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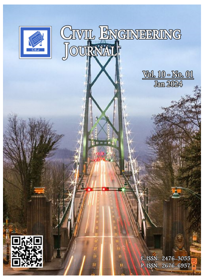

Evaluation of the Mechanical Behavior of Soil Stabilized with Asphalt Emulsion Using Multi-Stage Loading

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Abstract

The objective of this research was to assess the mechanical response (resilient and plastic) of soil stabilized with petroleum asphalt concrete using asphalt emulsion under multi-stage loading. To enhance the adhesion of the asphalt film to the soil grains, the stabilized soil underwent air-drying curing for seven days. Dosage was conducted through the indirect tensile strength test using diametral compression. With the optimum content determined in the dosage (2% emulsion), additions and removals of 0.5% asphalt emulsion from this content were performed. Consequently, three specimens were molded with concentrations of 1.5%, 2%, and 2.5% of slow-setting cationic asphalt emulsion. These specimens were then subjected to drained triaxial tests under multi-stage loading, using 5 different stress pairs, totaling 50,000 cycles. Analyzing the regions defined by the total and permanent deformation curves allowed studying the plastic and elastic response, the proportionality between these regions, and the increase in elastic and plastic regions of the soil and stabilized soil in a single test, providing a more accurate interpretation. Regarding the measured deformations, as the deviator stress was increased with each loading cycle, the stabilized samples exhibited an increase in plastic deformations compared to the natural soil (control). It was also observed a proportional increase in the resilient region, indicating that the addition of asphalt made the soil less rigid but provided cohesion that was absent before stabilization.

Keywords: Multi-Stage; Permanent Deformation; Resilient Deformation; Asphalt Emulsion.

1. Introduction

The manual for the design and construction of materials stabilized with asphalt emulsion in South Africa (2020) [1] highlights the beneficial potential of using asphalt emulsion or foamed asphalt for material stabilization in various situations. These advantages depend on the type of project and specific site conditions. Firstly, the incorporation of this technique can significantly increase the cohesion and strength of the material, contributing to greater durability and pavement lifespan. Moreover, the possibility of reusing existing materials reduces the demand for new resources and minimizes environmental impact. Another positive aspect is the ability to carry out construction in adverse weather conditions, such as low temperatures or excessive humidity, which can be crucial in certain regions. Finally, the reduction in construction time and costs, especially when recycling materials on-site, makes this method an economical and resource-efficient choice.

Therefore, this research began with a bibliometric analysis (a quantitative and statistical approach used to examine patterns, trends, and relationships in a set of bibliographic documents), aiming to find in the literature review a connection between multi-stage loading tests and soils stabilized with asphalt emulsion or asphalt. In the research conducted on the Scopus and Web of Science databases, using cluster analysis with the bibliometric interface accessed

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through R, no integration was observed between multi-stage loading tests and soil stabilization through asphalt emulsion. For the database search, the keywords "multistage," "multi-stage," "repeated loading test," and "permanent deformation" were used, and the results are displayed in the keyword co-occurrence network map in Figure 1. The analysis highlighted a research gap with the potential to be explored and developed. Consequently, discussions that encompass both topics simultaneously are insufficient, making it challenging to adequately address the convergence of both themes.

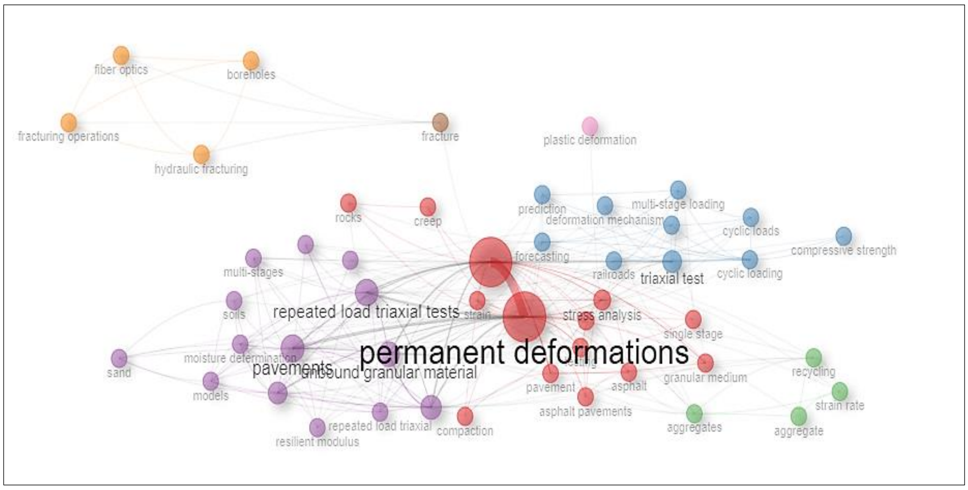


Figure 1. Co-occurrence Network Map

For ease of visualization of the clusters, they have been separated by number in Table 1**.** The clusters group the works based on research affinity, bringing to light the relationships between the keywords of these different studies

Table 1. Co-occurrence Network table by node

Node	Cluster	Node	Cluster	Node	Cluster	Node	Cluster
Deformation	1	Triaxial Test	2	Strain Rate	3	Sand	4
Permanent Deformations	1	Forecasting	2	Aggregate	3	Water Content	4
Stress Analysis	1	Cyclic Loading	2	Pavements	4	Hydraulic Fracturing	5
Pavement	1	Deformation Mechanism	2	*Repeated Load Triaxial Tests*	4	Boreholes	5
Testing	1	Railroads	2	Granular Materials	4	Fiber Optics	5
Granular Medium	1	Soil Mechanics	2	Unbound Granular Material	4	Fracturing Operations	5
Creep	1	Cyclic Loads	2	Moisture	4	Fracture	6
Deformation Characteristics	1	Prediction	2	*Multi-Stages*	4	*Plastic Deformation*	7
Asphalt	1	Compressive Strength	2	*Repeated Load Triaxial*	4		
Rocks	1	Multi-Stage Loading	2	Moisture Determination	4		
Single Stage	1	Triaxial Test	2	Soils	4		
Strain	1	Forecasting	2	Models	4		
Asphalt Pavements	1	Recycling	3	Particle Size	4		
Compaction	1	Aggregates	3	Resilient Modulus	4		

Cluster 1 suggests works with a focus on material properties used in pavements, especially related to permanent deformation. Cluster 2 highlights an experimental and analytical approach, focusing on tests and mechanical characteristics. Cluster 3 suggests themes associated with sustainable practices (recycling), aggregate characteristics, and aspects related to pavements. Cluster 4 focuses on the interaction between granular materials and pavement, emphasizing the importance of tests and prediction models. Cluster 5, covering terms such as hydraulic fracturing, boreholes, and fiber optics, suggests a geotechnical or field approach, focusing on investigation methods and monitoring in terrains. Cluster 6, with a focus on the concept of fracture, appears to explore phenomena related to material breakage or failure, possibly associated with specific loading conditions. Finally, Cluster 7, centered on concepts like plastic deformation, indicates a more detailed analysis of plastic behavior about multi-stage loading, suggesting an emphasis on material plasticity under specific loading conditions. However, none of them addresses the interaction between multi-stage loading and soil stabilization with asphalt emulsion or related topics, highlighting a research gap.

However, it's worth noting the existence of a study published in 2023 in the Transportation Geotechnics journal. This study addresses asphalt stabilization using 1, 2, and 3% of the dry weight of construction and demolition waste

(CDW) and crushed bricks through multi-stage loading. However, the abstract and keywords of the study do not specifically reference the use of multi-stage loading, focusing solely on permanent deformation. This study is included in the literature review. Thus, this study contributes to bridging two important topics in pavement engineering: triaxial testing with multi-stage loading and stabilization using asphalt emulsion.

Addressing the multistage loading technique, as highlighted in several studies such as those by Rahman et al. (2023) [2] and Maghool et al. (2023) [3], plays a crucial role in evaluating materials used in pavement construction and the behavior of granular materials. Its main contribution lies in the substantial reduction of time and effort required to test a wide range of stress levels in a single specimen, compared to single-stage tests. Furthermore, multistage loading allows for the assessment of the behavior of mixtures and materials under different stress levels, which is essential to understanding their performance under variable loading conditions, such as those encountered on pavements. This realistic approach not only saves resources but also enhances the accuracy and reliability of tests, providing a comprehensive understanding of the mechanical behavior of materials under different stress conditions.

The positive contribution of the multistage loading technique to research is feasible. The analysis of permanent and resilient deformation using multistage loading allows the designer to assess in greater detail how materials used in pavement construction respond to variations in loading conditions, similar to what occurs in the field. Multistage loading is a more efficient test, reducing experimental variability by eliminating the need to mold multiple specimens, as demonstrated in this study. This makes the test more realistic. As demonstrated in the literature review, research studies often use separate tests or assessments to analyze the resilient and plastic response of the material, as well as modeling to predict material behavior. As a scientific contribution, this study proposes a simultaneous evaluation method, i.e., both resilient and plastic responses from the same test displayed on the same graph, using total and permanent deformation. As a secondary objective, this research also aims to standardize dosage using asphalt emulsion. To achieve this goal, the diametral compression test was conducted, following the principle of economy for emulsion use, limiting its usage to up to 6% of the dry weight of the soil.

Considering the multistage loading test as an efficient method to assess the mechanical response (plastic and resilient performance) of materials, as evidenced in various studies presented in the literature review, it can be employed to measure the mechanical performance of asphalt-stabilized soil. However, as a limitation, stabilization will be studied at the optimal concentration determined during dosage, obtained through the diametral compression tensile test, and at the soil's optimum moisture content, as described in the methodology of this article.

Tests were conducted using six different quantities of asphalt emulsion about the dry weight of the soil. These quantities ranged from 1 to 6% of a slow-setting cationic emulsion. The stabilized soils underwent testing in a multipress to assess their mechanical response to diametral compression. The highest value was achieved with 2% of asphalt emulsion. From this point, 0.5% of the emulsion was added and removed. Specimens were then molded with 1.5, 2, and 2.5% and subjected to multi-stage loading tests.

In this way, it is possible to outline the objective of this study, which is to assess the mechanical response of asphalt-stabilized soil using asphalt emulsion for its application. To achieve this goal, dosage was performed through the indirect tensile test by diametral compression. The plastic and mechanical responses were assessed using multi-stage loading in 5 loading cycles. The purpose of this study was to simultaneously analyze the plastic and elastic regions, as well as the variation of these regions in each loading cycle. The regions were delimited by the curves of total and permanent deformation, and their area was calculated through trapezoidal approximations.

Therefore, this study aims to contribute to the expansion of knowledge regarding the use of petroleum asphalt concrete (PAC) contained in asphalt emulsions as a soil stabilizer, improving its mechanical performance without the need to heat the PAC for application. This represents an environmental benefit, as it allows the use of local materials, reducing emissions from transportation and optimizing economic resources, especially in remote road pavement infrastructure projects. The secondary objective is to specifically evaluate the influence of the asphalt film on stabilization. The stabilized soil was tested at the optimal moisture content of the natural soil, ensuring that moisture was a constant variable in all tests.

This article is divided into five distinct sections for a clearer and more organized understanding. In the first section (Section 1), the introduction is presented, where the problem is contextualized, the hypothesis is formulated, assumptions are outlined, and the objectives of this work are established. Next, in Section 2, the literature review is addressed, focusing on relevant studies that have investigated the use of asphalt emulsion and multi-stage loading. In Section 3, the methodology employed is detailed, along with the standards and guidelines used as a basis for the analyzes. Results and discussion are presented in Section 4, and finally, in Section 5, the research conclusions are presented.

2. Literature Review

The literature review is a fundamental step in research as it helps establish and guide the study, ensuring it is relevant, original, and well-informed by previous works related to the topic. Therefore, this literature review aimed to underpin this research with works addressing the use of asphalt emulsion and multi-stage loading.

2.1. Asphalt Emulsion

According to the results presented in the study by Brito et al. (2022) [4], in soil-emulsion mixtures tested under saturated conditions, there was no influence of curing time on the obtained results. However, in mixtures tested under unsaturated conditions, it was observed that an increase in curing time led to a significant increase in the cohesive intercept of the rupture envelopes obtained in the constant volume undrained (CIU) triaxial tests. This increase in the cohesive intercept was attributed to the increase in matric suction due to the evaporation of the water of constitution of the asphalt emulsion during the exposure of the specimens to ambient air at 25°C for the curing periods adopted in the study.

The study by Orosa et al. (2022) [5] investigated the shear and permanent deformation properties of cold in-place recycled (CIR) mixtures with bitumen emulsion using triaxial tests. The authors found that the binder content had a significant impact on the shear and permanent deformation properties of the CIR mixtures. Mixtures with higher binder contents exhibited higher cohesion but lower internal friction. The authors also found that the CIR mixtures exhibited critical stress ratios between 20% and 30%. The mixture with a 2.50% binder content exhibited the best response.

Regarding the use of emulsions, Andavam & Kumar (2020) [6] concluded in their review article that asphalt emulsions are an effective material for improving the properties of weak soils, especially in tropical and subtropical regions. The authors stated that asphalt emulsions offer advantages such as ease of application, low energy consumption, reduced environmental impact, and increased pavement durability. They also highlighted challenges and limitations in using asphalt emulsions, such as the need for quality control, appropriate dosage and emulsion type selection, the influence of climatic conditions, and the lack of standardized norms and specifications.

Kamran et al. (2020) [7] assessed the potential use of asphaltenes as a waste material to enhance the mechanical properties of emulsified asphalt-stabilized base mixes. The study used asphaltenes as a waste material derived from the asphalt sands of Alberta. They added 1% to 3% of asphaltenes by total weight to an aggregate mix stabilized with emulsified asphalt. The results showed that asphaltene-modified mixes had higher tensile strength and flow resistance, while their susceptibility to moisture was slightly lower than that of the control mix. The study used different percentages of asphalt emulsion to determine the optimal emulsion content concerning Marshall stability and flow.

The study by Oluyemi-Ayibiowu (2019) [8] concluded that the addition of asphalt emulsion could significantly improve the mechanical properties of lateritic soils, such as unconfined compressive strength (UCS) and California Bearing Ratio (CBR). The ideal proportion of asphalt emulsion varies depending on soil properties but generally falls between 4% and 6%. However, asphalt emulsion stabilization may not be effective in soils with high clay content.

The studies by Alizadeh & Modarres (2018) [9] investigated the mechanical properties of clayey soil stabilized with bitumen emulsion and limestone, using unconfined compression tests, indirect tensile tests, resilient modulus tests, and permanent deformation tests. The authors arrived at an optimal emulsion content of 6% and an optimal limestone content of 10% to achieve maximum soil strength and stiffness. It was observed that the stabilized soil exhibited lower plasticity, greater durability, and better resistance to moisture-related damage compared to untreated soil. They concluded that clayey soil stabilized with emulsion and limestone could be used as a suitable material for subgrade or base layers of pavements.

Based on the study by Bunga (2018) [10], the erosion rate of sandy clay stabilized with asphalt emulsion is subject to different influences, as observed in the tested parameters. The analysis of the results indicated that the erosion rate increased exponentially with the increase in rainfall intensity and linearly with the increase in slope. However, the erosion rate decreased exponentially with the increase in the volume of asphalt emulsion. Therefore, the application of asphalt emulsion may have a significant stabilizing effect on soil erosion, especially when confronted with factors such as rainfall intensity and slope. This conclusion could have practical implications for the management and control of erosion in areas where soil stabilization is a concern, such as drainage failure.

The study by Mignini et al. (2015) [11] evaluated factors affecting the short-term and long-term performance of a cement-treated base with bitumen emulsion through laboratory tests to determine its unconfined compressive strength (UCS), flexural strength (FS), and California Bearing Ratio (CBR). The study also investigated the durability of the cement-treated base with bitumen emulsion subjected to wetting and drying (WD) cycles and developed significant models to demonstrate the relationship between mixture characteristics. Regarding the results of permanent deformation tests, the addition of a mixture of 4% Portland cement and 3% bitumen emulsion reduced permanent deformation by 23.5% compared to using only cement and by 1682% compared to using only bitumen emulsion. Furthermore, the results showed that the Portland cement and bitumen emulsion mixture significantly improved the permanent deformation resistance of the mixture at different environmental temperatures.

As emulsion is a material that is easy to handle and offers numerous advantages in its application, researchers seek to refine the technique for using asphalt emulsion in soil stabilization, which is an important contribution of this study as mentioned in the introduction. However, as seen, there is still much to be done in the quest for standardizing the dosage method, tests, and normative standards to be followed.

2.2. Multi-Stage Loading

In Yaghoubi et al. (2023) [12], multi-stage loading was chosen to enhance the probability of extracting all three shakedown rating ranges discussed in the study. By conducting a series of multi-stage tests on five distinct combinations of confinement stress and deviator stress, it was possible to evaluate the permanent deformation of samples and classify them based on shakedown theory, using bituminous emulsion for the stabilization of construction and demolition waste. A fixed confinement stress of 40 kPa was chosen in conjunction with deviator stresses of 140, 220, 300, 380, and 460 kPa. These stress pairs were selected to cover a wide range of deviator-to-confinement stress ratios, ranging from 3.5 to 11.5, which represent typical stress conditions in pavement base and subbase layers.

Additionally, according to research conducted by the aforementioned authors, aggregate samples were mixed with a slow-setting cationic bitumen emulsion at different percentages of 0, 1, 2, and 3% of the dry weight of the aggregates. The study concluded that bitumen emulsion stabilization had no noticeable effect on improving the permanent deformation responses of recycled concrete and crushed brick aggregate mixtures. Finally, the contribution of multi-stage loading was the ability to classify the mixtures and assess their permanent deformation at different stress levels.

Maghool et al. (2023) [3] used different stress pairs in the study, which were applied in combinations of confinement stress (σc) and deviator stress (σd). The stress pairs used were: σc = 40 kPa and σd = 140 kPa, σc = 40 kPa and σd = 220 kPa, σc = 40 kPa and σd = 300 kPa, σc = 40 kPa and σd = 380 kPa, and σc = 40 kPa and σd = 460 kPa. These stress pairs were applied in each stage of the multi-stage test, involving 10,000 repetitions. The contribution of multi-stage loading is that it allows the evaluation of mixture behavior under different stress levels, which helps to better understand how mixtures perform under variable loading conditions. This is important for assessing the suitability of mixtures for use in pavements, where loading conditions may vary over time.

The objective of this study, conducted by Barbieri et al. (2023) [13], was to investigate and compare the stabilization potential of traditional and non-traditional binders used in road pavement engineering. Multi-stage loading was employed in one of the laboratory tests conducted in this study to assess the resistance of rock aggregates stabilized with different types of binders to repeated loads. This test was conducted both before and after 10 cycles of freeze-thaw action. The contribution of multi-stage loading was to evaluate the resistance of stabilized aggregates to repeated loads, which is crucial for assessing the durability and lifespan of road pavements. Multi-stage loading was performed following the Multi-Stage Low Stress Level (MS LSL) procedure, consisting of thirty loading sequences as defined in (EN 13286-7, 2004) [14].

Ghorbani et al. (2023) [15] studied the potential use of geothermal energy for heating and cooling pavements to reduce energy consumption and greenhouse gas emissions. This test was employed to assess the load-bearing capacity of unbound granular materials, which are often used as base layers in pavements. The multi-stage loading test allowed for the evaluation of deformation and recovery of granular materials under different load levels, essential for designing durable and safe pavements. The multi-stage loading procedure utilized a constant confining stress of 50 kPa and deviatoric stresses equal to 250, 350, and 450 kPa, applied to the samples according to the Austroads AG:PT/T053 [16] repeated-load triaxial test method. Each stage included 10,000 cycles of cyclic loads with loading and resting periods of 1 s and 2 s, respectively.

The authors Wang et al. (2023) [17] investigated the permanent and resilient deformation behavior of three types of recycled concrete aggregates (RCA) from different sources: demolished buildings (RCAB1 and RCAB2) and concrete pavement (RCAP). The contribution of the multi-stage test was to assess the material's behavior under different levels of stress and loading cycles, allowing the analysis of permanent and resilient deformation under various loading conditions. This provided a better understanding of the material's performance under real traffic conditions and helped evaluate its suitability for use in road base and sub-base. Repeated Load Triaxial Tests (RLTT) represent a significant method for investigating the permanent and resilient deformation behavior of Unbound Granular Materials (UGM) under traffic loads. In this study, RLTTs were conducted following the procedure outlined in the European Standard (EN 13286-7, 2004) [14].

The multi-stage loading technique was employed in the study by Medeiros et al. (2023) [18] to examine how moisture affects permanent deformation in tropical soils, using four different loading cycles. The results revealed that permanent deformation increases as moisture rises, with this effect being more pronounced in sandy and clayey soils compared to lateritic soil. In addition to providing specific insights for this research, the multi-stage method emerges as an effective tool for exploring the behavior of materials subjected to various loading conditions. It can be applied to investigate the influence of factors such as moisture, temperature, confinement, and loading history, thus contributing to advances in understanding the mechanical response of different materials.

Arulrajah et al. (2022) [19] applied the multistage loading technique to study geothermal pavements in their research. A geothermal pavement is a type of pavement that utilizes the thermal energy from the ground to heat or cool buildings. This type of pavement consists of a base layer, which is installed beneath the pavement surface, and a series of tubes buried in this layer. Water or another fluid circulates through the tubes, absorbing heat from the ground during winter and transferring it to the building for heating. The contribution of multistage loading was to provide a comprehensive understanding of the mechanical behavior of different materials under various stress levels. This understanding is considered essential for designing more sustainable pavement systems. Stresses at the ratio ($\sigma d/\sigma c$) of 2, 4, 6, and 8 were applied to characterize the deformation behavior of crushed brick (CB) and recycled concrete aggregate (RCA) in the multistage test.

The objective of Ghorbani et al. (2021) [20] study was to investigate the deformation properties of RCA mixed with recycled glass (RG) for pavement base applications. The study employed experimental analysis and artificial neural network modeling for the dynamic characterization of RCA/RG blends. A multi-stage loading test was used to assess the permanent deformation behavior of RCA/RG mixtures. The contribution of the multi-stage test was that it allowed the evaluation of mixture behavior at different levels of deviatoric stress, which was crucial for understanding the blend's performance under real traffic conditions.

The study by Lin et al. (2017) [21] used confinement and deviator or soliciting stresses based on typical field conditions for subgrade soils. Confinement stress was chosen to represent the vertical pressure exerted by the weight of the soil layer above the subgrade, while deviator or soliciting stress was chosen to represent the load applied by vehicle tires on the pavement surface. These stresses were chosen to simulate the realistic loading conditions that subgrade soils experience in the field and therefore provide more relevant information about the accumulated plastic deformation behavior under field conditions.

The study used different amplitudes of dynamic stress for cyclic loading, ranging from 25 to 114 kPa, depending on the group of samples tested. Additionally, different levels of confinement pressure were applied, ranging from 60 kPa to 150 kPa, depending on the group of samples tested. The study employed multi-stage cyclic loading to characterize the behavior of accumulated plastic deformation at different loading phases.

The overall objective of Salour & Erlingsson (2017) [22] was to investigate the applicability of using multi-stage RLT tests for modeling the permanent deformation of fine-grained subgrade soils. According to the authors, the contribution of the multi-stage test is that it allows a more realistic simulation of traffic loading conditions in the field, which typically involve load pulses with varying magnitudes. Moreover, the multi-stage test can provide a more comprehensive understanding of pavement behavior without the need to prepare and test multiple samples, which can be tedious and costly. The multi-stage loading test procedure involved conducting three loading sequences, each containing three stress cycles with a constant confining pressure and different deviator stresses (totaling 9 stress paths). In each stress path, 10,000 load cycles were applied, followed by the subsequent stress path (totaling 90,000 load applications). Each load pulse consisted of a 0.2-second load followed by a 0.4-second rest period. A constant contact stress of 5.5 kPa was always used between the load pulses.

Various deviator stress (Δq) and confinement stress (σ_3) values were applied to assess the material's response under different loading conditions. The loading sequences were structured with different combinations of these stresses. The confinement stress, representing the pressure applied to the specimen, varied between 27.6 and 55.2 kPa. Simultaneously, the cyclic deviator stress, indicative of the fluctuating stress levels during loading cycles, ranged from 13.8 to 124.2 kPa.

In summary, multi-stage loading allows for a comprehensive assessment of material behavior under various loading conditions, which is crucial for the design, safety, and durability of structures, pavements, and subgrade soils in real-world scenarios. Each study highlighted the importance of this approach in understanding the behavior of different types of materials under load variations.

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) and as A-2-4 per the HRB methodology (AASHTO, 2003) [23] was used. Table 2 presents a summary of the average geotechnical parameters of the soil. This is a sandy soil with pebbles that completely disintegrates in the presence of water because it lacks cohesion, making it even more suitable to be stabilized with asphalt emulsion.

Table 2. Geotechnical parameters of the soil

Parameters	Values
LL - Liquid Limit	NP
LP - Plastic Limit	NP
Real Grain Density	2.87 g/cm³
Bulk Dry Density	2.25 g/cm³
Void Ratio (e)	0,274
Optimum Moisture Content	9.42 %

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

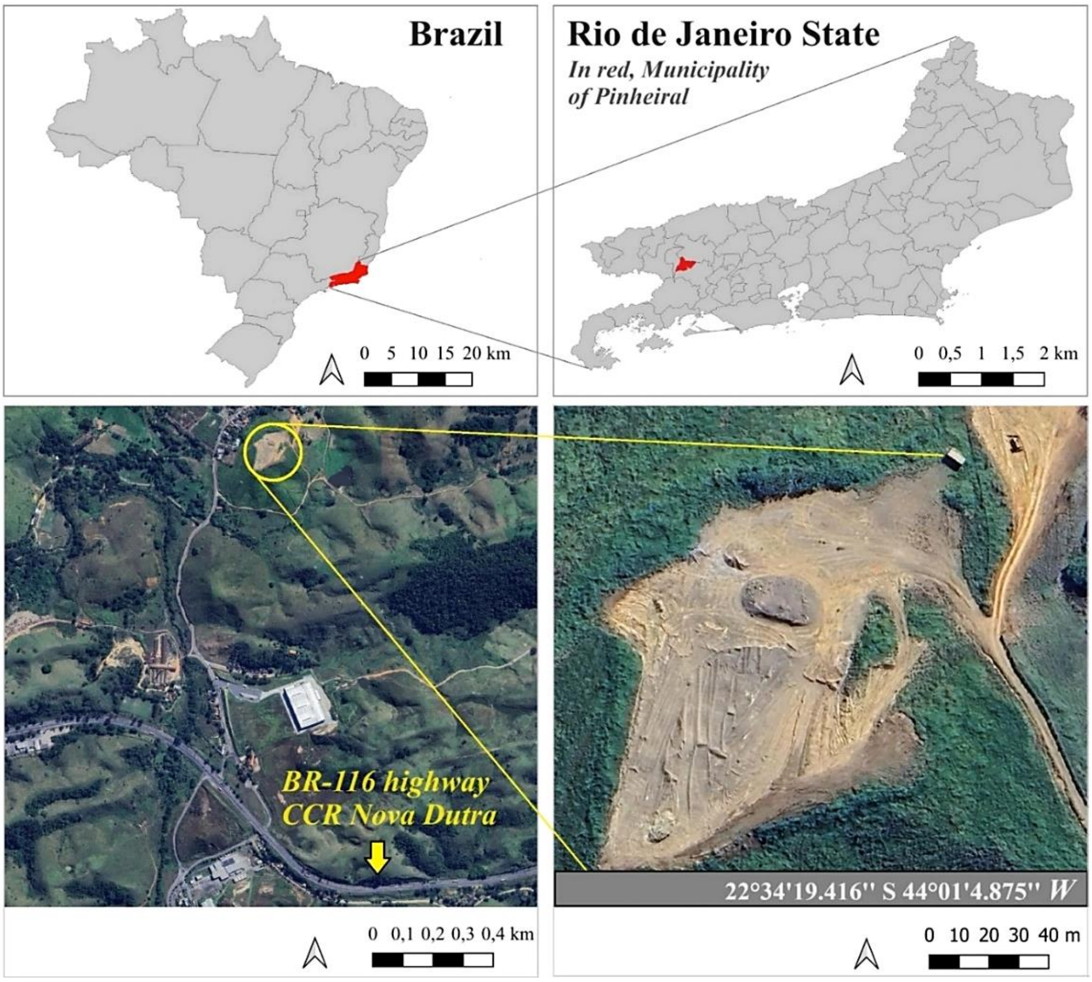


Figure 2. Location where the soil samples were extracted

The deposit where the soil was extracted exhibits a brownish color with low ground cover. It is also noteworthy that the presence of gravel can be observed in a sandy substrate, easily identified both visually and tactilely, as depicted in Figure 3.

Figure 3. Location where the soil samples were extracted

According to studies conducted by Zaroni & Santos (2021) [24], tropical regions exhibit an accelerated pedogenetic process influenced by a hot and humid climate, as well as intense water action and the presence of organisms. The greater the water availability, the more intense the chemical weathering reactions, resulting in soils with a higher proportion of secondary minerals, reflecting the alteration of the original material.

The authors conclude that, under tropical conditions, kaolinitic, lateritic, and soils rich in iron, aluminum, and titanium oxides predominate, characterized by being highly weathered and generally having low to very low fertility. This information is crucial for engineers who need to design in areas without access to laboratories, as it indicates the presence of soils with a significant number of oxides that can be effectively stabilized using cationic-type emulsions.

3.2. SEM/EDS

The SEM/EDS is an electron microscopy system that combines the Scanning Electron Microscopy (SEM) technique with Energy-Dispersive X-ray Spectroscopy (EDS). This system is used to analyze the elemental composition and structure of materials at micro and nano scales. The SEM operates by bombarding the material with a high-energy electron beam. This beam interacts with the material's surface, producing secondary electrons that are detected and transformed into a high-resolution image. The generated image allows for a detailed visualization of the material's surface and topography.

The image, Figure 4, brings to light what can be observed in the particle size distribution, indicating that the soil is poorly graded, featuring rounded particles and a tendency to have a high number of voids, not containing micelle-like structures. This observation is consistent with the results of plasticity tests and the optimum moisture content recorded at 9.42%.

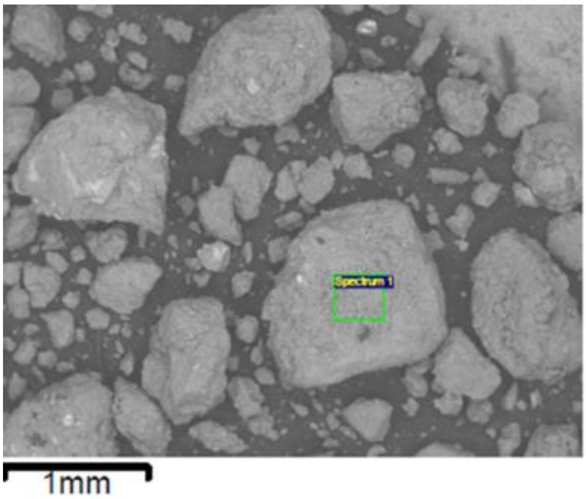


Figure 4. Image of the soil generated by the SEM

The EDS technique, on the other hand, is employed to identify the chemical elements present in the material. When the electron beam from the SEM interacts with the material, it also generates characteristic X-rays of the elements within the sample. These X-rays are detected by the EDS detector and transformed into an energy spectrum, enabling the identification of elements present in the sample and their concentration, Table 3.

Table 3. Elements present in the smoothed 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	-	O_2

When analyzing the chemical composition of the sample, some of the authors' conclusions Zaroni & Santos (2021) [24] can be corroborated. For instance, a significant presence of aluminum (6.842% as Al_2O_3) and iron (19.360% as FeO) in the sample is noted, information that aligns with the characterization of soils rich in oxides of these elements. Similarly, the substantial presence of silicon (22.970% as SiO_2) is consistent with the description of lateritic soils.

3.3. Emulsion

As can be seen in the emulsion classification shown in Table 4, the residual asphalt content for each emulsion percentage is as follows: 1% emulsion (0.62%), 2% emulsion (1.24%), and 3% emulsion (1.86%).

Table 3. Classification of asphalt emulsion

Essays (SS-1C)	Limits	Results
Saybolt Viscosity at 25°C (SSF)	70 max	17
Residue by Weight after Evaporation	60 min	62.0
Sieving at 0.84mm, % by Weight	0.1 max	0
Sedimentation for 5 Days, % by Weight	5 max	2
Particle Load	Positive	Positive
Mixing with Cement %	2 max	0.2

The emulsion percentage was determined based on the dry weight of the soil in an oven. For a 4000 g sample, 40 g of emulsion was used in the stabilization with 1% emulsion, and so on. These 40 g of emulsion, whose volume is approximately 43 ml at a temperature of 26°C, contain 62% of PAC. The remaining percentage of water, after deducting that of the emulsion, was added to reach the optimum soil moisture content.

All the water was incorporated into the emulsion, resulting in a less viscous mixture. Then, the soil was homogenized. Finally, samples of the mixture (soil + emulsion + water) were collected to check the moisture content to ensure that the presence of water would not influence the mechanical response of the tests as an additional variable.

In the images from Figure 5, we can observe the visual characteristics of color and grain size of the natural soil and the soil stabilized with asphalt emulsion. More precisely, this pertains to the grains encapsulated by the petroleum asphalt concrete.

Figure 5. From left to right - natural soil and soil stabilized with asphalt emulsion

3.4. Tests, Standards, and Procedures

The physical and mechanical characterization of the material used in this study was conducted following the testing standards described in the norms listed in Table 4.

Table 4. Tests and standards

Parameter	Test Title	International Standard
Granulometry	Particle Size Analysis by Sieving	ASTM D422 [25]
Sedimentation	Particle Size Analysis by Sedimentation	ASTM D422 [25]
LL	Liquid Limit Determination	ASTM D4318 [26]
PL	Plastic Limit Determination	ASTM D4318 [26]
Compaction	Compaction Using Unworked Samples	ASTM D698 [27]
Moisture Content	Soil - Determination of Moisture Content	ASTM D2216 [28]
TCD	Determination of Tensile Strength by Diametral Compression	ASTM D3967 [29]

The test specimens underwent a 7-day air-dry curing process, as it is necessary for materials stabilized with asphalt emulsion or foamed asphalt to cure before testing. This curing process allows the materials to reach an equilibrium condition before tests are conducted. Proper curing is important to ensure that test results are accurate and representative of the material's actual performance, following the guidelines established in the manual for the design and construction of emulsion-stabilized bituminous materials from South Africa (South Africa, 2020) [1]. As a benchmark for comparison, the natural soil also underwent the same 7-day air-dry curing. An example of molded specimens undergoing curing can be observed in Figure 6.

Figure 6. Curing specimens

Six different proportions of asphalt emulsion about the dry weight of the soil were tested, ranging from 1% to 6%, for indirect tensile or diametral compression tests. The test specimens were subjected to a multi-stage press with the assistance of the Lottman gantry. To perform the tests, the specimens with 10×20 cm were split in half, and the upper part was used (Figure 7).

Figure 7. Lottman portal and 10×10 cm test specimen

For the methodology of this study, the multi-stage loading technique was used with 10,000 loading cycles per stress pair. The tests were conducted at the optimum moisture content of the natural soil, which was of the drained type, totaling 50 thousand cycles of load application and a frequency of 2 Hz (with 0.1 s of load application and 0.4 s of rest). Cylindrical molds of 100×200 mm with samples passing through a 25.4 mm (1 inch) sieve were used. The tests were conducted on a triaxial press for drained-type tests, and their images can be seen in Figure 8.

Figure 8. Triaxial dynamic testing machine

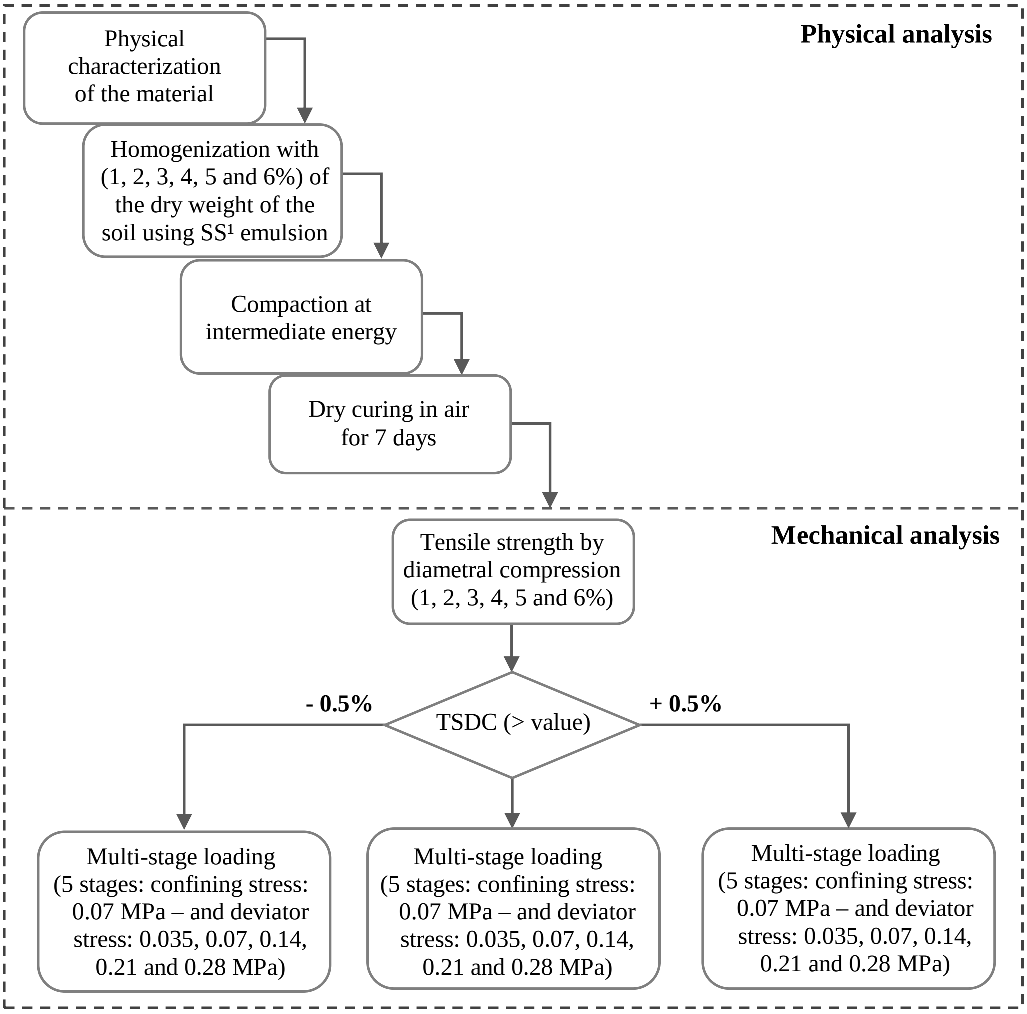
The multi-stage loading tests were carried out following the European standard EN-13286-7 (CEN, 2004a) [14]. This standard presents two sets of stress levels, referred to as "high-stress level" and "low-stress level." Each set is divided into five sequences. Each of these sequences contains several pairs of soliciting stresses, with constant confining stress and 10,000 loading cycles. For the tests conducted here, the sequences were applied using the "low-stress level," consistent with the stresses to which the material would be subjected in the field. Table 6 provides the stresses used in this study as explained.

Table 5. Stress ratio

Stage	σ1	σ3	σd	σd/ σ3
1	105	70	35	0.5
2	140	70	70	1
3	210	70	140	2
4	280	70	210	3
5	350	70	280	4

The selected loading values took into consideration the proportionality of typical loads due to the specificity of the procedure, considering additional evaluations based on current knowledge in the literature. The choice of these stress combinations considered the depth and typical loads found in road pavement subbases and subgrades, conforming to the experimental procedure of the European standard, as mentioned. Some of these loads were measured using the Multiple Layer Elastic Analysis modeling software [30], considering relevant increases of interest. The Multiple-Layer Elastic Analysis Program is a tool that can be used to calculate stresses and strains in pavement structures with up to eight layers. It is designed to simulate the effects of wheel loading from road vehicles. The choice was made to use intermediate compaction energy, considering the hypothesis that the improved soil could be employed in the sub-base of a low-traffic road pavement or as a stabilized subgrade. Therefore, the intention was to investigate the behavior of this stabilized soil under the mentioned compaction energy in these boundary conditions, as justified in the literature review.

As observed in the literature review, the stress pairs used to study materials employed in the road pavement base are 40 kPa for confining stress, and deviatoric stress varying in the ratio from three and a half to eleven times the value of the confining stress. Beyond this point, more resilient materials such as RAP, RCA, and CB are used, justifying the choice of more subdued stresses to test less noble materials used in deeper layers, where the soliciting stresses are less attenuated, and the confining stresses are higher. In this methodology, a confining stress of 70 kPa was used, with deviatoric stresses ranging from 0.5 to 4 times the value of the confining stress. To make the study methodology more understandable, the proposed experimental procedure can be visualized in Figure 9.



[1] ***Slow setting type (SS)***

Figure 9. Experimental plan

3.5. Plastic Region and Resilient Region

To define the plastic and resilient regions, the sum of the trapezoidal area was used, where the height is defined by the loading cycle, and the average base is determined by the arithmetic average of the percentages of permanent and total deformation. The resilient region was defined by subtracting the total deformation area from the plastic deformation area. The deformation history from the previous cycle was subtracted in each cycle. This allowed for the analysis of the soil and stabilizations concerning each loading cycle.

Plastic Region: An increase in the plastic region indicates that the material is undergoing permanent deformations and cannot recover its original shape after the application of the load. A larger plastic region signifies irreversible deformation. Plastic deformation is associated with wheel rutting in the pavement.

Plastic Variation: Plastic variation reflects the increase in the plastic region between loading cycles, indicating how much the material is experiencing permanent deformations with an increase in deviator stress. A higher plastic variation is associated with less favorable mechanical performance, as it indicates more significant plastic deformation between cycles.

Elastic Region: The elastic region is the part of the material that undergoes temporary deformation and can partially recover its original shape after the application of the load. A large elastic region may suggest a less rigid material. Elastic deformation is associated with fatigue cracking in the pavement.

Resilient Variation: Resilient variation indicates the increase in the elastic region, i.e., how much the material is behaving elastically and recovering its original shape after an increase in deviator stress between loading cycles.

Resilient/Plastic Ratio: A higher value of this ratio indicates that the material is accommodating and returning to its original shape after the application of the load. This suggests that the material retains its elasticity and recovery capacity. A lower value in this ratio indicates that plastic deformation is dominant, which is undesirable in many applications, as it indicates that the material is not accommodating even after becoming more compacted with a history of stresses.

4. Results and Discussions

4.1. Compaction

The compaction was performed at intermediate energy using a tripartite mold and an electric rammer, with a total of 27 blows per layer in 10 layers. The optimum moisture content of the soil was 9.42%, and the maximum dry density achieved was 2.25 g/cm³, as can be seen in Figure 10.

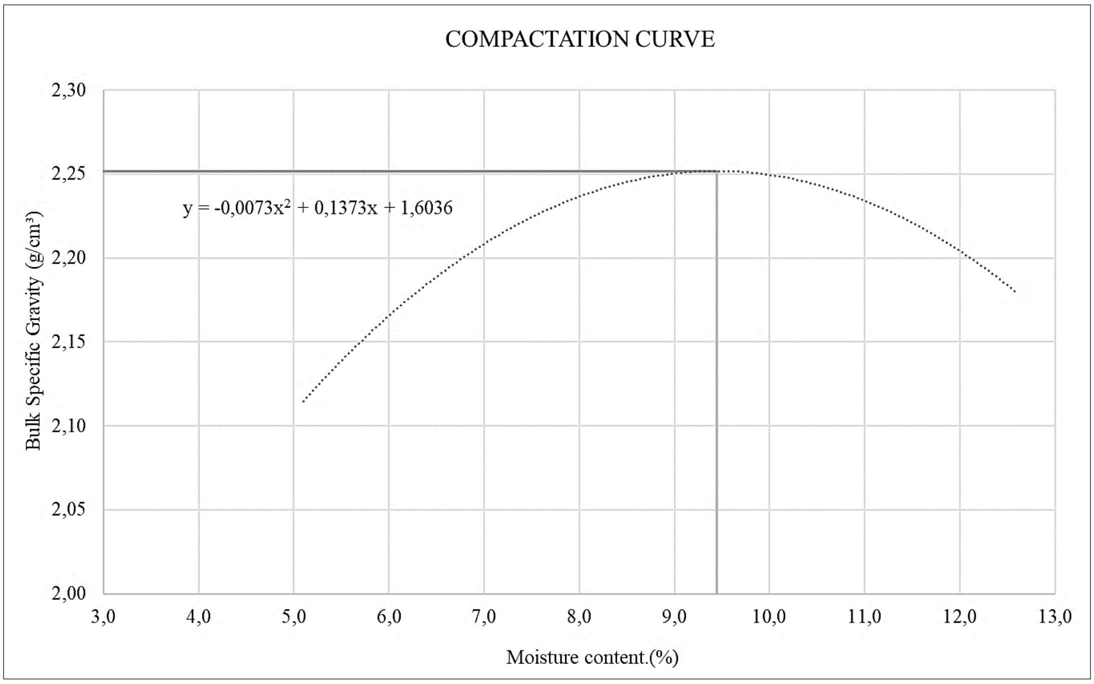


Figure 10. Tripartite Mold Compaction Curve

4.2. Granulometry

The soil has a poorly graded particle size distribution, with an effective diameter (D10) of 0.074 mm, an intermediate diameter (D30) of 0.166 mm, and a maximum diameter (D60) of 0.641 mm.

Using the Ferret triangle to classify the fine fraction of the soil, the following distribution is 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 18% passing through the No. 200 sieve, as shown in the graph in Figure 11.

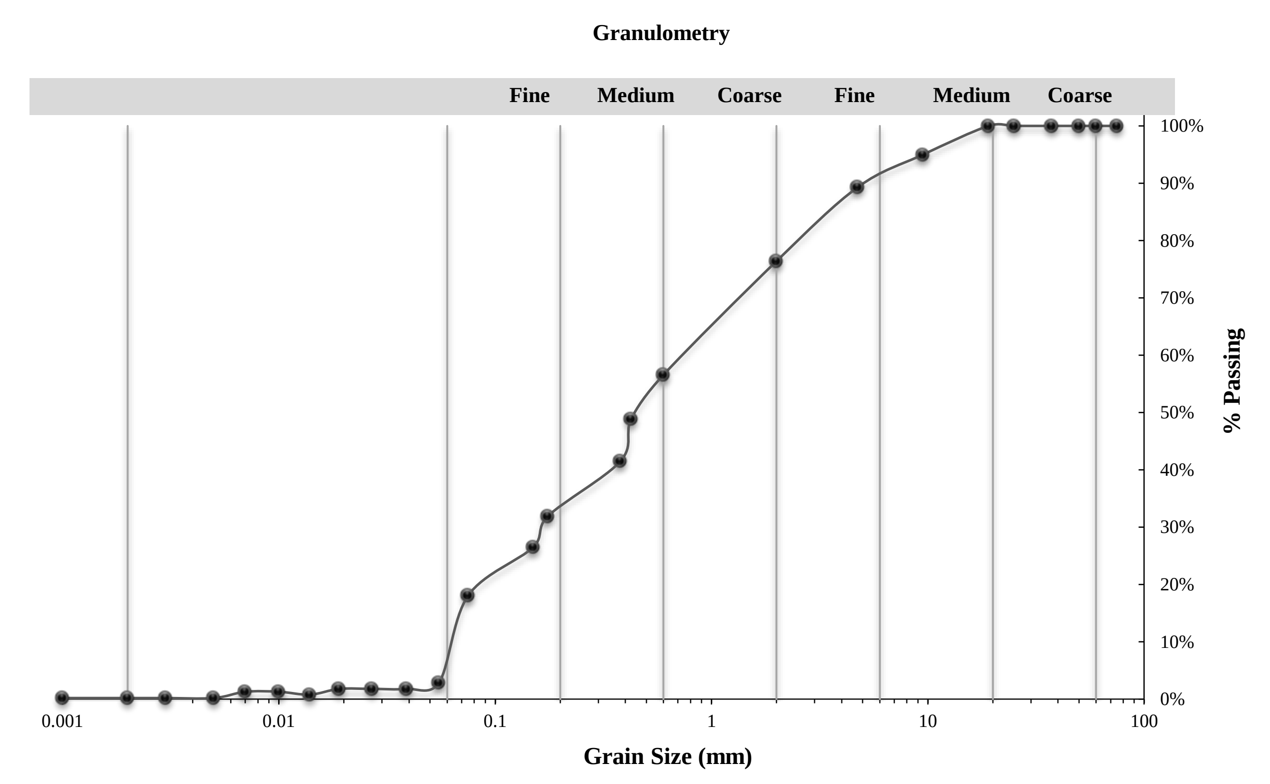


Figure 11. Granulometric Curve of the Soil under Study

4.3. Diametral Compression Testing

In the graph in Figure 12, values for different percentages of emulsion for both soil and soil stabilized with emulsion that have been air-dried for 7 days are displayed. It can be observed that, in general, the strength values reach an optimum level when 2% of emulsion is added to the soil.

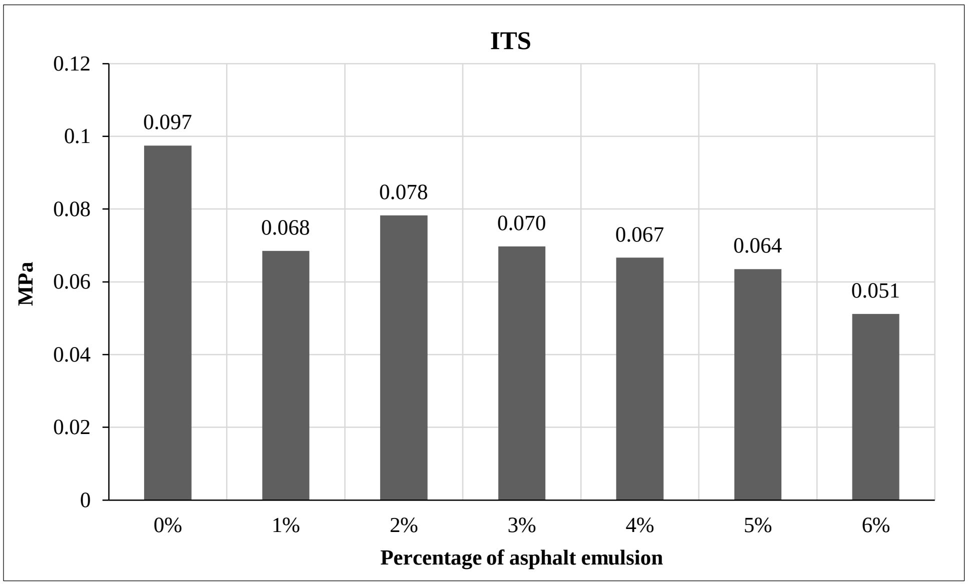


Figure 11. Indirect Tensile Strength of Natural Soil and Stabilized Soil

4.4. Multi-stage Loading

All materials undergo plastic deformation during loading, but natural soil stands out for its more effective recovery capacity, reducing plastic deformations with each new loading cycle compared to materials stabilized with slow-setting cationic emulsion SS, as observed in the graphs in Figure 12.

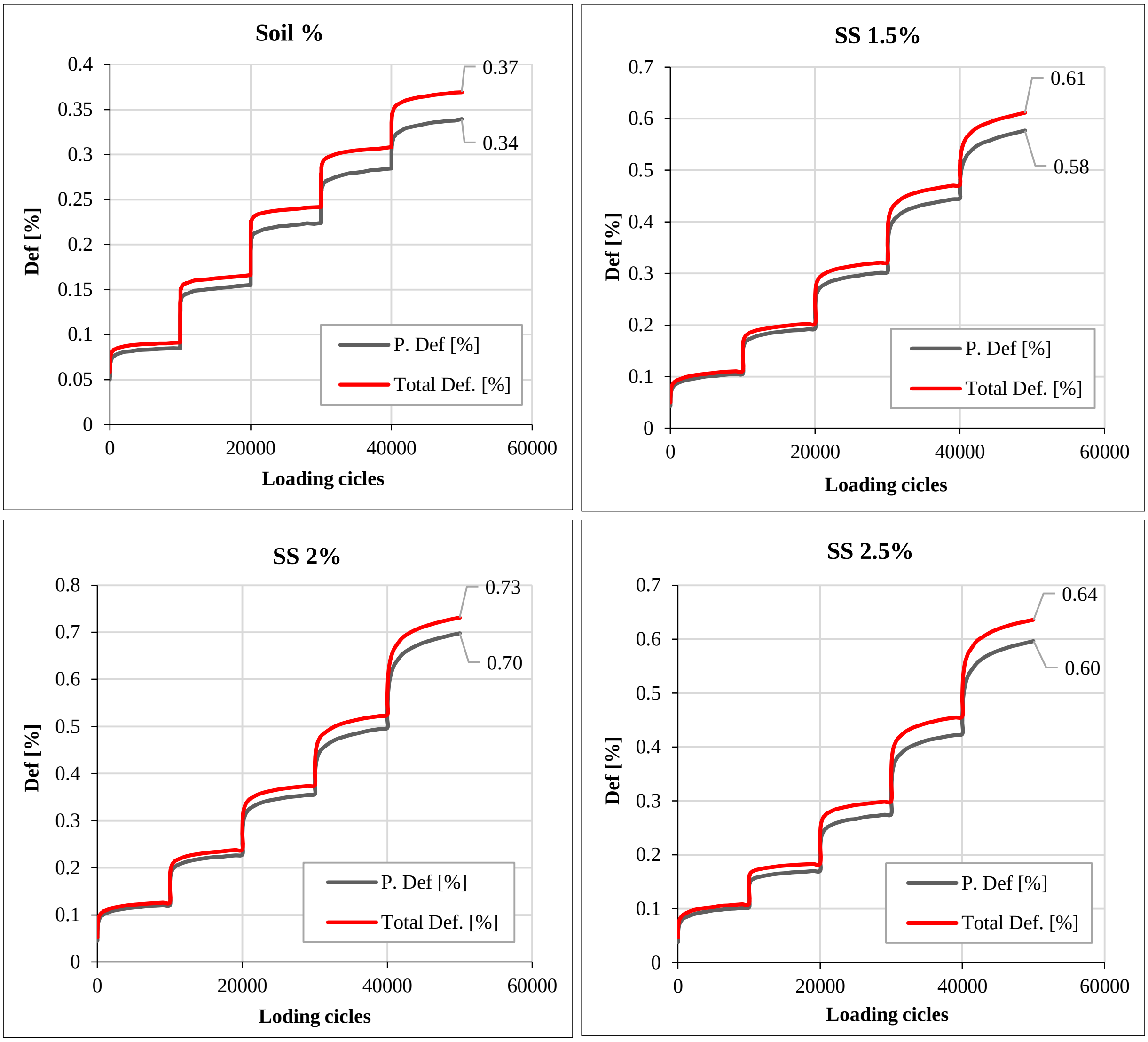


Figure 12. Plastic and Elastic Deformation

The natural soil, functioning as the control in the experiment, behaves differently from materials stabilized with emulsion. The plastic region decreases in all loading cycles, and the elastic region exhibits a lower value in most loading cycles compared to other results, indicating that it is a stiffer material compared to materials stabilized with emulsion. However, it showed the highest ratio between the elastic and plastic regions, suggesting that the soil became more compact with each loading cycle, tending towards greater grain interlocking with the increase in stresses and loading history. The plastic regions decrease while the resilient regions increase, suggesting a more resilient behavior of the natural soil, which serves as a comparison parameter, as can be seen in Table 7.

Table 6. Mechanical Performance of Natural Soil

Cycles	Elastic Region	Plastic Region	Resilient/Plastic	Resilient Strain	Plastic Strain
1-10000	62.71	820.77	7.64%	-	-
10001-20000	112.46	659.46	17.05%	79.32%	-19.65%
20001-30000	181.74	648.13	28.04%	61.61%	-1.72%
30001-40000	244.75	545.89	44.83%	34.67%	-15.77%
40001-50000	308.51	482.18	63.98%	26.05%	-11.67%

The stabilization with slow-setting cationic emulsion SS (1.5%) exhibits interesting behavior over the loading cycles. As the number of cycles increases, there is a tendency for an increase of approximately 55% in the plastic region during the intermediate cycles, between 20,001 and 40,000. Using a thin bitumen film (0.938 µm), it is observed that the material tends to diminish the plastic region while increasing the elastic response, resulting in a ratio between elastic and plastic regions of approximately 30% in the last loading cycle. Three distinct regions can be identified over the loading cycles for this stabilization percentage: one composed of the first and second cycles, where the material shows higher resistance; another consisting of the third and fourth cycles, where a significant loss of resistance occurs, evidenced by the expansion of plastic regions and the reduction of elastic regions. Finally, in the last loading cycle, with the material more compacted, there was a reduction in the plastic region and an increase in the elastic response, as can be seen in Table 8, indicating that the thinner bitumen film did not prevent greater interlocking of grains at this stage.

Table 7. Mechanical Performance of Soil Stabilized with 1.5% Emulsion

Cycles	Elastic Region	Plastic Region	Resilient/Plastic	Resilient Strain	Plastic Strain
1-10000	61.01	976.59	6.25%	-	-
10001-20000	108.75	788.36	13.79%	78.26%	-19.27%
20001-30000	204.18	972.83	20.99%	87.75%	23.40%
30001-40000	274.47	1251.12	21.94%	34.43%	28.61%
40001-50000	350.64	1115.24	31.44%	27.75%	-10.86%

The stabilization of the soil with slow-setting cationic emulsion SS (2%) and a bitumen film of (1.250 μm) exhibits two distinct regions: the first region from 1 to 20,000 cycles and the other from 20,001 to 50,000 loading cycles. In the first region, there is a decrease in plastic deformations with a significant increase in resilient variation. As the loading cycles progress, plastic deformations increase, not indicating accommodation and suggesting a worsening in the ability of the stabilized soil to maintain its properties under different loading conditions. The resilient variation follows a more logical pattern compared to the mechanical performance of other stabilized materials, despite the soil being an anisotropic material. Of all the materials, this one shows the worst performance in the last loading cycle, with the highest increase in the plastic region among all tested materials but with the smallest variation in plastic deformation in the penultimate loading cycle, indicating a possible limit for shear stress, as shown in Table 9.

Table 8. Mechanical Performance of Soil Stabilized with 2% Emulsion

Cycles	Elastic Region	Plastic Region	Resilient/Plastic	Resilient Strain	Plastic Strain
1-10000	58.40	1132.66	5.16%	-	-
10001-20000	110.06	968.72	11.36%	88.46%	-14.47%
20001-30000	195.06	1142.56	17.07%	77.24%	17.94%
30001-40000	284.23	1210.42	23.48%	45.71%	5.94%
40001-50000	340.93	1719.33	19.83%	19.95%	42.04%

For soil stabilization using 2.5% emulsion with a bitumen film of (1.563 μm), the ratio between the elastic and plastic regions remains relatively constant. Plastic variation increases with the number of cycles, while resilient variation stays around 20 - 30%. This material maintains the stability of the elastic/plastic ratio, with a tendency to become less plastic as the number of cycles increases, and resilient variation remains relatively high, indicating an increase in the recovery capacity and therefore reduced stiffness, as shown in Table 10. Despite a positive variation in permanent deformation starting from the second loading cycle, the increase in this indicator decreases. This material exhibits more proportional elastic and plastic responses with a more stable behavior compared to other stabilized soils.

Table 9. Mechanical Performance of Soil Stabilized with 2.5% Emulsion

Cycles	Elastic Region	Plastic Region	Resilient/Plastic	Resilient Strain	Plastic Strain
1-10000	69.11	943.89	7.32%	-	-
10001-20000	136.22	621.08	21.93%	97.11%	-34.20%
20001-30000	248.79	939.73	26.47%	82.64%	51.31%
30001-40000	326.09	1310.76	24.88%	31.07%	39.48%
40001-50000	400.81	1462.93	27.40%	22.92%	11.61%

When comparing performance, it becomes evident that the presence of a bitumen film hinders the effective interlocking of grains within the soil. Stabilized soils exhibit comparable performance to that of natural soil during the initial two loading cycles. However, as the ratio between shear stress and confinement is elevated to 2:1, the stabilized soils experience a significant decline in their strength.

Considering the first two loading cycles, the stabilized soil performed well, indicating that it could be used under conditions of lighter loading. However, with the increase in deviatoric stress, the stabilized soil tended to increase its plastic region by almost 35% on average, suggesting that this soil would not perform well in upper or more critical layers of pavements, especially with this increase in demand. The resilient/plastic indicator only reaches a good value in the soil stabilized with 1.5% emulsion, which could indicate that this could be a more suitable mixture for this soil, depending on its use.

In general, the results suggest that the composition of SS emulsion and the thickness of the bitumen film have a significant impact on the mechanical behavior of the material during loading cycles. Each system has its advantages and disadvantages, highlighting the importance of selecting the appropriate material for specific applications based on its mechanical performance over time.

The Pareto chart is a visualization tool that combines bars and a line, used to identify and prioritize the key factors contributing to a specific problem or dataset. To generate these charts, the statistical analysis software Jamovi [31] was used.

Concerning plastic performance, it is observed that the soil stabilized with 2% asphalt emulsion was more affected by the stabilization influence, followed by the soil stabilized with 2.5% and 1.5% asphalt emulsion. The plastic performance result was not similar to the resilient performance, measured by the resilient region. Here, as asphalt emulsion was added, it suggested an increase in the resilient response of the stabilization, as can be seen in the graphs in in Figure 14.

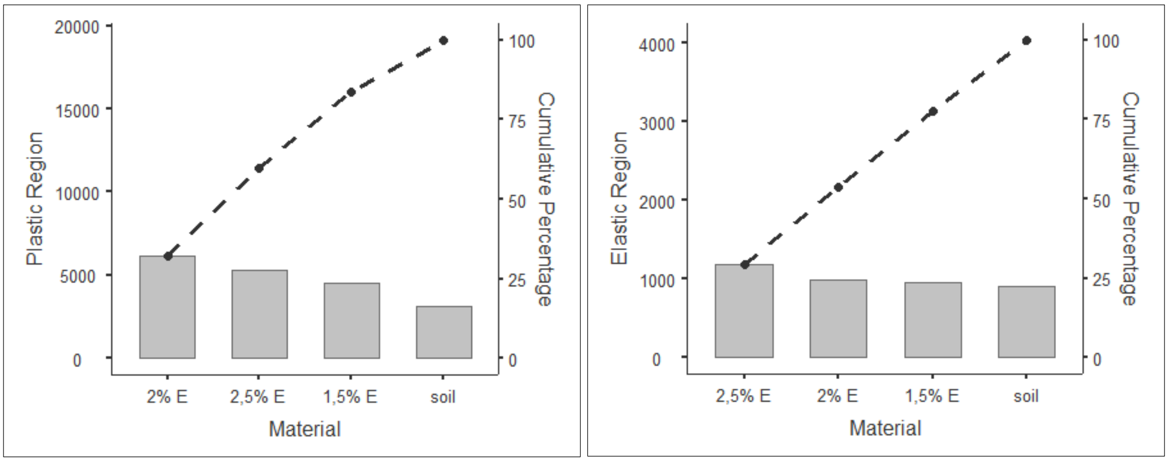


Figure 13. Pareto Chart, Influence of Plastic and Elastic Regions

An interesting insight can be observed in the graph in Figure 15. It is possible to see how much the relationship between the resilient/plastic region influenced the material's performance, where having a higher ratio between these regions is indicative that the material tends to accommodate. After the soil (control), the soil stabilized with 2.5% asphalt emulsion performed the best according to this indicator.

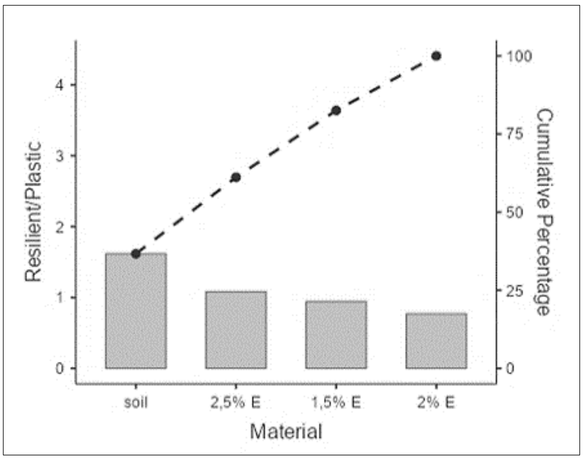


Figure 14. Pareto Chart, Influence of the Ratio between Elastic and Plastic Regions

Here, in Figure 16, another interesting piece of information can be noticed. The performance of the material's resilient variation replicated similarly in its plastic variation. In this case, both resilient and plastic variations increased for all materials as emulsion was added to the stabilization. The plastic variation decreased for the natural soil and achieved the lowest variation for the soil stabilized with 1.5% asphalt emulsion.

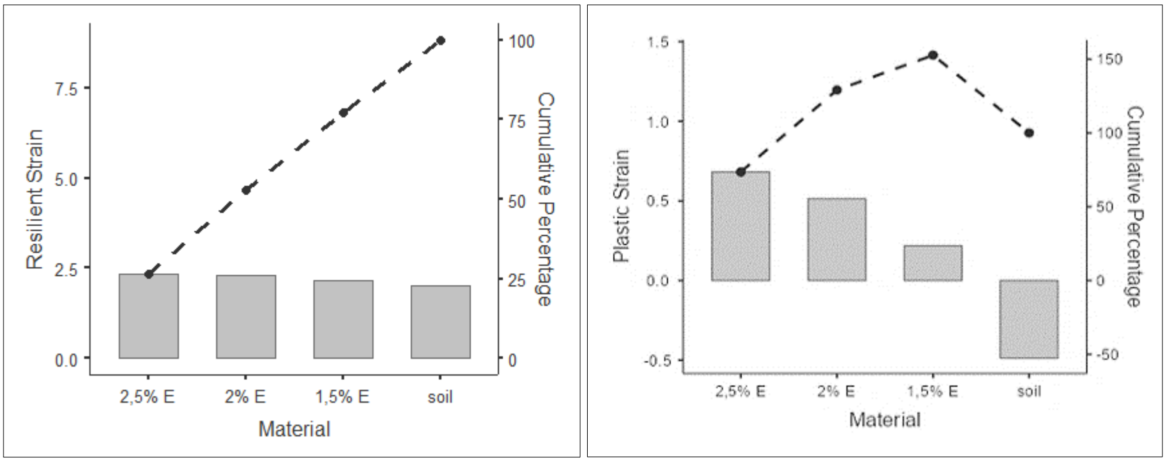


Figure 15. Pareto Chart, Influence of Variation in Elastic and Plastic Regions

Concerning the influence of stresses, it is observed that elastic performance is not influenced in the same way as plastic performance. The smallest plastic regions occurred in the second loading cycle and the largest in the fourth. On the other hand, elastic performance was directly influenced by the increase in shear stresses, as seen in the graph in Figure 17.

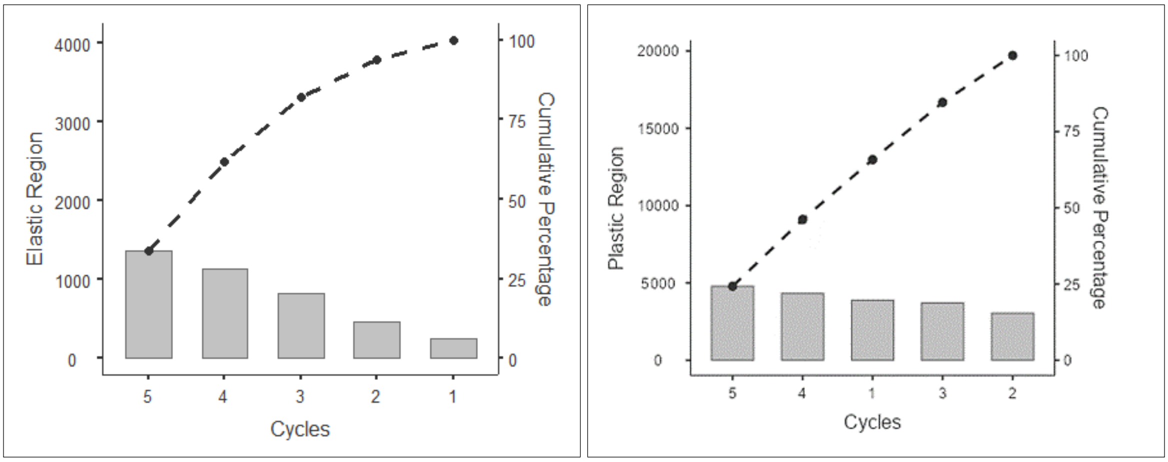


Figure 16. Pareto Chart, Influence of Loading Cycles

Yaghoubi et al.'s research (2023) [12] aimed to assess the impact of adding a slow-setting anionic bitumen emulsion (SS), using 1, 2, and 3% of the dry weight of aggregates, in stabilizing recycled materials (RCA) and (CB), in addition to controls without asphalt emulsion. After compaction, the aggregates were dried to reach 70 and 90% of the optimum moisture content of these materials. The materials were compacted using modified energy, and based on the literature review, the authors chose to conduct multi-stage loading tests with 40 kPa confining stress and deviatoric stresses of 140, 220, 300, 380, and 460 kPa.

In the current study, samples were air-dried for 7 days, resulting in an average 60% moisture loss, making them drier than those in the aforementioned research. Specimens were molded at optimum moisture content and intermediate energy. Multi-stage loading tests were conducted at three emulsion percentages: 1.5, 2, and 2.5%. Deviatoric stresses were adjusted, maintaining material proportionality and objectives, with 70 kPa confining stress and deviatoric stresses of 35, 70, 140, 210, and 280 kPa.

Under low deviatoric stresses, permanent deformation of emulsion-stabilized RCA decreased, increasing with higher stresses. The addition of asphalt emulsion to RCA and CB resulted in a decrease and increase in permanent deformation rate, respectively. This behavior was similar, respecting test proportions, to that observed with stabilized soils, which reduced permanent deformation in the first two loading cycles.

Samples tested at 90% optimum moisture content exhibited higher permanent axial strains, permanent strain rates, and resilient strains compared to those at 70%. These differences were more pronounced under higher stress conditions, indicating that higher moisture contents led to higher permanent strains, permanent strain rates, and lower resilient modulus. This aligns with the importance of curing specimens subjected to asphalt emulsion stabilization.

In conclusion, in Yaghoubi et al.'s studies (2023) [12], despite the increase in permanent deformation at all shear stresses due to the addition of bitumen emulsion, the majority of mixtures remained within the shakedown classification

Range B. This makes them suitable for use as base and sub-base layers. However, under higher shear stresses, some mixtures fell into Range C, suggesting they may not be suitable for use in more demanding pavement layers. Similar observations were made when using emulsion in soil, with a significant increase in permanent deformation for all stabilized soils in the last three loading cycles. This increase could contribute to rutting under loading conditions three times higher than the confinement stress, except for the soil stabilized with 1.5% emulsion. This phenomenon was not observed with natural soil, serving as a performance benchmark. With increased compaction and stress history, the natural soil reduced its plastic response and increased its elastic response.

Oluyemi-Ayibiowu's study (2019) [8] assessed the stabilization of lateritic soils with slow-setting asphalt emulsion (SS), aiming to analyze the impact of soil physical properties in this process and determine the optimal emulsion ratio to enhance its characteristics. Several laboratory tests were conducted on the collected samples, including natural moisture content, particle size analysis, Atterberg limits, chemical composition, compaction, unconfined compressive strength (UCS), and California Bearing Ratio (CBR).

The study utilized three representative lateritic soil samples collected along the Ado-Ekiti - Ikare Akoko road, connecting the states of Ekiti and Ondo in southwestern Nigeria. Three samples were examined: Sample A classified as sandy clay, Sample B as intermediate plasticity sandy clay, and Sample C as high plasticity clay. Additionally, the text notes that Sample A has 3.4% coarse aggregate, 62.4% sand, and 34.2% fines; Sample B contains 5.8% coarse aggregate, 62.2% sand, and 32.0% fines; and Sample C has 0.5% coarse aggregate, 44.0% sand, and 55.5% fines. These soils differ significantly from the ones used in this study, which are described as non-plastic, gravelly sand with approximately 18% fines.

Tests were conducted on remolded samples at 7, 14, and 28 days to assess the curing effect on strength. The results demonstrate a progressive increase in the strength of Sample A over the curing period, from 0.85 MN/m^2 at 7 days to 1.20 MN/m^2 at 28 days. Sample B exhibited an increase from 0.50 MN/m^2 at 7 days to 0.85 MN/m^2 at 28 days, while Sample C showed an elevation from 0.41 MN/m^2 at 7 days to 0.68 MN/m^2 at 28 days. This underscores the importance of curing in the mechanical performance of materials stabilized with asphalt emulsion. In this study, a standard air-dry cure for 7 days was used, with moisture loss similar to a 40 °C oven cure for 3 days.

Furthermore, the results reveal an increase in strength with a rise in emulsion content up to 6%. However, for an 8% emulsion content, a decrease in UCS was observed for Samples A and B. These findings emphasize the influence of curing on strength development and the significance of precise adjustments in emulsion ratio to optimize soil properties during the stabilization process. This reaffirms the proposed dosage limit of up to 6% emulsion for non-cohesive soils in the current study.

5. Conclusions

Over the loading cycles, it was observed that materials stabilized with SS emulsion (1.5%, 2%, and 2.5%) showed a significant increase in plastic deformation, as indicated by the indicator. This behavior suggests a loss of strength in these materials as they undergo repeated cycles of loading. On the other hand, natural soil exhibited a less pronounced transition to the plastic region, indicating a greater ability to maintain its initial strength under variable loading conditions.

Regarding the relationship between the elastic and plastic regions, natural soil tends to increase the ratio between these two regions with each loading cycle, suggesting soil accommodation and grain interlocking, reducing plastic response, and increasing elastic response. This did not occur with stabilized soils, where the ratio between these regions decreased, demonstrating a significant increase in the plastic response of the material. Additionally, it was observed that elastic deformations were greater, in most cycles, in stabilized soils, indicating greater flexibility compared to natural soil.

While stabilized soils showed a tendency towards increased plastic deformation, the variation in resilient deformation increased, indicating some recovery capacity. This suggests that even with an increase in permanent deformation, these materials are still capable of regaining some of their original shape after the load is removed.

The elastic response of the stabilized soils follows a behavior pattern whereas asphalt is added to the stabilization, the resilient response increases. However, the plastic behavior does not follow a pattern. The lowest permanent deformation occurs when 1.5% emulsion is added, and then there is lower plastic deformation when 2.5% emulsion is added to the soil.

It is possible to observe better resilient variation in stabilized soils after the second loading cycle, because of adding asphalt to the soil. However, plastic variation decreased in natural soil, which did not occur in the stabilizations, indicating that the bitumen film, in this case, impaired the plastic performance of the material.

It was identified that the optimal value of indirect tensile strength was achieved by adding 2% asphalt emulsion. However, the bitumen film also reduced the indirect tensile strength in all percentages of asphalt emulsion used for soil stabilization compared to natural soil.

When analysing grain interlocking and stress history in the tested samples, it was observed that starting from the second loading cycle, all stabilized samples began to show an increase in plastic deformations, which was not observed in the natural soil. This indicates that the presence of the bitumen film hurt the mechanical response of the soil, except for soil stabilized with a thinner bitumen film.

Bitumen emulsion stabilization proved to be satisfactory in the first two loading cycles for all stabilized soils, indicating that it could be a good solution for stabilizing the subgrade, especially in regions where there may be a failure in the drainage system. However, when shear stress is increased too much, there is a significant loss of strength in the stabilized soil. Therefore, its use is more restricted in pavement applications.

Based on the present study, we can conclude that bitumen emulsion stabilization had a positive effect, especially in the first two loading cycles, resulting in a significant reduction in permanent deformation in all stabilized soils. However, there is a loss of strength when increasing the shear stress, indicating that the stabilized soil does not tend to accommodate.

It is crucial to delve into the understanding of the underlying causes of these changes in mechanical response, especially concerning permanent deformation. Additionally, it is essential to explore optimization strategies in emulsion dosage to ensure sustainable improvement in soil properties. Other areas of interest include investigations into the environmental impact and long-term durability of these stabilized soils, which can provide valuable information for practical applications in civil and geotechnical engineering.

As a suggestion for future work, it is possible to consider the use of total and permanent deformations to create predictive models of mechanical behavior that incorporate both resilient and plastic performance, thereby bringing greater fidelity to the mechanical response of materials. Additionally, it is worthwhile to analyze grain interlocking due to load increments, leading to the development of new shakedown prediction models using total deformations.

6. Declarations

6.1. Author Contributions

Conceptualization, A.S.M.; methodology, A.S.M.; software, A.S.M.; validation, A.S.M.; formal analysis, A.S.M.; investigation, A.S.M. and M.A.V.S.; resources, A.S.M. and M.A.V.S.; data curation, A.S.M.; writing—original draft preparation, A.S.M., M.A.V.S., and M.H.S.C.; writing—review and editing, A.S.M., M.H.S.C., and M.A.V.S.; visualization, A.S.M., M.H.S.C., and M.A.V.S.; supervision, A.S.M. and M.A.V.S.; project administration, A.S.M. 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

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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