers and heterogeneous variances, which contributes to a more accurate analysis of the key factors affecting the mechanical performance of stabilized mixtures.

3. Material and Methods

3.1. Soil Samples

For the mechanical analysis, a soil sample classified as silty sand (SM) according to the Unified Soil Classification System (USCS) [27] and as A-2-4 according to the HRB [28] methodology was used. Table 1 presents a summary of the average values of the soil's geotechnical parameters.

Table 1. Geotechnical Parameters of the Soil

Parameter	Value
Liquid Limit (LL)	NP (Non-Plastic)
Plastic Limit (LP)	NP (Non-Plastic)
Real Grain Density	2.87 g/cm³
Apparent Dry Density	2.28 g/cm³
Void Ratio (e)	0.26
Optimum Moisture Content	8.2%

The deposit where the material was collected, as shown in Figure 1, is located at latitude 22°34'19.416'' S and longitude 44°01'4.875'' W, in the municipality of Pinheiral, approximately 2 km from a major highway in the state of Rio de Janeiro, the BR-116 (Rodovia Presidente Dutra), in Rio de Janeiro, Brazil.

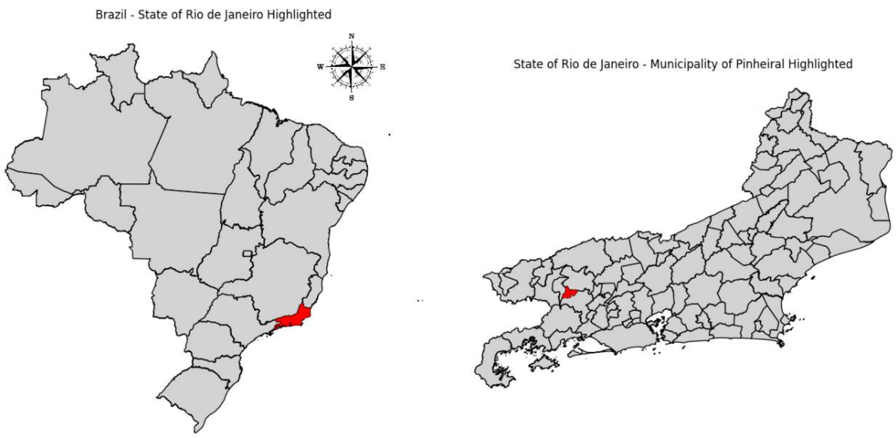

Figure 1. Location of the Deposit

3.2. Tests and Standards

The physical, chemical, and mechanical characterization of the material used in this study was conducted according to the standardized test procedures described in the standards listed in Table 2. These standards ensure consistency, reliability, and comparability of the results, following recognized methodologies for soil stabilization and asphalt emulsion performance evaluation.

Table 2. Geotechnical Parameters of the Soil

Test Title	Standard
Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort	ASTM D1557 [24]
Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes	AASHTO M145-1973 [28]
Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)	ASTM D2487 [27]
Standard Test Method for Particle-Size Analysis of Soils	ASTM D422 [29]
Standard Test Methods and Practices for Emulsified Asphalts	ASTM D244-20 [30]
Standard Test Method for Determining the Resilient Modulus of Soils and Aggregate Materials by Dynamic Triaxial Test	DNIT 134/2018 [31]
Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials	AASHTO T 307-99 (2007) [32]

3.3. Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS)

The Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS) system is an advanced analytical tool that combines Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDS) [33-35]. This system is widely used to analyze the elemental composition and microstructural characteristics of materials at micro and nanoscales. The SEM technique operates by bombarding the sample with a high-energy electron beam. This beam interacts with the sample's surface, generating secondary electrons that are detected and processed to produce a high-resolution image. These images provide a detailed visualization of the topography and morphology of the material's surface.

The EDS technique, in turn, is employed to identify the chemical elements present in the sample. When the SEM electron beam interacts with the material, it also produces characteristic X-rays emitted by the sample's elements. These X-rays are detected by the EDS detector and converted into an energy spectrum, enabling the identification and quantification of the elemental composition of the sample. The sample preparation and the SEM/EDS equipment setup used in this study can be seen in Figure 2.

Figure 2. Preparation of Soil Sample for SEM/EDS Analysis

3.4. pH and Weathering

The tests were conducted at the Geotechnics Laboratory of COPPE/UFRJ, as shown in Figure 3.

Figure 3. Soils Being Prepared and Testing Bench at the Geotechnics Laboratory/COPPE/UFRJ

Based on the Manual of Soil Analysis Methods by EMBRAPA [36], the soil analysis testing program is structured into several critical stages. The measurement of soil pH is essential, as the difference between pH values in H_2O and KCl indicates the nature of the charges present in the soil. If the pH in H_2O is higher than in KCl, the soil predominantly exhibits negative charges; if lower, it has a predominance of positive charges. This information is crucial for selecting the appropriate ionic charge of the asphalt emulsion (anionic or cationic) to ensure effective interaction and soil stabilization.

Sulfuric acid digestion and the subsequent analysis of Fe_2O_3, Al_2O_3, and SiO_2 help determine the soil's mineralogical composition. Soils rich in iron and aluminum oxides tend to have positive charges under acidic conditions, while silica contributes to negative charges in neutral to alkaline conditions. Understanding the mineralogical composition aids in predicting how the soil will interact with different types of asphalt emulsions. Silica quantification is important since silica generally contributes to negative charges in the soil. Soils with high silica content are often more compatible with anionic emulsions, which have a negative charge and better interact with negatively charged soils. Weathering indices help assess the degree of soil weathering and mineral stability. Highly weathered soils tend to contain a greater amount of clay minerals, which exhibit significant surface charges that interact strongly with asphalt emulsions. Understanding these indices allows for the formulation of asphalt emulsions tailored to optimize soil stabilization.

The Ki and Kr weathering indices are calculated based on the molar content of SiO_2, Al_2O_3, and Fe_2O_3, using the following Equations 2 and 3.

$$Ki = (SiO_2/Al_2O_3) \times 1.7 \quad (2)$$

$$Kr = (SiO_2/0.6)/(Al_2O_3/1.02 + Fe_2O_3/1.60) \quad (3)$$

When the Ki or Kr indices are below 2, this indicates that the soil has undergone significant chemical weathering. This phenomenon reflects the extent of mineral decomposition the soil has experienced. The residue that remains undecomposed during chemical analysis typically corresponds to the amount of quartz present in the sample.

3.5. Sample Preparation and Soil-Emulsion Compaction

The soil compaction process was performed using a split-mold (100 mm in diameter and 200 mm in height), as shown in Figure 4, following the Modified Proctor compaction effort. The compaction was conducted at three different moisture contents—5.2%, 8.2% (optimum moisture content, Wot), and 11.2%. The compaction energy was applied in 10 layers, with 56 blows per layer, using a 2.5 kg rammer. The same mold used for compaction was also utilized for preparing the specimens for the triaxial test.

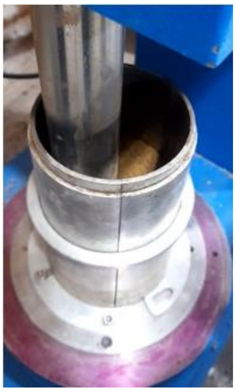

Figure 4. Split Mold

The compaction of soil mixed with emulsion followed the steps below:

- The amount of water to be added to the mixture (soil + emulsion + dilution water) was calculated so that the final moisture content equaled the soil's optimum moisture (5.2%, 8.2%, or 11.2%);
- The dilution water corresponded to the same amount of emulsion and was used to reduce the viscosity of the emulsion;
- The remaining water was used to pre-moisten the soil; and
- Once the soil was moistened, the emulsion mixed with the dilution water was added.

This procedure allowed better workability of the soil-emulsion mixture, as recorded in Figure 5.

Figure 5. Soil-Emulsion Mixing Procedure

The uniformity of emulsion dispersion was not quantitatively assessed; however, during sample preparation, greater workability and homogenization were observed in the dry branch of the compaction curve. Under low-moisture conditions, the limited water content hindered the adequate spreading of the asphalt emulsion, potentially affecting its uniform distribution within the soil matrix. The modified Proctor compaction method was selected due to its ability to reduce voids and enhance the efficiency of soil stabilization. This choice aligns with the intended use of the material as a primary surface layer in a low-volume rural road, where increased density is expected to improve resistance to environmental weathering and mechanical degradation.

3.6. Resilient Modulus

Soils, when subjected to deformation, partially recover. This recoverable portion of the deformation, which is related to the applied stress, is known as the Resilient Modulus (RM). Its mathematical expression is given by Equation 4:

$$RM = \sigma_d/\varepsilon_r \tag{4}$$

where:

- σ_d − Deviatoric stress
- ε_r − Recoverable vertical strain

The axial stress is calculated as Equation 5:

$$\sigma_1 = \frac{P}{A} \tag{5}$$

where:

- σ_1 − Axial stress
- P − Applied force (N) in Newtons
- A − Cross-sectional area of the specimen's top

The deviatoric stress is given by Equation 6:

$$\sigma_d = \sigma_1 - \sigma_3 \tag{6}$$

where:

- σ_3 − Confining stress

The recoverable strain is calculated as Equation 7:

$$\varepsilon_r = \frac{\delta_r}{H_0} \tag{7}$$

where:

- ε_r − Recoverable strain (dimensionless)
- δ_r − Recoverable displacement (mm)
- H_0 − Reference height, discounting the accumulated plastic deformation (mm)

Alternatively, it can be expressed as Equation 8:

$$\varepsilon_r = \varepsilon_t - \varepsilon_p \tag{8}$$

where:

- ε_t − Total strain
- ε_p − Non-recoverable plastic strain

The force from the mechanical actuator is applied to the top cap, which distributes the load over the upper surface of the specimen. This force is applied for 0.1 seconds, followed by a rest period not exceeding 0.9 seconds. This cycle is designed to simulate the effect of a standard axle load passing over the pavement, correlating the laboratory conditions with real traffic loads.

The resilient modulus (RM) is directly related to the development of cracks in flexible pavements. The higher the recoverable strain, the more flexible the material is, which may contribute to the formation of fatigue cracks in the asphalt pavement. The loading cycles were defined in accordance with DNIT standards, which provide a framework for modeling the resilient modulus. They follow established procedures that aim to replicate representative stress conditions in pavement structures, enabling a more realistic evaluation of the material's response to traffic-induced loads.

To determine the resilient modulus of the soil, six (6) loading cycles were applied, with increasing deviatoric and confining stresses, as shown in Table 3.

Table 3. Loading Cycle for Resilient Modulus Calculation

σ3 (MPa)	σd (MPa)	σd/σ3	σ3 (MPa)	σd (MPa)	σd/σ3
0.02	0.02	1	0.07	0.07	1
	0.04	2		0.14	2
	0.06	3		0.21	3
0.035	0.035	1	0.105	0.105	1
	0.07	2		0.21	2
	0.105	3		0.315	3
0.05	0.05	1	0.14	0.14	1
	0.1	2		0.28	2
	0.15	3		0.42	3

For each pair of applied stresses, a minimum of 10 loading cycles was performed, ensuring data acquisition from at least 5 repeated load applications. These repetitions had to maintain a maximum variation of 5% between them to guarantee measurement consistency. The resilient modulus (RM) calculation was based on the average of these 5 readings.

3.7. Experimental Design and Statistical Analysis

To analyze the data, Robust ANOVA was applied—an extension of the traditional Analysis of Variance (ANOVA) To analyze the data, a Robust ANOVA was applied, which is a variation of the traditional ANOVA adapted for scenarios where the assumptions of normality and homogeneity of variances are violated. This approach was chosen after performing normality tests (Shapiro-Wilk, Kolmogorov-Smirnov, and Anderson-Darling) and homogeneity of variances tests (Levene and Bartlett), which indicated significant deviations from these assumptions. Robust ANOVA uses trimmed means, which remove 20% of the most extreme observations, providing greater robustness against outliers and heteroscedasticity.

Robust ANOVA has proven to be an effective extension of traditional ANOVA, particularly in scenarios where classical assumptions, such as residual normality and variance homogeneity, are violated. According to Schmider et al. (2010) [37], Robust ANOVA performs consistently well even when applied to non-normal distributions, such as rectangular and exponential distributions. This is due to the use of trimmed means and robust variance estimators, which minimize the influence of outliers and asymmetric distributions. The experimental design adopted was a full factorial design with three main factors:

- Cycles (Factor A): Divided into six levels, representing different loading cycles (1, 2, 3, 4, 5, and 6).
- Moisture (Factor B): Included three moisture levels (5.2%, 8.2%, and 11.2%), selected to represent typical conditions found in pavement stabilization.
- Emulsion Type (Factor C): Categorized into three types of asphalt emulsion:
    - NE (No Emulsion): Reference condition without emulsion.
    - SBE (Slow Brake Emulsion): Slow-breaking asphalt emulsion.
    - MBE (Medium Brake Emulsion): Medium-breaking asphalt emulsion.

These categories were selected to evaluate how different chemical compositions and rheological properties of emulsions influence the mechanical performance of stabilized soil. The combination of these three factors resulted in a total of: 6 (Cycles)×3 (MoistureLevels)×3 (Emulsion Types) = 54 experimental. Each condition was replicated three times, leading to a total of 162 observations. The dependent variable (Resilient Modulus - RM) was chosen due to its relevance in characterizing the mechanical behavior and deformation resistance of pavement materials. Table 4 provides a detailed summary of the experimental design, illustrating the resilient modulus (RM) values for each combination of factors.

Table 4. Experimental Design

Cyclos - Factor A	Emulsion Type - Factor C								
	No Emulsion			Medium Brake Emulsion			Slow Brake Emulsion		
	Moisture - Factor B								
	5.20%	8.20%	11.20%	5.20%	8.20%	11.20%	5.20%	8.20%	11.20%
1	47.42	123.46	21.74	88.10	456.15	227.28	118.99	228.71	216.84
	54.86	108.74	26.83	136.53	428.50	223.02	138.81	281.55	247.25
	55.36	105.52	32.41	162.93	392.65	239.00	154.82	314.80	266.70
2	74.92	139.59	26.08	169.28	789.03	297.76	170.02	464.98	380.51
	73.74	126.19	38.20	219.09	614.27	312.11	197.86	450.62	396.04
	73.70	122.00	45.96	256.32	565.02	339.72	213.25	455.90	416.70
3	86.77	174.05	32.29	221.81	816.89	394.74	216.27	678.90	474.43
	85.60	140.67	44.75	281.11	723.62	408.95	241.77	578.15	512.80
	89.42	133.55	55.68	307.42	709.73	425.00	254.25	622.33	549.32
4	107.11	189.32	36.15	231.70	789.07	432.27	254.62	818.32	363.76
	105.00	158.15	53.78	316.26	844.10	475.82	278.97	911.96	436.21
	112.37	158.35	68.26	362.36	795.68	509.39	306.11	1009.89	497.28
5	144.09	230.68	45.48	330.49	1255.55	400.62	327.83	2057.29	455.36
	143.63	195.88	69.32	395.89	1049.73	467.13	363.29	1533.43	563.53
	147.85	203.28	90.61	440.85	916.98	529.41	384.14	1312.80	657.43
6	175.69	272.16	54.85	400.00	1433.22	493.17	364.11	1722.53	546.14
	177.41	238.63	84.61	506.18	1006.60	554.69	401.60	1978.70	674.37
	179.35	246.24	104.47	550.83	954.60	622.20	411.83	1480.09	732.92

In the variance analysis, main effects were considered for each of the three factors, as well as all possible interactions between them, including two-way interactions (Cycles ✻ Moisture, Cycles ✻ Emulsion Type, Moisture ✻ Emulsion Type) and the three-way interaction (Cycles ✻ Moisture ✻ Emulsion Type). The inclusion of interactions was essential to evaluate how the combination of multiple factors affects the mechanical response of the material, providing a more comprehensive understanding of Resilient Modulus (RM) behavior.

In Robust ANOVA, the Q-test statistic replaces the traditional F-test statistic used in classical ANOVA. The Q statistic reflects the relationship between the between-group variance and the within-group variance, utilizing robust estimators to provide more reliable results when dealing with heteroscedastic data or outliers. The p-value is computed using permutation methods or bootstrap techniques, as Q does not follow a classical F-distribution. This approach makes Robust ANOVA less sensitive to outliers and asymmetric distributions, maintaining the validity of hypothesis testing even when classical assumptions are violated [37]. Robust ANOVA proved to be particularly robust regarding Type I and Type II error control. According to Schmider et al. [37], even under non-normal distributions, Type I and Type II error rates remain consistent, suggesting that the test is resistant to violations of normality assumption. Furthermore, the regression analysis conducted in this study indicated that the type of distribution did not significantly influence the ANOVA results, reinforcing the method's robustness.

The study by Schmider et al. [37] strengthens the validity of Robust ANOVA as a reliable alternative to traditional ANOVA, particularly in studies where data do not follow normal distributions or exhibit heteroscedasticity. The application of trimmed means and robust variance estimation ensures greater reliability and statistical accuracy. Therefore, Robust ANOVA is recommended for variance analysis in non-ideal conditions, maintaining the integrity of hypothesis testing.

For the variance analysis in this study, Jamovi software was used, an open-source and free statistical software based on the R programming language, offering features for descriptive analysis, inferential statistics, and statistical modeling.

3.8. Research Flowchart

The methodological framework adopted in this study (Figure 6) is structured into seven sequential stages, each designed to ensure the reliability and reproducibility of the experimental results. Beginning with the selection and classification of the soil sample, the process advances through the choice of emulsion type, precise sample preparation under controlled moisture and compaction conditions, and detailed curing protocols. Mechanical behavior was evaluated through repeated load triaxial testing, followed by granulometric characterization using computer vision tools. Finally, the dataset was subjected to robust statistical analysis using Robust ANOVA to ensure the validity of results even under non-normal distribution assumptions. The diagram summarizes all procedures carried out throughout the experimental campaign.

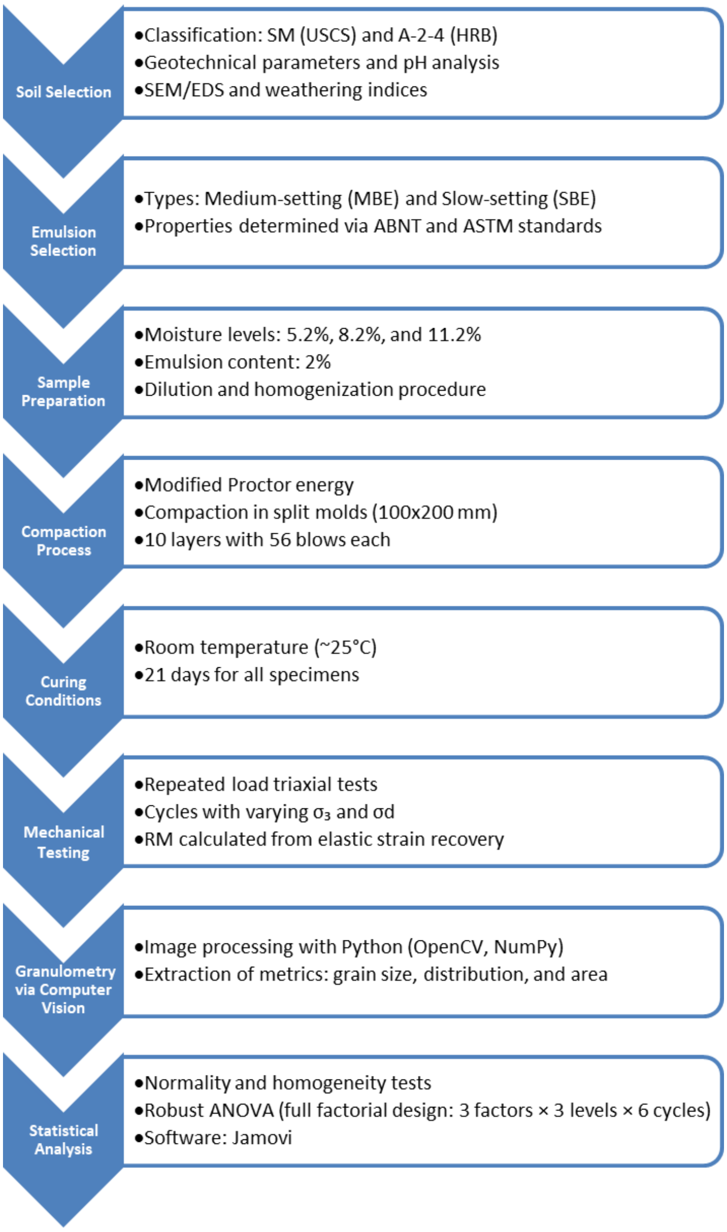

Figure 6. Research Methodology Flowchart for Evaluating Stiffness in Emulsion-Stabilized Soils

4. Results and Discussions

4.1. Grain Size Distribution

Grain size classification is a fundamental step in soil characterization; however, it has limitations regarding the prediction of geotechnical behavior. Using the Ferret triangle to classify the fine fraction of the soil, the following distribution was obtained: 74.2% sand, 2.0% silt, and 0.20% clay. The total sum of these fractions is 76.43%. The soil is considered coarse and poorly graded, with approximately 18% passing through the No. 200 sieve, as shown in Figure 7.

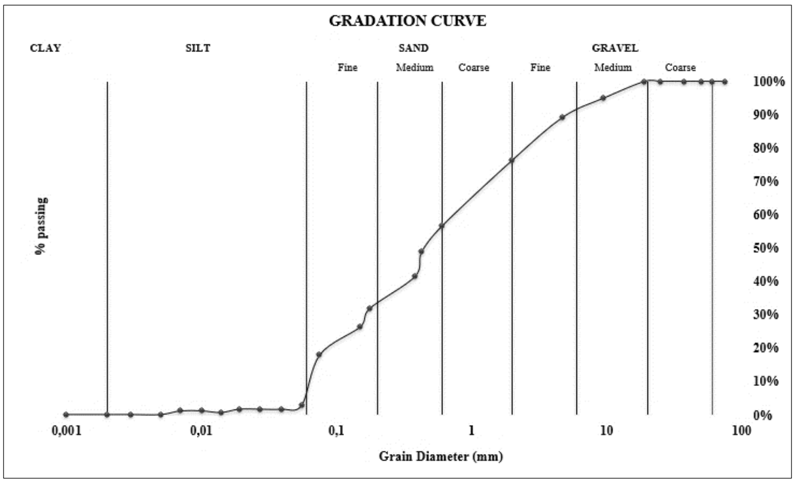

Figure 7. Soil granulometry

4.2. SEM/EDS Analysis

The analyzed image is a micrograph obtained through Scanning Electron Microscopy (SEM) at a magnification of 500x (x500), with a scale of 200 µm. The observed particles exhibit a predominantly angular and irregular shape, suggesting that the material has not undergone significant weathering or mechanical rounding processes. Some larger particles display rough surfaces, indicating fracture or fragmentation. Additionally, the heterogeneous distribution of particles suggests a mixture of materials of different sizes. The qualitative grain size distribution analysis reveals significant variation in particle size, with large and smaller fragments scattered throughout.

The presented image consists of three representations of a granular material, possibly obtained through electron microscopy and subjected to different stages of digital processing. The first image, labeled "Original Image," shows the initial capture of the material without any processing. At this stage, the image quality depends directly on capture conditions such as lighting, focus, and equipment resolution.

The second image, labeled "Histogram Equalization," displays an enhanced version of the original image with increased contrast. Histogram equalization is a widely used technique to enhance details in images by redistributing pixel intensity levels. This process makes dark areas more visible and reduces the dominance of mid-tones, allowing a clearer view of the particles. In Python, this technique can be implemented using the cv2.equalizeHist() function from the OpenCV library, applied to a grayscale-converted image.

Finally, the third image, labeled "Enhanced Segmentation," represents a more advanced processing step where specific elements of the image are highlighted. Segmentation is a technique that separates objects from the background or other regions of interest, enabling both quantitative and qualitative analysis. Common methods for this type of processing include thresholding, edge detection, and watershed segmentation. Depending on the technique used, different algorithms can be implemented, such as binary thresholding, which can be applied in Python using the cv2.threshold() function, or edge detection using cv2.Canny().

The processing of these images, Figure 8, was conducted with the aid of specialized libraries for computer vision and image manipulation. The OpenCV (cv2) library was used for image loading, grayscale conversion, histogram equalization, and segmentation. NumPy (numpy) was employed for mathematical operations and pixel array manipulation. To visualize and display the results, the Matplotlib (matplotlib.pyplot) library was utilized.

Figure 8. Image Generated by SEM

The digital analysis of the image enabled the extraction of quantitative metrics regarding the grains present in the sample. Through the processing performed, it was possible to identify fundamental characteristics of the grain distribution, aiding in the understanding of the material's properties.

The first metric obtained was the number of detected grains, totaling 88 particles. This count was performed through the segmentation process, where techniques such as thresholding and contour detection allowed for the separation of individual grains within the image.

Additionally, the total area occupied by the grains was calculated, corresponding to 193,629 pixels. This value represents the sum of the areas of all detected particles and provides an estimate of the material's density in the image. This information is useful for assessing the spatial distribution of particles. Another relevant metric was the average grain diameter, calculated as 8.85 pixels. This value was obtained by averaging the individual diameters of the segmented particles. In more detailed analyses, this measurement can be converted into physical units, based on the image scale.

The dispersion of particle sizes was analyzed through the variance of the diameter, which resulted in 2723.24 pixels^2, and the standard deviation of the diameter, which was 52.18 pixels. A high standard deviation relative to the mean indicates variability in grain sizes: the greater the value, the larger the difference between particle sizes in the sample. These metrics were calculated using OpenCV (cv2) for segmentation and particle counting, and NumPy (numpy) for the mathematical operations associated with obtaining the mean, variance, and standard deviation of the diameters. The visualization of results was performed using Matplotlib (matplotlib.pyplot), allowing for the display of processed images and extracted metrics.

The significance of a high standard deviation, as identified in the fine fraction of the analyzed soil, in geotechnics, depends directly on the type of material and its application. Generally, when there is a large variation in particle size, compaction tends to be more efficient, as smaller particles fill the voids between larger ones, reducing porosity and increasing the material's density. On the other hand, a soil or aggregate with a low standard deviation—meaning more uniform particle sizes—may exhibit high permeability since the spaces between grains are larger and more continuous, facilitating water flow. Conversely, materials with broader particle size distribution (high standard deviation) tend to have greater particle interlocking, increasing shear resistance. This behavior is particularly desirable in pavement bases and sub-bases, as it enhances structural stability and load-bearing capacity.

In the context of pavement engineering, a wide variability in particle sizes can be advantageous, both for efficient compaction and mechanical performance, resulting in lower deformability and higher resistance to traffic loads. However, in cohesive soils, a high standard deviation may indicate heterogeneity in composition, potentially leading to unpredictable mechanical behavior, which could negatively affect stability and durability in geotechnical applications.

Through EDS analysis, a significant presence of silicon oxides (SiO_2) and aluminum oxides (Al_2O_3) was observed in the soil grains, as detailed in Table 5. These oxides exhibit good adhesion with cationic emulsions. This type of analysis is essential to ensure proper adhesion between the emulsion and the soil, leading to effective stabilization results.

Table 5. Chemical Elements Present in the Polished Sample

Element	Weight (%)	Weight (%) σ	Atomic	Compound	Formula
Sodium	0.903	0.254	0.901	1.217	Na_2O
Magnesium	4.275	0.297	4.036	7.088	MgO
Aluminum	6.842	0.334	5.821	12.928	Al_2O_3
Silicon	22.970	0.530	18.772	49.140	SiO_2
Potassium	0.675	0.189	0.396	0.813	K_2O
Calcium	2.793	0.267	1.600	3.908	CaO
Iron	19.360	0.826	7.957	24.906	FeO
Oxygen	42.182	0.751	60.517		

4.3. pH and Chemical Weathering

The difference between the pH measured in H_2O and in KCl can indicate the predominance of charges in the soil. In the soil studied in this research, the pH in H_2O (5.4) is higher than the pH in KCl (3.95), suggesting a predominance of negative charges. This condition is favorable for the adsorption of cationic emulsions, enhancing physicochemical interaction between the stabilizing agent and the soil particles.

The Ki index, when higher, indicates lower chemical weathering. With a value of 10.52, the analyzed soil exhibits low chemical alteration over time. The Kr index, associated with resistance to weathering, is also relatively high (5.28), indicating greater stability against decomposition. These characteristics are detailed in Table 6.

Table 6. Chemical Properties and Sulfuric Attack Resistance of the So

Samples	pH			Sulfate Attack					
	H_2O	KCL 1M	ΔP (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	Ki	Kr	Res. (%)
solo	5.4	3.95	1.59	31	5.01	7.78	10.52	5.28	71.36

4.4. Selection of the Emulsion

After determining the mineralogical structure of the soil, it was possible to confidently select the most suitable emulsion for soil stabilization. Table 7 presents the physical characteristics of the asphalt emulsions used in this experiment.

Table 7. Characterization of emulsions

Tests (SBE1C)	Limits (SBE1C)	Results (SBE1C)	Standard (SBE1C)
Saybolt Viscosity at 25°C, SSF	70 max	17	ABNT NBR 14491 [38]
Residue by Evaporation, % by weight	60 min	62.0	ABNT NBR 14376 [39]
Sieving 0.84mm, % by weight	0.1 max	0	ABNT NBR 14393 [40]
Sedimentation (5 days), % by weight	5 max	2	ABNT NBR 6570 [41]
Particle Charge	Positive	Positive	ABNT NBR 6567 [42]
Compatibility with Cement, %	2 max	0.2	ABNT NBR 6297 [43]
Tests (MBE1C)	**Limits (MBE1C)**	**Results (MBE1C)**	**Standard (MBE1C)**
Saybolt Viscosity at 50°C, SSF	70 max	44	ABNT NBR 14491 [38]
Residue by Evaporation, % by weight	60 min	62.8	ABNT NBR 14376 [39]
Sieving 0.84mm, % by weight	0.1 max	0	ABNT NBR 14393 [40]
Sedimentation (5 days), % by weight	5 max	1	ABNT NBR 6570 [41]
Particle Charge	Positive	Positive	ABNT NBR 6567 [42]
Demulsibility, % by weight	50 max	19	ABNT NBR 6569 [44]

4.5. Test Results (ANOVA)

Robust ANOVA was applied to evaluate the influence of the factors Cycles, Moisture, and Emulsion Type on the stiffness of the stabilized soil, Table 8. The methodology utilized trimmed means (level 0.2) to minimize the impact of extreme values and provide a more robust statistical analysis.

Table 8. Robust ANOVA

Factors	Q	P
Cycles	916	<.001
Moisture	518	<.001
Emulsion Type	1747	0.001
Cycles ✻ Moisture	168	0.001
Cycles ✻ Emulsion Type	522	0.001
Moisture ✻ Emulsion Type	572	0.001
Cycles ✻ Moisture ✻ Emulsion Type	213	0.001

Note: Trimmed means method (trimming level: 20%).

The results indicate that emulsion type was the most influential isolated factor in soil stiffness, with $Q = 1747$ ($p = 0.001$). This finding confirms that the choice of emulsion has a significant impact on the strength of the stabilized material. Following this, loading cycles ($Q = 916$, $p < 0.001$) and moisture content ($Q = 518$, $p < 0.001$) also demonstrated important effects, directly influencing soil behavior over time.

Beyond the isolated factors, interactions between them were statistically significant. The Cycles ✻ Moisture interaction ($Q = 168$, $p = 0.001$) indicates that moisture influence may vary across loading cycles, affecting the mechanical response of the stabilized soil. The Cycles ✻ Emulsion Type interaction ($Q = 552$, $p = 0.001$) suggests that certain emulsions offer greater resistance over time, playing a key role in material durability. The Moisture ✻ Emulsion Type interaction ($Q = 572$, $p = 0.001$) shows that moisture levels can alter emulsion effectiveness in soil stabilization, possibly affecting particle adhesion. Finally, the triple interaction Cycles ✻ Moisture ✻ Emulsion Type ($Q = 213$, $p = 0.001$) indicates that the relationship between these factors is non-linear, requiring strict control of variables to ensure optimal performance of the stabilized soil.

Post hoc tests revealed statistically significant differences among the analyzed groups. Regarding loading cycles, the highest increases in stiffness occurred in the initial loading phases. The difference between the 1st and 6th cycles was highly significant ($\Delta_{stiffness} = -3823$, $p < 0.001$). Optimal moisture content was identified at 8.2%, where the soil exhibited the highest resilient modulus (RM). Post hoc analysis revealed that the transition from 5.2% to 8.2% led to a significant increase in stiffness ($\Delta_{stiffness} = -1064$, $p < 0.001$), whereas increasing moisture content to 11.2% drastically reduced material stiffness ($\Delta_{stiffness} = -2979$, $p < 0.001$). This confirms that excessive moisture levels compromise stabilization efficiency. The emulsion type analysis confirmed that slow-breaking emulsion (SBE) exhibited the best mechanical performance. The difference between natural soil and stabilized soil with SBE was $\Delta_{stiffness} = -1817$ ($p = 0.003$), indicating a significant increase in material strength. Additionally, SBE significantly outperformed medium-breaking emulsion (MBE) ($\Delta_{stiffness} = -2369$, $p < 0.001$), reinforcing its superiority in soil stabilization.

Interactions between cycles, moisture, and emulsion were analyzed in detail. The combination of low moisture content (5.2%) and slow-breaking emulsion (SBE) provided the highest stiffness but became less effective as loading cycles increased. Conversely, when moisture reached 8.2%, the slow-breaking emulsion maintained its high performance throughout the cycles, indicating that this is the most suitable condition for stabilization.

The graphs presented, Figure 9, illustrate the variation of Resilient Modulus (RM) across loading cycles for different emulsion types: NE (No Emulsion), SBE (Slow-Breaking Emulsion), and MBE (Medium-Breaking Emulsion). Each graph also shows the effects of three moisture contents (5.2%, 8.2%, and 11.2%), enabling a detailed analysis of the impact of these factors on the stiffness of the stabilized soil.

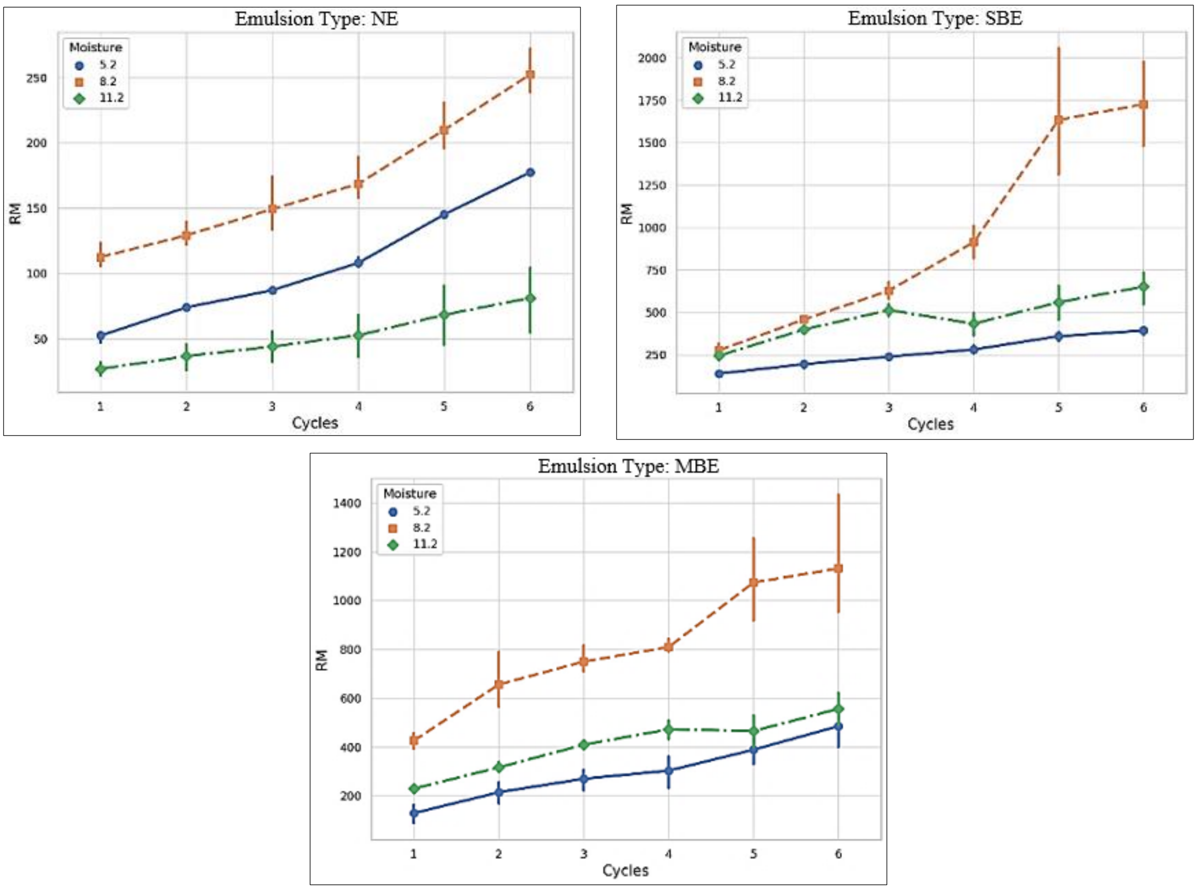

Figure 9. Post-hoc graphics for performance of emulsions

For the untreated soil (NE – No Emulsion), RM values increase gradually over the cycles for all tested moisture levels, with the highest values observed at 8.2%. This behavior indicates that even in the absence of emulsion, the soil benefits from compaction energy and proximity to the optimum moisture content. Nonetheless, the RM values remain significantly lower than those obtained in stabilized conditions, confirming the limited mechanical performance of the untreated material under cyclic loading.

In the case of slow-breaking emulsion (SBE), the increase in RM is much more pronounced, especially at the optimum moisture content of 8.2%. A substantial stiffness gain is observed after the fourth cycle, with peak performance reached by the sixth. This trend confirms the synergistic effect of slow-setting emulsions and optimum moisture in promoting a cohesive internal structure and effective binder-soil interaction, which enhances the material's elastic response. On the other hand, when the moisture is either too low (5.2%) or too high (11.2%), the stiffness curves are flatter, suggesting that emulsion dispersion and curing were suboptimal, thus limiting the structural benefits.

For the medium-breaking emulsion (MBE), the RM also increases with the number of cycles, though at a slower rate than observed for SBE. While the 8.2% moisture condition again yields the best results, the overall gains are more moderate, indicating that MBE may be less efficient in promoting interparticle bonding under the same compaction and curing parameters. At the extremes of moisture (5.2% and 11.2%), the behavior mirrors that seen in the SBE condition, with lower stiffness values and limited improvement over time.

It is important to highlight that a significant change in soil behavior is observed after stabilization. In the dry branch of the compaction curve, the natural (unstabilized) soil exhibits superior performance compared to its behavior in the wet branch. However, this trend reverses once the soil is stabilized with asphalt emulsion: in the dry branch, the stabilized soil tends to exhibit lower stiffness. This shift indicates that stabilization modifies the interaction between particles and the binder, especially under different moisture conditions, altering the mechanical response of the material.

4.6. Discussion

Soil stabilization is a widely used technique to improve the mechanical performance of base layers in pavements, playing a fundamental role in ensuring greater strength and durability of road structures. However, the choice of stabilizer and application conditions, such as compaction energy, curing time, and moisture content, directly influence the mechanical properties of the treated material. This study investigates the stabilization of gravelly-sandy soil with asphalt emulsion and compares its results with the stabilization of an expansive clay using ethylene-vinyl acetate (EVA) copolymer emulsion, as analyzed in the study by Liu et al. [4].

Compaction plays a key role in achieving the optimal density of the stabilized soil. In this study, modified compaction was applied, ensuring a higher dry density and promoting better adhesion between soil particles and asphalt emulsion. In contrast, Liu et al. [4] adopted the Standard Proctor compaction, a less intensive method that is more suitable for highly plastic soil but may result in lower density and, consequently, lower final stiffness. This methodological difference directly influences the resilient modulus values, as modified compaction is expected to provide a more resistant material due to the higher energy applied to the formation of the granular structure of the stabilized soil. Curing time also has a significant influence on the development of strength in stabilized materials. In this study, the samples were cured for 21 days at room temperature (≈25°C), allowing the formation of the asphalt matrix and ensuring the progressive adhesion of mineral particles to the residual binder. On the other hand, Liu et al. [4] adopted a curing time of seven days in a humidity chamber (20°C and 95% relative humidity), promoting EVA polymerization and stabilization of the clay particles.

Previous studies indicate that curing periods longer than seven days can continue contributing to increased stiffness, especially in mixtures stabilized with asphalt emulsion, where longer curing favors the complete adhesion of the binder to the granular material. The materials studied have distinct characteristics, directly impacting the behavior of the stabilized mixtures. The gravelly-sandy soil treated with asphalt emulsion presents low plasticity and a mixed particle size distribution, with particles of different sizes that favor residual binder anchoring and improved mechanical strength. In contrast, the soil analyzed by Liu et al. [4] is an expansive clay, characterized by high plasticity and strong volumetric variation due to moisture changes. EVA stabilization proved effective in reducing clay expansion, promoting better aggregation among its particles and minimizing swelling effects. Thus, while asphalt emulsion improves compaction and resistance of granular soils, EVA appears to be a more effective alternative for stabilizing clayey soils, reducing their sensitivity to moisture variations. Moisture significantly influences the performance of stabilized soils. In this study, it was observed that the resilient modulus reached its peak at an optimal moisture content of 8.2%, with a sharp reduction when compaction occurred in both the dry and wet branches, demonstrating that high moisture levels can compromise the stiffness of the stabilized soil.

Both studies demonstrated significant gains in material stiffness but identified optimal stabilizer contents to ensure the best performance. In this study, the best stiffness was observed with 2% asphalt emulsion, resulting in a 452.32% increase in resilient modulus for the slow-breaking emulsion and 375.29% for the medium-breaking emulsion. Higher percentages resulted in a reduction in stiffness, possibly due to the excess emulsion acting as a lubricant between soil particles.

In Liu et al. [4], the best performance was achieved with 1% EVA, promoting a 35.8% increase in resilient modulus and a 177.8% increase in CBR. Beyond this content, stiffness decreased, probably due to the polymer's plasticizing effect, which weakened the cohesion between soil particles. Thus, both studies indicate that, although stabilizers improve mechanical strength, dosage must be carefully controlled to avoid adverse effects. The stabilization of soils and recycled mixtures using asphalt emulsion has been extensively studied for application in pavement base layers. However, different approaches can be adopted depending on material gradation, emulsion type, and compaction and curing conditions. This study evaluates the performance of a gravelly-sandy soil stabilized with asphalt emulsion, while Coelho et al. [45] investigated granular mixtures stabilized with emulsion and reclaimed asphalt pavement (RAP) materials. The comparison between the studies allows for an in-depth analysis of the factors influencing the resilient modulus (RM), permanent deformation (PD), and stabilization efficiency.

The compaction of stabilized materials presents relevant methodological differences between the studies. In this study, modified compaction energy was adopted, ensuring better densification of the soil and promoting stronger adhesion of the emulsion to mineral particles, like Coelho et al. [45]. The choice of compaction energy directly influences the stiffness of the final mixture, and higher compaction efforts typically result in materials with lower deformation under cyclic loading. The curing time of stabilized mixtures also varied between the studies. In this work, samples were cured for 21 days at room temperature (≈25°C), allowing the formation of the asphalt matrix and gradual adhesion of the binder to soil particles. Conversely, Coelho et al. [45] used a reduced curing period of 48 hours in open air, simulating field conditions. Literature indicates that longer curing times can enhance mechanical strength, especially in cold-stabilized mixtures, where emulsion evaporation and granular structure consolidation occur progressively.

The nature of the stabilized material in the two studies also differs. This study analyzed gravelly-sandy soil stabilized with 2% asphalt emulsion, focusing on moisture's influence on final stiffness. In contrast, Coelho et al. [45] investigated mixtures containing fractions of RAP and natural aggregates stabilized with different emulsion contents (1% to 5%). The addition of RAP significantly alters the mechanical response of the mixture, as RAP's residual binder interacts with the emulsion, potentially modifying cohesion between particles and compaction capacity.

Moisture's influence on the stiffness of stabilized material was analyzed in both studies but with different focuses. In this work, the resilient modulus peaked at the optimal moisture content of 8.2%, with significant stiffness loss at higher moisture levels. This behavior is typical of asphalt emulsion-stabilized mixtures, as excess moisture can compromise adhesion between mineral particles and residual binder.

In contrast, Coelho et al. [45] evaluated mixtures with different emulsion contents, finding that the best performance was achieved with 1% emulsion, while higher contents led to greater permanent deformation, suggesting that excess emulsion may act as a lubricant, reducing shear resistance. Regarding stiffness, both studies demonstrated significant increases in resilient modulus (RM) of stabilized materials, but with different optimal emulsion contents. In this study, the highest stiffness was obtained with 2% asphalt emulsion, providing a 452.32% increase in RM for slow-breaking emulsion and 375.29% for medium-breaking emulsion. Meanwhile, Coelho et al. [45] observed RM values ranging from 350 to 500 MPa, depending on emulsion content and RAP proportion in the mixture. The comparison indicates that, while asphalt emulsion alone improves cohesion in granular soil, the presence of RAP introduces variability in results, requiring careful adjustment of stabilizer dosage.

Overall, the results of this study are consistent with the literature and further strengthen the evidence supporting the effectiveness of soil stabilization using asphalt emulsion—particularly when slow-setting emulsion is applied at optimal moisture content—for improving the mechanical performance of gravelly-sandy soils. When compared with other techniques, such as EVA stabilization for expansive clays or mixtures using RAP and emulsion, this study reinforces the importance of moisture control and compaction energy in achieving higher material stiffness.

While each type of stabilizer offers specific advantages depending on soil type and field conditions, the findings presented here highlight the potential of asphalt emulsion as a technically efficient and environmentally favorable solution for use as a primary surface layer or unpaved road base, provided the material is technically suitable for asphalt stabilization. These results contribute to pavement design optimization and support the broader applicability of asphalt stabilization in diverse geotechnical contexts.

5. Conclusion

This study confirms that the stabilization of gravelly-sandy soils with 2% asphalt emulsion and modified compaction energy is an effective technique for increasing the structural stiffness of pavement base layers. The choice of emulsion type and moisture content proved to be critical variables, directly influencing the resilient modulus (RM) of the stabilized material. The results showed that the slow-setting emulsion (SSE) provided better mechanical performance, especially at the optimal moisture content of 8.2%, which resulted in the highest RM values. It was also observed that the strength of the stabilized material is more sensitive to moisture deficiency than to excess moisture: in the dry branch (5.2%), the low moisture content hindered the proper dispersion of the emulsion in the soil, significantly compromising final stiffness. In the wet branch (11.2%), although the excess moisture reduced the adhesion of asphalt globules to soil particles, the negative impact was less pronounced. The application of Robust ANOVA enabled a reliable statistical analysis of the main factors — moisture, emulsion type, loading cycles — and their interactions, even under conditions of non-normality or heteroscedasticity.

The study also innovated by incorporating quantitative analyses using computer vision and SEM-EDS techniques. These analyses confirmed the soil's favorable morphology and chemical composition for stabilization. The angular grain structure and wide particle size distribution promoted compaction and intergranular interlocking, while the presence of silicon (SiO_2) and aluminum (Al_2O_3) oxides enhanced adhesion with cationic emulsions. Furthermore, the soil's chemical stability and low weathering indices (Ki = 10.52; Kr = 5.28) reinforce its suitability for long-term applications in road infrastructure. The findings contribute to the advancement of technical and scientific knowledge on emulsion-based stabilization and provide practical support for the optimization of pavement design. Complementary studies are recommended to assess aspects such as durability under environmental exposure and fatigue resistance, to ensure the safe and effective application of these techniques under real field conditions.

5.1. Research Opportunities

Based on the identified gaps, this study opens new opportunities for research in soil stabilization, including:

- Long-term durability analysis of stabilized mixtures – Evaluating the behavior of these mixtures under different moisture and temperature cycles over time to understand their resistance to weathering and mechanical fatigue.
- Application of artificial intelligence and machine learning in soil characterization – The use of machine learning algorithms can enhance segmentation and particle size analysis of images, increasing accuracy in particle detection and classification.
- Combined analysis of asphalt emulsion with other stabilizers – Testing the interaction between emulsion and other stabilizing agents (e.g., lime or cement) to verify if there is synergy in improving the mechanical properties of the soil.
- Full-scale experimental validation – Implementing field tests to validate laboratory findings and verify the practical applicability of the recommendations.
- Exploring different compaction energies – Assessing whether the relationship between moisture, emulsion, and resilient modulus remains consistent under different compaction energy levels, particularly in soils with different compositions.
- Environmental safety and groundwater protection - Analyzing the potential environmental impact of different stabilization types—bituminous, chemical, or blended—on the quality and potability of groundwater, particularly in regions with permeable soils or shallow aquifers.

6. Declarations

6.1. Author Contributions

Conceptualization, A.S.M.; methodology, A.S.M.; software, A.SM.; validation, A.S.M.; formal analysis, A.SM.; investigation, A.S.M. and M.A.V.S.; resources, A.SM. and M.A.V.S.; data curation, A.S.M.; writing—original draft preparation, A.S.M. and M.A.V.S; writing—review and editing, A.S.M. and MHSC.; visualization, A.S.M. and M.A.V.S.; supervision, A.S.M. and M.A.V.S.; project administration, A.SM. and M.A.V.S.; funding acquisition, A.S.M. and M.A.V.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

This study was partially funded by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) Brazil – Finance Code 001 and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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