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Applying the Porosity-to-Cement Index for Estimating the Mechanical Strength, Durability, and Microstructure of Artificially Cemented Soil

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Abstract

Fine, expansive, and problematic soils cannot be used in fills or paving layers. Through additions to these soils, they can be converted into technically usable materials in civil construction. One methodology to make them viable for construction is through a stabilization process. Nevertheless, current methodologies regarding dosage based on compaction effort and the volumetric amount of binder used are unclear. Thus, this research describes cement-stabilized sedimentary silt's strength and durability properties from Curitiba (Brazil) for future application in paving. Splitting tensile strength, unconfined compressive strength, and loss of mass against wetting and drying cycles (W-D) were investigated in the laboratory utilizing greenish-gray silt (originating from one of the Guabirotuba Formation layers, Paraná) and high-early strength Portland cement- ARI (CPV). Utilized were cement concentrations (C) of 3, 5, 7, and 9%, molding dry unit weights (d) of 14, 15, and 16 kN/m^3, curing periods (t) of 7, 14, and 28 days, and constant moisture content (w) of 23%. With an increase in cement concentration and curing time, the compacted mixes demonstrate an increase in strength, an improvement in microstructure, and a decrease in accumulated mass loss (*ALM)* and initial porosity (η). Using the porosity/volumetric cement content ratio (η/C_{iv}), the lowest amount of cement required to stabilize the soil in terms of strength and durability was determined. The porosity/cement index provided an appropriate parameter for modeling the mechanical and durability properties, and a unique equation between the strength/accumulated loss of mass and the porosity/binder index was obtained for the curing times studied. Lastly, C = 5% by weight is the minimum acceptable amount for prospective subbase soil application.

Keywords: GNSS Network; Aitolo-Akarnania; Trichonis Lake; Slip Rate; Velocity Field; Soil.

1. Introduction

Sometimes, in processes that precede civil works, the local soil can be considered unsuitable, both for the execution of foundations and for the construction of pavements, railroads, or embankments, which makes the project unfeasible due to technical or economic problems. Therefore, soil renovation has become a technique that enables the use of this material or its situated area, thereby decreasing the need for complex technologies or even its replacement. The soil stabilization process alters one or more physicochemical properties to guarantee improvements to its resistance, durability, and deformation properties. However, when changing these parameters, it is essential to consider changes in other properties during the stabilization process, arising from the effects of water content, permeability, and degree of saturation, among others.

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The addition of cement to the soil is a very suitable technique when it comes to stabilizing problematic soils. It is possible to build structures on soft soils and use this material as a base for road and rail pavements [1, 2]. Bunawan et al. [3] highlight that surface stabilization by deep mixing or light backfill methods is some of the techniques developed capable of allowing construction on soft soils and leading to improvements in the mechanical properties of this soil to be considered economical and practical. Deep mixing is semi-rigid columns made from a mixture of soil with a specific binder (cement or lime). In the wet process, the soil is homogenized with cement by injecting a mixture of binder and water through a rotating instrument. The success of these methods is due to the cement's binding properties, which, when added to the soil, significantly contribute to strength gains, reduced permeability, and compressibility [4]. The deep mixing method was initially developed in Sweden and Japan. In the mid-1970s, it was used in Sweden only for mixing with lime and later with cement and other materials. Deep mixing is a subject of study in several countries, such as China [5], Thailand and Australia [6, 7], Malaysia [3], and Egypt [8].

Portland cement is recommended for stabilizing soil, except for highly organic ones. According to Ghadir and Rinjbar [9], using this material in soil stabilization guarantees increases in strength and durability and a decrease in compressibility. The use of cement-stabilized soils is every day in pavement bases and subgrades. Due to its fragility to cracks, its use as a coating material, for example, is rare. The cement content of the mixture is an important variable to be analyzed. In soil-cement columns, the object of study by Horpibulsuk et al. [10], the consolidation behavior of the mixture showed improvements in soil load capacity and low tension in reinforced soils with higher cement contents. Results from physical and numerical models reported that, in long soil-cement columns, the pressure variation in the pores around the drainage is considered negligible. Additionally, the strength of cement-stabilized soils varies inversely with the water content. That is, as the water-cement content increases, the compressive strength of the mixed soil decreases. This aspect has been recently studied by Sukman et al. [11], creating a general equation for the dosage of clays with cement-varying curing and stabilization conditions. Study the roles of clay minerals, cement, and water content on strength development. Clay minerals, water, and cement content were the prime factors controlling strength development in cement-stabilized clays at a particular curing time. The three influence factors were incorporated to develop the generalized strength predictive model. The total soil water-to-cement content and soil water/cement were the prime parameters considering the effect of water content and cement content.

In the research by Yaghoubi et al. [7], marine clay was stabilized with different percentages of fly ash and slag, and a noticeable strength gain was observed when the percentage of this material went from 10% to 20%. Regarding the modulus of elasticity, the water-cement factor has almost insignificant effects. According to the findings of Forcelini et al. [1], an increase in the cement content resulted in a higher modulus of elasticity and a reduction in the void content of the tested samples. It is essential to emphasize the exponential correlation between the soil-cement compressive strength and the cement dosage. Using lower cement contents, the variation in compressive strength is relatively small; with higher contents, the increase in strength is improved. However, ductility is lost, and it is worth remembering that recent research has addressed adding other materials to the stabilization process of soft soils, such as geopolymers. Using these new materials is of environmental interest since it contributes to reducing carbon dioxide emissions and cost reduction.

According to studies, the efficient use of cement for soil stabilization may apply to paving. Horpibulsuk et al. [6]. The research investigates the evolution of qu as mold density, cement concentration, and curing time increase. Goodary et al. [12] also analyzed many soils stabilized with cement of volcanic origin using typical compaction energy. The scientists added 3% and 18% cement to the compacted mixes to increase their strength. During an experiment by Jan and Mir [13] to determine the effect of cement additions ranging from 4% to 16% on the stability of dredging clay soil, it was discovered that the qu increased by approximately 15 times compared to the soil in its natural form. The optimal cement content was 12 percent. Chompoorat et al. [14] enhance the mechanical qualities of sedimentary soil for possible application in pavement construction by using PC. Using adjusted compaction effort, the sedimentary soil was combined with cement in a proportion of 3% to 10% by weight. The improved soil's strength and durability were evaluated using basic unconfined compression and durability tests against drying and wetting cycles. Using a semi-empirical porosity/cement ratio, Baldovino et al. [15] determined the equations determining the mechanical strength of cement-enhanced silty soil. Depending on the curing period, the authors determined a split tensile/compression ratio (ξ) between 0.15 and 0.17. Baldovino and Luis dos Santos Izzo [16] determined the value of ξ for the Guabirotuba Formation silt-cement mixture to be 0.15 for seven days of curing and standard, intermediate, and modified compaction energies. Besides, recent studies have advanced the development of alkaline types of cement to reduce high percentages of CO_2 emissions. Ferreira et al. [17] developed an alkaline cement from burnt eggshells mixed with rice husk ash. Silvani et al. [18] studied fly ash-lime as a green cement to stabilize sand soil under multiaxial stress conditions. Buritatum et al. [19], introduced natural latex as an additive to improve the fatigue properties of soils for paving applications.

Water plays an essential role in the geopolymerization of soil and its mixtures. Comparing soils stabilized with cement and geopolymers, it was found that Portland cement treatment is excellent in humid environments, while geopolymers are efficient in dry conditions [9]. In cemented soils, the curing time is an important variable to be observed as it directly influences the strength gain. Such a parameter was evidenced in the works of [1, 7, 10, 20, 21]. In soil-lime mixtures studied by Nematzadeh et al. [22], compressive strength tests showed an increase in strength from 7 to 14 days and 14 to 28 days of 62 and 53.57%, respectively.

Although there are important studies on changes in soil behavior after the addition of cement in the development of new composites, there is no knowledge about their effects on the properties of mixtures of sedimentary soils mixed with cement in sedimentary silts in southern Brazil. Furthermore, the effects of this addition on the durability of new geomaterials using wetting/drying (W-D) cycles and on soil microstructure have not been studied enough in the literature.

1.1. Research Motivation and Objective

Most soils in the metropolitan region of Curitiba (Paraná/Brazil) are of sedimentary and expansive origin [23, 24]. Recent studies have sought to stabilize these soils for application, mainly in paving. Among the studies, the stabilization with hydrated lime [20, 21], with pozzolanic cement [25], and with high-strength cement and a low initial curing temperature. The soils of the city of Curitiba belong mainly to the Guabirotuba Formation (GF). The typical profile of this formation is presented in Figure 1. The first layers of the Guabirotuba Formation are composed of different types of soils, mainly clays and expansive silts [24]. In Figure 1, the main feature between the layers is coloring. These different colors can be in the same profile or separately. Thus, four primary colors are observed: red, pink, yellow, and gray. The red layer can be found at depths of up to 5 m, and the yellow and pink ones are. The gray layer can reach up to 50 m in depth. However, as it is the layer with the most significant volume within the Guabirotuba profile, further studies on the soil stabilization characteristics of this layer are needed. Thus, this article aims to stabilize gray soil with the addition of Portland cement and to study its strength and durability for its potential use in paving. The present paper proposes studying the mechanical properties of a soil characteristic of the superficial layer of the Formation Guabirotuba (yellow layer), enabling the technical use of cement as an alternative to enhance strength and durability characteristics. Thus, an alternative procedure is used to stabilize the soils of the Guabirotuba Formation using residues that can be used in civil construction.

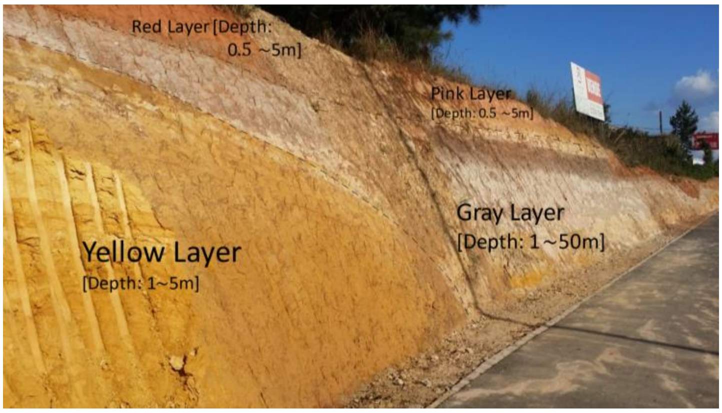

Figure 1. Profile of the Guabirotuba Formation in Curitiba (Brazil)

2. Experimental Program

The experimental program consisted of three distinct phases. The initial phase involves the characterization of the soil and cement. The second step involves molding, curing, and breaking specimens through unconfined compression and split tensile. In the third and final step, specimens subjected to wetting/drying cycles are shaped, cured, and their mass loss due to brushing is determined (W-D). Figure 2 describes the experimental program and preliminary test conducted in this paper.

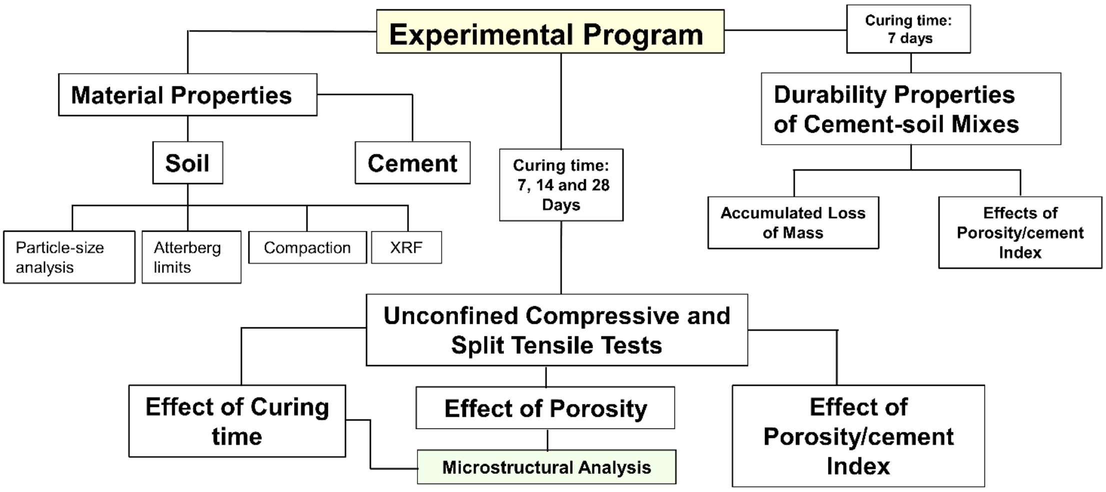

Figure 2. Description of the experimental program

2.1. Materials

The investigation utilized a gray silty soil from the Guabirotuba Formation (FG), high initial strength cement (ARI), and purified water. The location of the soil site collection is shown in detail in Figure 3. The dirt was physically collected in a distorted state on a road slope 2.5 m above the natural ground in So José dos Pinhais, Brazil, near the city of Curitiba, in order to avoid possible contamination. Table 1 displays the soil's physical properties. D_{10}=0.01 mm, D_{30}=0.024 mm, D_{50}=0.04 mm, D_{60}=0.055 mm, and D_{90}=0.28 mm were computed as the diameters of the soil particles corresponding to 10%, 30%, 50%, and 60%, and 90% of passing material, respectively. In addition, the coefficients of uniformity (i.e., $C_u=D_{60}/D_{10}$) and curvature [i.e., $C_c=(D_{30})^2/(D_{10}/D_{60})$] were determined as C_u=5.5 and C_c=1.05, respectively. The soil was classed as silt according to the Unified Soil Classification System (SUCS) (ML) [26]. The gray soil contains an average of 15% sand, 25% fine sand, and 60% silt, with silt (0.002 mm<diameter <0.075 mm) being the biggest share. The soil has a plasticity index of 18.31% and a specific gravity of 2.83 g/cm^3.

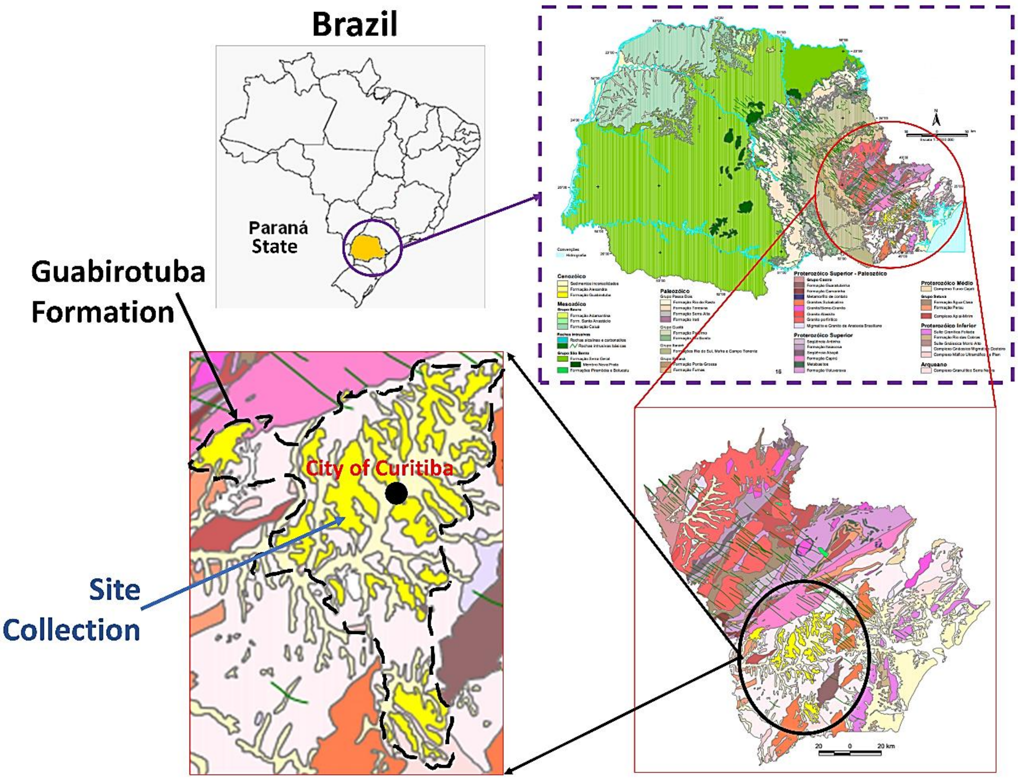

Figure 3. Location of the Guabirotuba Formation and site collection of the soil sample

Table 1. Soil properties

Properties	Value or comment	Standard
Liquid Limit LL, %	44.74	[27]
Plasticity Limit PL, %	26.43	[28]
Plasticity Index, PI=LL-PL, %	18.31	-
The specific gravity of soils grains (G_{SS})	2.83	[29]
Medium sand (0.2 mm< diameter <0.6 mm), %	15	[30]
Fine sand (0.06 mm< diameter <0.2 mm), %	25	[30]
Silt (0.002 mm < diameter <0.06 mm), %	60	[30]
Clay (diameter < 0.002 mm), %	0	[30]
Effective Diameter (D_{10}), mm	0.01	-
Medium Diameter (D_{50}), mm	0.04	-
Uniformity Coefficient (C_u)	5.5	-
Coefficient of curvature (C_c)	1.05	-
Soil classification (SUCS)	ML	[31]
Color	gray	-
pH in water	4.7	-
Optimum water content (Proctor standard), %	27.0	[32]
Maximum dry unit weight (Proctor standard), kN/m^3	14.52	[32]
Optimum water content (modify effort), %	17.6	[32]
Maximum dry unit weight (modify effort), kN/m^3	17.57	[32]

According to the road classification system - HRB/AASHTO [33], the soil is classified as A-7-6 with poor behavior as a subgrade material. According to the MCT (Miniature Compacted Tropical) system, the soil is classified as non-lateritic silty with coefficient e'=1.68 and coefficient c'=0.85. For the MCT classification, the procedure described in the DNER (National Department of Roads and Highways) –ME 256 [34] and M-196 [35] was adopted. A scanning electron microscope (SEM) of the soil is shown in Figure 4. Note that soil particles have angular and sub-angular shapes. The results of EDX Study Area 1 (performed on a soil particle) are presented in Table 2.

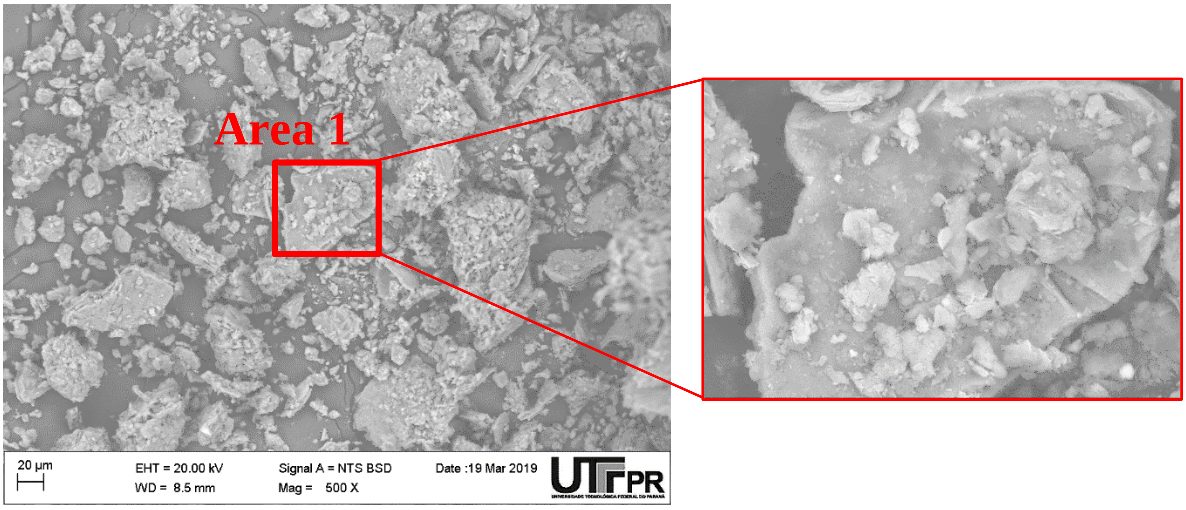

Figure 4. SEM-EDX test in a soil sample

Table 2. Chemical composition of soil and cement

Compost	Concentration by weight (%)	
	Soil	Cement
SiO_2	49.82	18.96
Al_2O_3	43.40	4.30
Fe_2O_3	0.12	2.95
K_2O	0.29	-
TiO_2	0.52	-
SO_3	4.82	3.18
CaO	-	60.76
MgO	-	3.26
LOI	1.03	0.77

Table 2 displays the chemical composition of soil and ARI cement as determined by X-Ray Fluorescence (FRX). The soil consists primarily of silica and alumina, with traces of sulfuric oxide, iron oxide, potassium oxide, and titanium dioxide. The primary components of cement are calcium oxide and silica. According to Brazilian standard NBR 16605 [36], the specific mass of cement grains was calculated to be 3.11. According to the manufacturer's statistics, the cement's axial strength is 44.7 MPa at seven days and 54.2 MPa at 28 days. This type of cement was chosen because, according to Baldovino et al. [15] study, it delivers more significant increases in mechanical strength to the soils of the Guabirotuba Formation than other types of cement.

Distilled water was used to characterize materials, perform compaction tests, prepare specimens subjected to compression, split tensile and durability, and avoid unwanted reactions for the saturation of the samples.

2.2. Definition of Cement Contents, Molding Points, and Curing Times

The molding points used to make the specimens for the durability, split tensile, and unconfined compression tests were defined as γ_d=14 kN/m^3, γ_d=15 kN/m^{3,} and γ_d=16 kN/m^3 with the content of constant molding moisture content of ω=23%. Such points were strategically defined considering possible field conditions with the dry unit weight (γ_d) variation in 1 kN/m^3. Similar impression points with ω=23% fixed were recently studied by Baldovino et al. [15] in soil-cement mixtures using pink silt from the Guabirotuba formation. Additionally, at 23% of moisture content, the highest strengths are suitable for the porosity/cement ratio. This content was chosen for molding the soil-cement samples [37].

In the present study, the cement contents were C = 3, 5, 7, and 9% of the soil's dry mass. This parameter was determined based on the Brazilian experience with cement-based soil stabilization [15, 25, 38, 39]. Regarding the adopted curing time, seven (when cement hydration occurs), fourteen, and twenty-eight days were employed to test split tensile and unconfined compression. In addition, the specimens for the durability test were allowed to cure for seven days.

2.3. Molding Specimens

100 mm in height and 50 mm in diameter specimens were molded for the unconfined compression and split tensile tests. In the durability testing, the molded specimens measured 12.72 cm in height and 10 cm in diameter (volume=1000 cm^3). After collecting the soil from the field, it was completely dried in an oven at 100±5°C and divided into sections for mixing with the cement. The amount of dry cement applied with the soil sample's dry weight was varied across four levels: 3, 5, 7, and 9%. Soil and cement were combined to be as homogenous as possible. Then, a percentage of water by weight equal to 23% of the molding moisture content was applied. The combination of soil-cement with distilled water was completed in less than seven minutes to reduce the cement-water reactions before the specimen molding process. The samples for molding the specimens were statically compacted in three layers in a stainless-steel mold. The regular scarification operation was performed during compaction between the specimen's layers. For each specimen, the mold volume and the wet mixture's weight (split into three parts) were calculated in order to determine the dry unit weight of the molding. After completing these calculations, the required materials for each specimen were weighed. The molding was accomplished using a manual hydraulic press. After each molding operation, three samples of the mixture were obtained to determine its moisture content in a 1002 °C oven for 24 hours.

The specimens were weighed on a 0.01 g precision balance, and their measurements were measured using a caliper with an error of 0.1 mm. The extracted specimens were wrapped in transparent plastic film to preserve their moisture content. Lastly, the specimens were maintained in a humid chamber for the curing process for 7, 14, and 28 days (for the durability test, just seven days) at an average temperature of 2.3°C to prevent significant temperature variations and moisture content until the day of the test. For the samples to be used in the unconfined compression tests, the following maximum errors had to be met: molding dry unit weight (γ_d) of 1% and moisture content (w) of 0.5% [21]. The specimens were submerged in distilled water for 7 hours before the unconfined tensile and split compression testing to saturate the samples and eliminate the influence of suction on the final strength measurements [25]. Figure 5 depicts the materials used (a), the homogeneous soil-cement mixture (b), and the specimen used to conduct unconfined compression and split tensile tests (c).

(a) (b) (c)

Figure 5. (a) Raw materials, Soil and cement CPV, (b) Soil-cement homogenized mix, (c) The specimen to strength testing

2.4. Strength and Durability Tests

An automatic press with a capacity of 30 kN was used to carry out the unconfined compressive and split tensile tests. The tests were carried out with an automated system, mainly measuring the applied force and the deformation with a sensitivity of 0.01 mm with a test speed of 1.10 mm/min. The unconfined compressive (q_u) test procedure will follow the Brazilian standard NBR 5739 [40]. The procedures of the tensile strength tests (q_t) followed the Brazilian standard NBR 7222 [41] based on the American standard ASTM C496 [42].

Regarding the durability tests, each wetting-drying (W-D) cycle commenced with wetting the samples in water at 23°C for 5 hours. After soaking, the samples were removed and dried in a 70°C oven for 42 hours. After the drying cycle, mass loss was measured by brushing the samples with an ASTM D559-15-specified brush. Two cycles of 18 to 19 brushes were used on the side faces of the test cups, and four brushes were used on the transverse faces, with the average force of 1.5 kg being monitored by a precision balance. The same operator conducted all brushing tests over 24 days and 12 cycles to eliminate as many operational error variables as possible. Durability testing procedures followed the American standard ASTM D559 [43].

2.5. Microstructural Analysis

Chemical microanalysis of two soil-cement samples (with 3 and 5% cement compacted at a dry specific weight of 14 kN/m^3), after 28 days of curing, were studied using Energy Dispersive Spectroscopy (EDX) with an X- ACT Oxford (Penta FET125 Precision) (Penta FET125 Precision). A laser micro mass analyzer was utilized for mass microanalysis (LAMMA-1000. model X-ACT).

3. Results and Discussions

3.1. Effects of Porosity/Cement Index on the Split Tensile and Unconfined Compressive Strength of the Compacted Blends

Figure 6 shows the results of the simple compressive strength of soil-cement mixtures influenced by the porosity/volumetric cement content ratio (η/C_{iv}). Note that unconfined compression results increase when η/C_{iv} decreases. To have compatibility between η and C_{iv}, the factor C_{iv} must be adjusted to an exponent "x" [η/C_{iv}^x]. The exponent depends on the soil type and cement properties [15]. In this paper, the value of x was calculated as 0.25. The $\eta/C_{iv}^{0.25}$ index also directly influences the split tensile strength results, as shown in Figure 7.

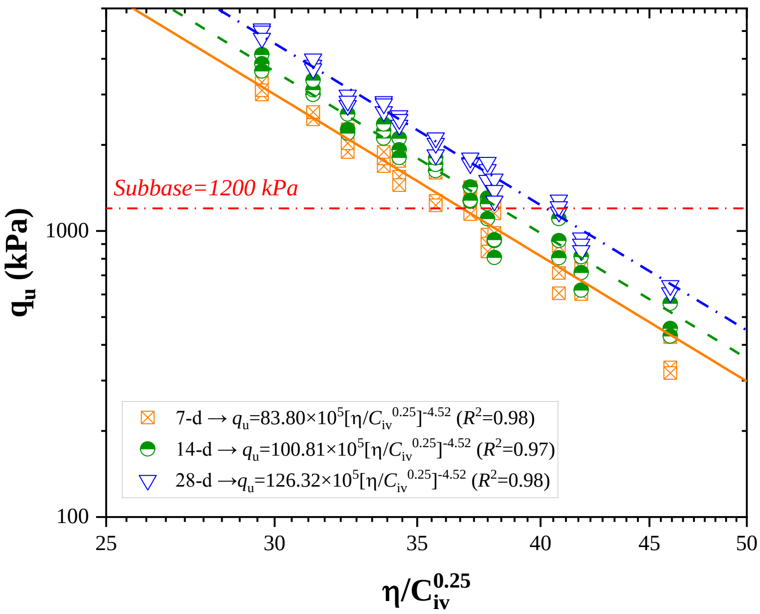

Figure 6. Effects of porosity-to-volumetric cement index ($\eta/C_{iv}^{0.25}$) on unconfined compressive strength considering 7, 14, and 28-days of curing

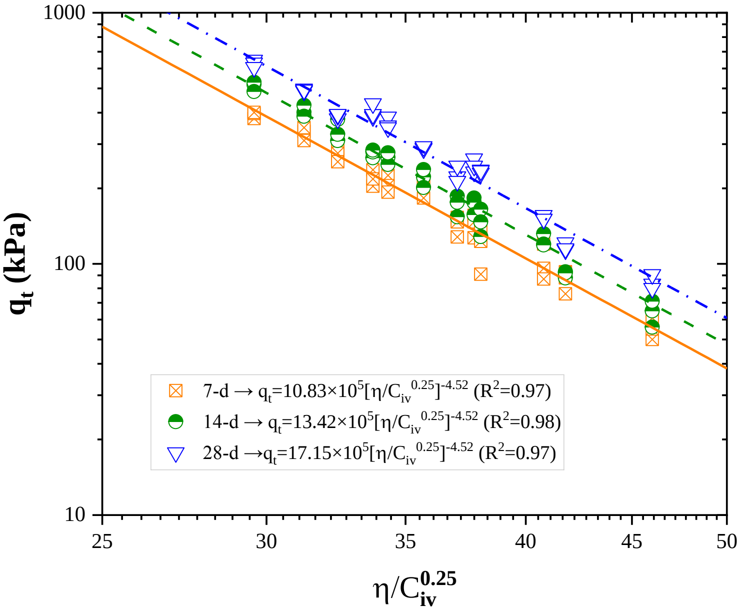

Figure 7. Effects of porosity-to-volumetric cement index ($\eta/C_{iv}^{0.25}$) on split tensile strength considering 7, 14, and 28-days of curing

The values of q_u-[$\eta/C_{iv}^{0.25}$] and q_t-[$\eta/C_{iv}^{0.25}$] are independent of the curing time. The initial η value of the mixtures depends on the molding dry unit weight: γ_d=14 kN/m^3 (η=49.22%), γ_d=15 kN/m^3 (η=45.5%) and γ_d=16 kN/m^3 (η=42.2%). On the other hand, C_{iv} depends on the amount of cement (in volume) per volume of soil+voids (voids=water+air) in which it is contained. Thus, lower values of η and higher values of C_{iv} mean higher values of mechanical strength. It can also be seen in Figures 3 and 4 that there is an increase in the values of q_u and q_t with increasing curing time (t). For each curing time, an equation was obtained that correlates $\eta/C_{iv}^{0.25}$ to which $\eta/C_{iv}^{0.25}$ at q_t. The equation has the general form: $q_u \vee q_t = A[\eta/C_{iv}^{x}]^{-y}$, where y is a fitting exponent that depends on the properties of the binder, and A is a constant (in kPa) that grows depending on the curing time for both q_u and q_t. The parameters "*x*" and "y" were also calculated for other mixtures. Moreira et al. (2019) calculated x=0.28 and y=4.47 for silt-cement-ground tile residue mixtures. Baldovino et al. [44] calculated *x*=0.45 and y=2.00 for mixtures of GF yellow silt and CPV cement and suggested that *x* values less than one are more common for fine soils stabilized with cement, and *x* values close to 1 are more common, more common in sand-cement. Diambra et al. [45] verified that the *x* and *y* parameters are linked to soil characteristics, and the y parameter can be approximated to the inverse of *x*. In turn, parameter A depends on both the stabilized soil and the cement matrix, strongly influencing parameters such as curing time, curing temperature and molding humidity, which influence the dynamics of soil-cement reactions. The authors made such findings based on a mathematical model that assumes that the mechanical strength at the failure of the soil matrix (based on the critical state theory) and the cement matrix (based on the Drucker-Prager failure criterion) overlap, concluding that the parameters A, x, and y are not purely empirical.

Due Diambra et al. [45] suggested that *x*=1/y for modeling the strength of fine sand-cement mixtures; theoretically, for the present study, the value of *x* should be *x*=1/y=1/4.52=0.22, but it is noted for the proposed mixtures of gray-cement silt that: *x*=1.13/y. Excellent correlations between q_u-[$\eta/C_{iv}^{0.25}$] and q_t-[$\eta/C_{iv}^{0.25}$] were obtained (with R^2 greater than 0.97). The equations that control q_u for 7, 14, and 28 days are, respectively (Equations 1 to 3):

$$q_u = 83.80\times10^5[\eta/C_{iv}^{0.25}]^{-4.52}\ (R^2=0.97) \tag{1}$$

$$q_u = 100.81\times10^5[\eta/C_{iv}^{0.25}]^{-4.52}\ (R^2=0.98) \tag{2}$$

$$q_u = 126.32\times10^5[\eta/C_{iv}^{0.25}]^{-4.52}\ (R^2=0.97) \tag{3}$$

The equations that control q_t for 7, 14, and 28 days are, respectively, (Equations 4 to 6):

$$q_t = 10.83\times10^5[\eta/C_{iv}^{0.25}]^{-4.52}\ (R^2=0.98) \tag{4}$$

$$q_t = 13.42\times10^5[\eta/C_{iv}^{0.25}]^{-4.52}\ (R^2=0.97) \tag{5}$$

$$q_t = 17.15\times10^5[\eta/C_{iv}^{0.25}]^{-4.52}\ (R^2=0.98) \tag{6}$$

Considering field applications, dosages and cure times will depend on the specifications of the paving project, which is almost always short due to the execution schedule. Overall, 78% of compacted cement-soil mixes meet the minimum requirements for sub-base use, according to the standard American TxDOT-Tex-120-E [46] and the Brazilian standard DNIT 143 [47].

As can be seen in Figure 6 (see the dotted horizontal line). According to these standards, the minimum requirement would be q_u=1200 kPa and q_u=2100 kPa for the sub-base and base, respectively. The minimum required in the standard is obtained with 5% cement and 3% cement when compacted above γ_d=15 kN/m^3. In order to avoid high cement contents, the criterion $\eta/C_{iv}^{0.25}$ can be used to reach 1200 kPa of strength, increasing the compaction energy and decreasing the amount of cement to 4% without the need for confirmatory tests. Baldovino et al. [20] obtained 1200 kPa unconfined compressive strength in 90-day curing for pink soil mixtures of GF-9% lime. This value is equal to that obtained with 3%C, compacting at γ_d=16 kN/m^3 and curing for seven days (Figure 6).

Consequently, adding CPV cement to the gray GF soil decreases lime consumption. For the 28-d soil cured with 7% CPV, Baldovino et al. [48] also obtained 1200 kPa of simple compressive strength. Baldovino et al. [48] stabilized the yellow soil of the FG stabilized with CPV. After 28-d of curing, the authors found that the compressive strength of adding 9% cement was approximately 1200 kPa. Thus, comparing the stabilization of the gray soil used in the present study and the other soils of the Guabirotuba profile with cement/lime, it can be stated that cement consumption can be reduced if gray soil is used for paving. This superiority is due to the chemical composition of the soil and the particle size distribution (i.e., C_c and C_u). As demonstrated in previous studies [49]. Recent studies have introduced, for example, latex to reduce the percentages of cement. For example, Buritatum et al. [19] reduced the amount of cement by 5% by adding natural latex into the stabilized soil. Krishnan et al. [50] analyzed the glass fines and plastic residues to enhance the strength properties of a new geomaterial.

3.2. Splitting Tensile-to-Compressive Index

An empirical relationship between unconfined compression and split tensile can be calculated regarding the curing time of soil-cement samples. This relation can be called $\xi = q_t/q_u$, independent of the relation $\eta/C_{iv}^{0.25}$. In this way, the equations that describe the growth of q_u and q_t as a function of $\eta/C_{iv}^{0.25}$ (see Figures 4 and 5 and Equations 1 to 6 can be expressed as a constant by dividing Equations 3 to 8 by $10^8 \times [\eta/C_{iv}^{0.25}]^{-4.52}$. The relationship q_t/q_u is a scalar independent of the curing time and cement content, as shown in Figure 8. In general, "ξ" index has a value of 0.13. Thus, it turns out that q_t is 13% of the value of q_u. The "ξ" relationship can also be calculated directly, correlating the experimental split tensile and unconfined compression values in the same Cartesian plane, as shown in Figure 9. The values of "ξ" is measured in a range of 0.10-0.17 (with ±3% error). Nevertheless, the tensile/compressive index can be calculated with the mean value ξ = 0.13. Thus, it is concluded that the value does not change and is independent of the molding conditions.

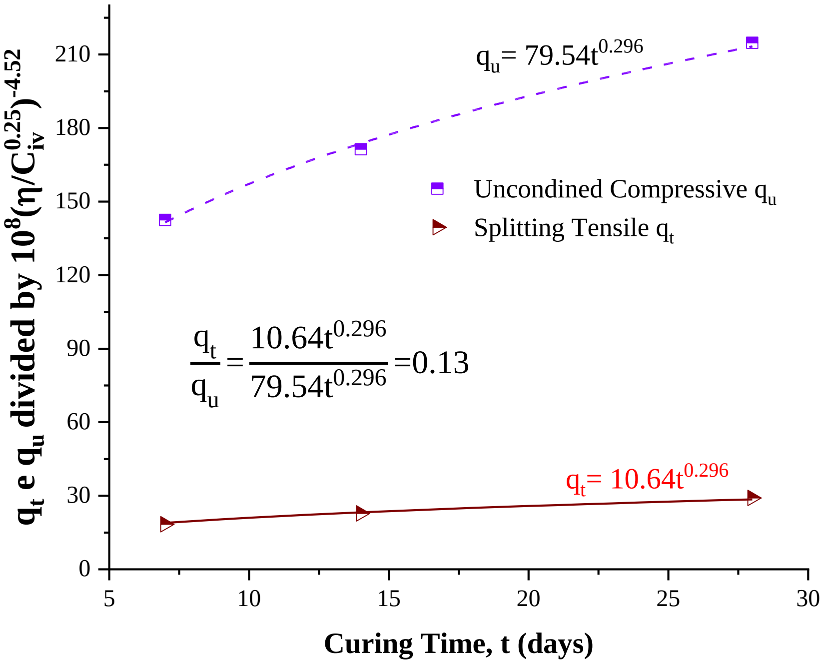

Figure 8. Effects of curing time on normalized unconfined compressive and split tensile strength at $10^8[\eta/C_{iv}^{0.25}]$ index considering 7, 14, and 28-days

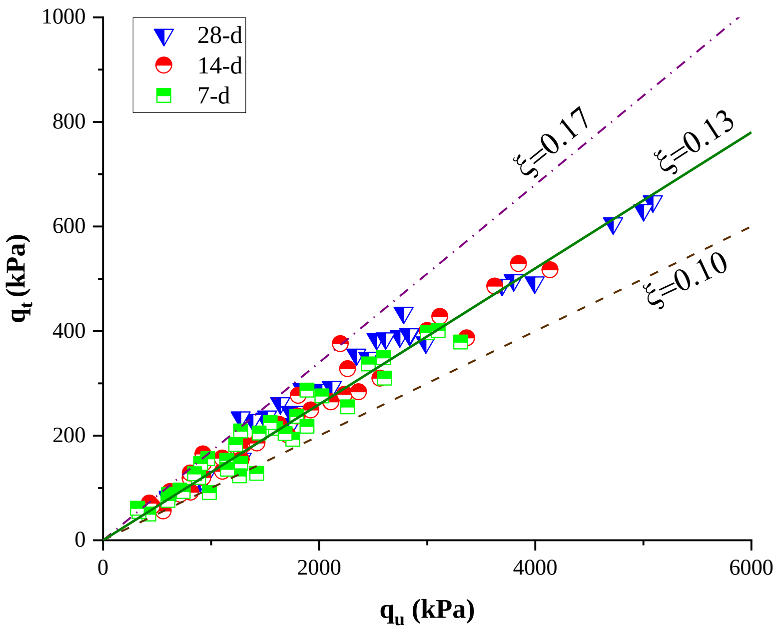

Figure 9. The split tensile-to-compressive empirical relationship

According to Diambra et al. [45], for artificially cemented sandy soils, the existence of a relationship between the tensile/compressive strengths ($q_t/q_u = \xi$) is independent of the curing time and is mainly governed by the tensile relationship (or friction properties) of cement. Authors such as Consoli et al. [37] calculated a q_t/q_u ratio of 0.13 for mixtures of compact fine soils with Portland cement using molding moisture contents of 17, 20, and 23% and molding dry unit weights between 14 kN/m^3 and 16 kN/m^3 equal to those presented in this article. Festugato et al. [39] made mixtures of sandy soil with cement and polypropylene fibers; for the soil without fibers, they calculated a value for "ξ" of 0.10, and for the soil reinforced with fibers, they found a value of ξ =0.15 using a ratio of $\eta/C_{iv}^{0.28}$. Other authors, such as Baldovino et al. [48] calculated the ξ ratio between 0.15 and 0.17 for Guabirotua Formation yellow soil and CPV cement mixtures. Baldovino & Izzo [16] concluded that the value of ξ for soil-cement mixtures cured for seven days is 0.15. Finally, it is noted that the strength ratio ξ for cemented/reinforced soils varies on average between 10% and 27%. Thus, this study's empirical relationship of q_t and q_u (ξ=0.13) is within this range.

3.3. The Durability of Soil-Cement Compacted Blends

Each wetting-drying (W-D) cycle started with the specimens immersed in water for 5 hours and dried in an oven for 42 hours. The appearance of the specimens before the first cycle is shown in Figure 10. as well as the appearance after 12 W-D cycles. It is observed that all specimens maintained their cylindrical shape except for those compacted with 3% cement, which progressively deteriorated and lost large mass percentages, as seen in Figure 11. Figure 12 shows the mixtures' cumulative mass loss (ALM) influenced by the number of wetting-drying (W-D) cycles. It is observed that the mixtures with 3% of cement lost 100% of their mass after the 3rd and 11th cycles in the specific weights of γ_d=14 kN/m^3 and 15 kN/m^3, respectively (i.e., mixtures C3γ14 and C3γ15). Additionally, the C3γ16 mixture lost 75% of its mass (Figures 7 and 9). Mixtures with 5, 7, and 9% cement lost less than 10% mass, as shown in Figure 13 (enlargement of Figure 12). ALM is directly related to the amount of cement used and initial voids in the specimen. Therefore, ALM was correlated to the ratio $\eta/C_{iv}^{0.25}$, as seen in Figure 13. The voids/cement ratio also controls the ALM of the compacted mixtures that rises with increasing $\eta/C_{iv}^{0.25}$. The correlations between ALM-$\eta/C_{iv}^{0.25}$obtained excellent adjustments with $R^2 \geq 0.93$.

Figure 10. Durability samples before the W-D cycles and their appearance of them after the 12th cycle

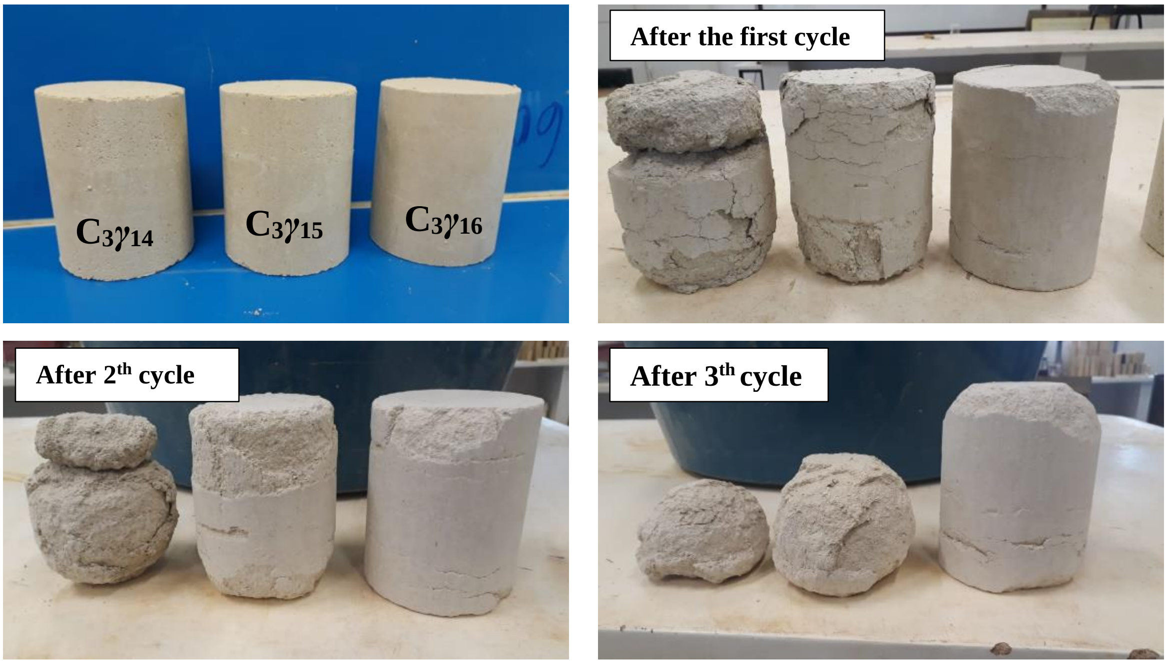

Figure 11. Durability samples using 3% cement before the W-D cycles and their appearance after 1, 2, and third cycles

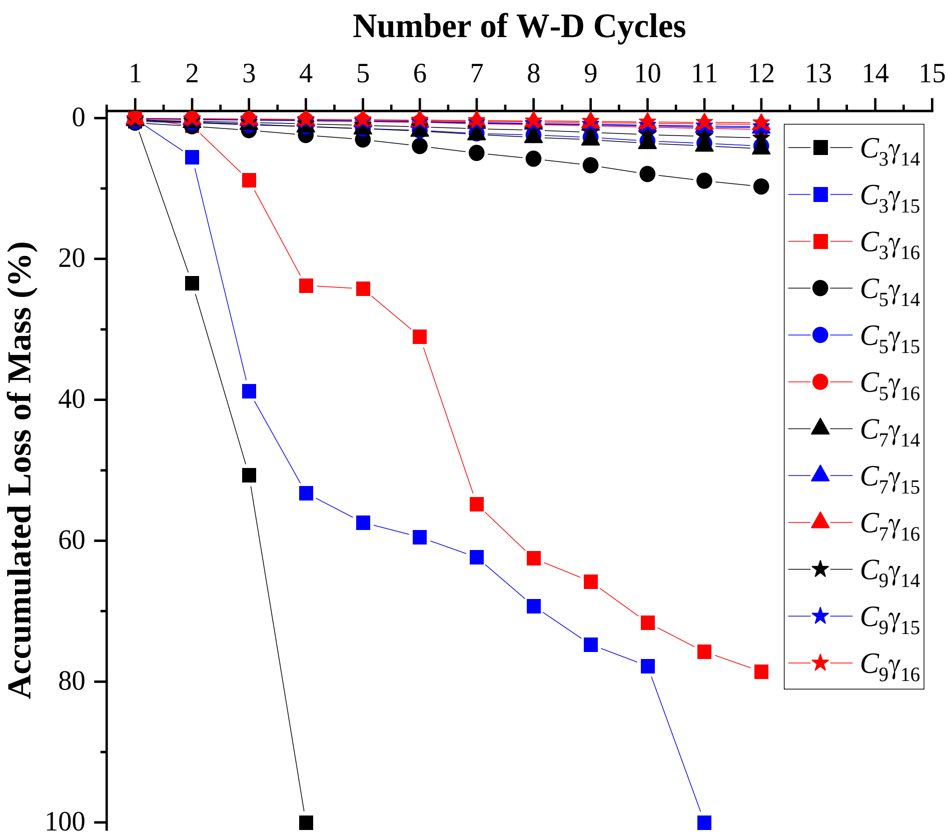

Figure 12. Influence of number of W-D Cycles on ALM for each soil-cement compacted blend

According to PCA standards, the ALM value should not exceed 7-8% for chemically stabilized silty soils with paving application [51]. All mixtures, except those molded with 3% cement, meet this requirement. However, even if 3% of cement above γ_d=15 kN/m^3 is viable from a strength point of view, it could not be used for durability. Thus, 5% is the most appropriate cement content to stabilize the gray FG silt, based on this type of soil's mechanical and durability properties. Recently, durability evaluation has become one of the most important parameters for evaluating the use of geomaterials in pavements. Udomchai et al. [52] evaluated the durability against wetting/drying cycles of natural rubber latex stabilized unpaved under cycling tensile loading. Mustafa et al. [53] measured the durability and strength of stabilized soil for usage as earth construction material.

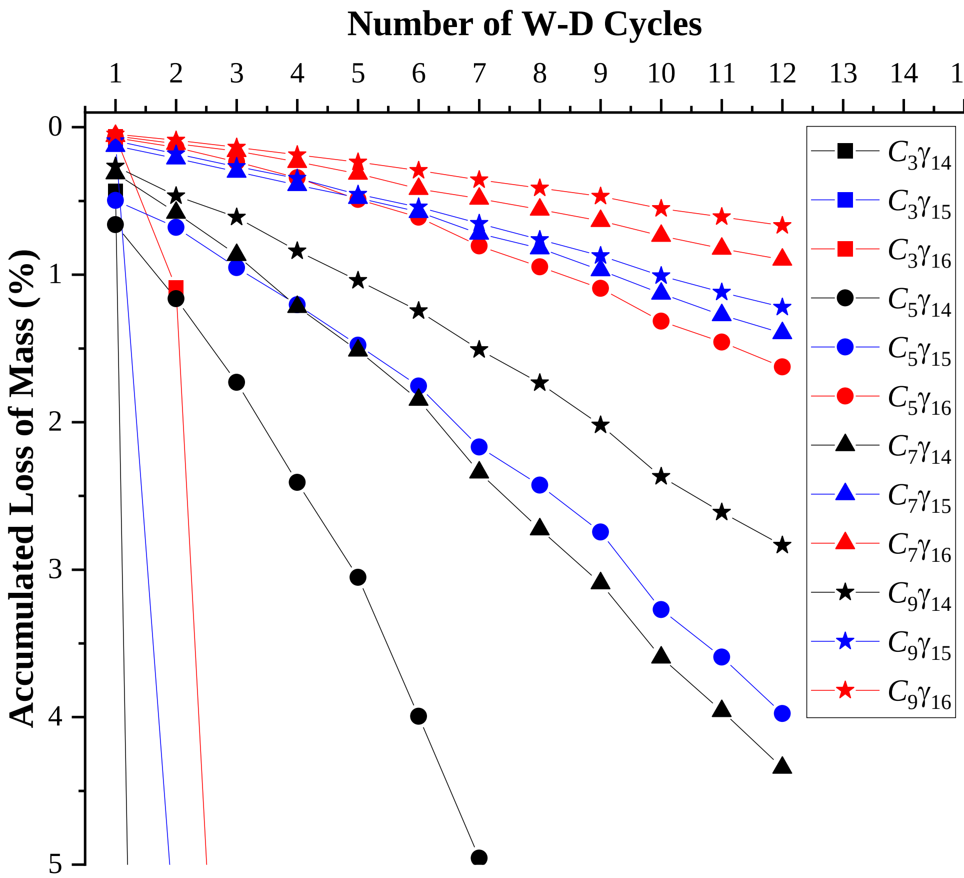

Figure 13. Enlargement of the influence of W-D cycles on ALM (from 0 to 5%) for each soil-cement compacted blend is presented in Figure 12

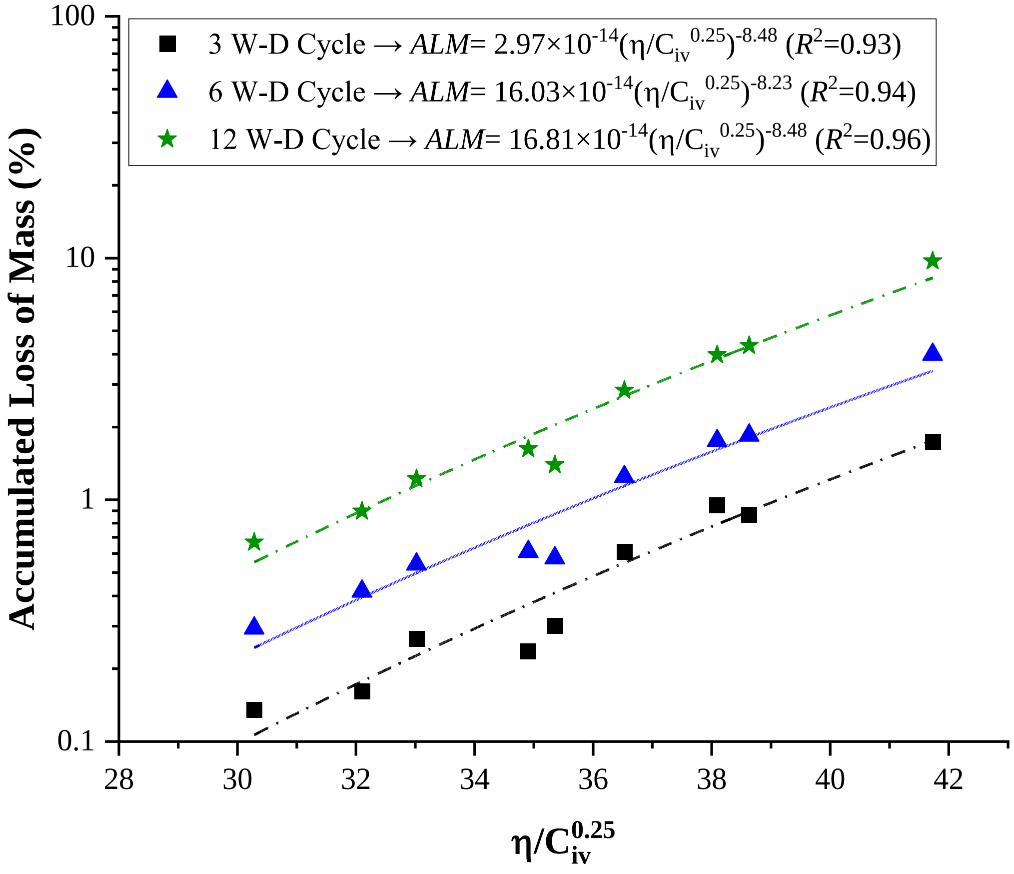

Figure 14. Impact of $\eta/C_{iv}^{0.25}$ index on ALM for 3, 6, and 12th cycles

3.4. Microstructure of Soil-Cement Compacted Blends

Using SEM and EDX, the chemical composition of the geomaterial (soil-cement) was investigated. Figure 15 depicts the micro analysis, while Table 4 displays the EDX results. The content of each chemical element in regions 2 and 3 of the glassy morphology (Figure 15 and Table 3) closely matches the results of the XRF (Table 2) examination of raw materials (soil and cement). The microanalysis results reveal a significant level of heterogeneity characteristic of raw materials. The absence of amorphous elements can explain the non-formation of new minerals. The lack of new elements can be explained by the moderate curing temperature of the mixtures (approximately 23° C). Finally, it can be seen in Figure 15 that when adding 5% of cement, a more compact and homogeneous structure was formed, reducing voids after 28 days of curing compared to 3% of cement.

Table 3. EDX results from areas 1, 2, and 3 are shown in Figure 4 and Figure 15

Area	C	O	Mg	Al	Si	K	Ca	Ti	Fe
1-soil	7.99	61.40	14.56	14.81	0.34	0.90	-	-	-
2- 3% cement	9.81	61.81	0.33	9.14	13.35	0.16	4.18	0.42	0.81
3 -5% cement	10.41	58.91	0.28	10.33	12.40	5.41	0.73	1.54	10.41

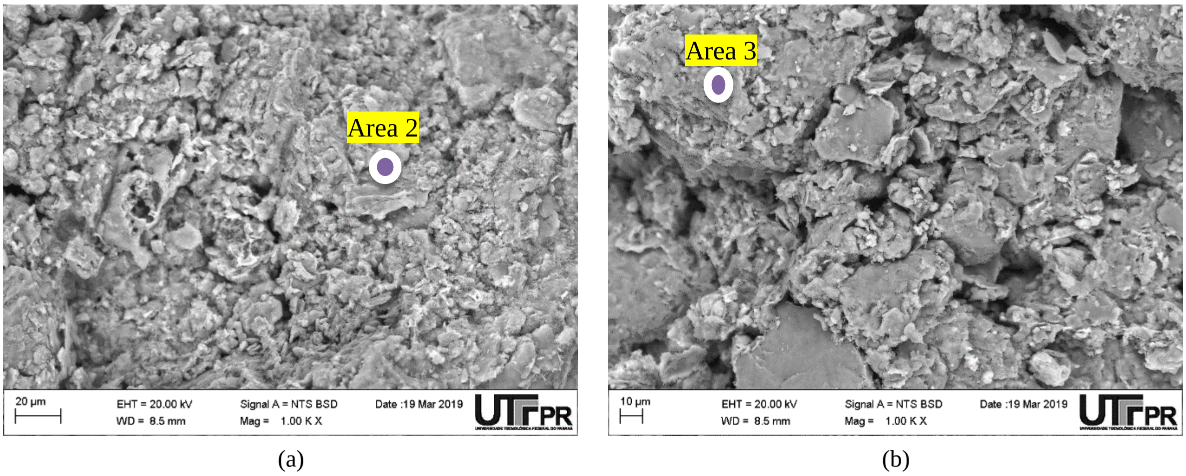

Figure 15. SEM of the soil-cement compacted blends and area positions of the EDX microanalysis. (a) Sample compacted at $\eta/C_{iv}^{0.25}$=40 (3% of cement) cured during 28-days and (b) Sample compacted at $\eta/C_{iv}^{0.25}$=37 (5% of cement) cured during 28 days.

4. Conclusions

In this article, soil from the gray layer of GF was stabilized with different cement contents for application in paving in the metropolitan region of Curitiba. To verify its potential use in constructing the sub-base of pavements, a program of unconfined compressive and split tensile was carried out, using curing times of 7, 14, and 28 days. Durability tests were also performed using 12 W-D cycles. According to the results, the following conclusions can be considered:

- The increase in the cement content and the mold's specific weight increased the unconfined compressive and split tensile strength and improved the mixtures' microstructure by reducing voids. The strength of the mixtures also increased (by 50%. comparing 7 and 28 days) with curing time. q_u values greater than 1200 kPa (minimum value required for sub-base) were obtained using 4% cement.
- A tensile/compressive ratio was calculated to be 0.13, independent of cure time.
- Such strength, durability, and microstructural benefits can be further enhanced (e.g., by increasing or decreasing the overall mass mixture or the mass of particular material), thus enabling dosages that are best suited to different scenarios to be created.
- The strength (both unconfined compression and split tensile) and the accumulated loss of mass (*ALM*) of the mixtures are directly influenced by the porosity/cement index adjusted to an exponent of 0.25, which made the variation of porosity, volume of cement, and values of q_u, q_t, and ALM compatible. Potential equations described the compatibility of variables with adjustments of $R^2 \geq 0.93$ and $R^2 \geq 0.97$ for durability and strength, respectively.
- Although the content of 3% satisfied the requirements for mechanical strength., regarding durability, 5% of cement is the minimum content to be used in the soil. Thus, 5% becomes the most appropriate content to stabilize the gray GF silt. Furthermore, comparing the stabilization of the gray soil used in the present study and the other soils of the Guabirotuba profile with cement/lime, it can be affirmed that cement consumption can be reduced if the gray soil is used.

5. Declarations

5.1. Author Contributions

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

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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