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Study of modified soils with polymers addition for use in roads pavements

Estudo de solos modificados com adição de polímeros para uso em pavimentos rodoviários

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ABSTRACT
Soil is a supporting material and composes the pavement layers. Therefore, it must possess characteristics that confer stability and mechanical resistance to the stresses due to traffic during the pavement's service life. When soils do not have the characteristics the projects require, stabilization techniques can make the natural soil suitable for highway requirements. Based on this assumption, this study aimed to evaluate the effectiveness of polymer association in soil stabilization for use in road pavement. Mechanical behavior and wear tests were conducted on four different soils using pure soil samples and samples with the addition of the polymer association. The polymer association increased the values in the California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), Indirect Tensile Strength (ITS), Resilient Modulus (MR), and reduced wear in the LWT and WTAT tests. Overall, the polymer association studied in this research effectively stabilizes soils, making this technique efficient in highway pavement layers.

RESUMO
O solo é considerado um material de suporte e compõe as camadas do pavimento. Portanto, ele deve possuir características que conferem estabilidade e resistência mecânica aos esforços decorrentes do tráfego durante a vida útil do pavimento. Quando os solos não possuem as características exigidas pelos projetos, técnicas de estabilização podem tornar o solo natural adequado para os requisitos de rodovias. Com base nessa premissa, este estudo teve como objetivo avaliar a eficácia da associação de polímeros na estabilização de solos para uso em pavimentos rodoviários. Foram realizados ensaios de comportamento mecânico e desgaste em quatro tipos diferentes de solos, utilizando amostras de solo puro e amostras com a adição da associação de polímeros. Com base nos resultados obtidos, a associação de polímeros aumentou os valores do Índice de Suporte Califórnia (CBR), da Resistência à Compressão Simples (UCS), da Resistência à Tração Indireta (ITS), do Módulo Resiliente (MR) e reduziu o desgaste nos ensaios LWT e WTAT. De forma geral, a associação de polímeros estudada nesta pesquisa estabiliza eficazmente os solos, tornando essa técnica eficiente nas camadas de pavimentos rodoviários.

1. INTRODUCTION

Soil is considered a supported material on highways and compound pavement layers. So, it must have characteristics that confer stability and mechanical resistance to traffic internal forces during the pavement's life.

When soils do not have the required characteristics by the project, two procedures can generally be used. The first is to withdraw the original material and replace it with the desired geotechnical characteristics. This procedure can become impractical for roads requiring a large volume of replacement or large transport distances. The second procedure is to use stabilization techniques that make the natural soil adequate for road requirements.

Chemical treatment of pavement base, subbase, and subgrade materials improves workability during compaction, creates a firm working surface for paving equipment, increases the strength and stiffness of a foundation layer, reduces potential shrink and swell due to moisture changes and frost action, and controls dust on unpaved roads (Rauch et al., 2002).

The mechanical behavior tends to improve with the incorporation of a certain percentage of cement, lime, fly ash, polymers, or other stabilizers and with the curing time (Lovato, 2004; Fall et al., 2007; Silva, 2016; Mengue et al., 2017; Biswal, Sahoo and Dash, 2018a; 2018b; Tan et al., 2020; Jose, Krishnan and Robinson, 2022). However, the increased stiffness of treated or stabilized layers increases their brittleness and, consequently, reduces their flexibility, which inevitably leads to accelerated crack propagation under traffic loads, ultimately reducing their structural performance. It is important to note that crack initiation and propagation are distinct processes and should be analyzed as such (Wirtgen Group, 2012).

The flexibility of stabilized soils is crucial for evaluating their ability to bear loads without experiencing damage or compromising stability. Soil stabilization involves modifications that enhance the soil's properties, making it more resilient under load. Various additives, including mineral modifiers, chemical compounds, rubber powder, aggregates, and elastomeric polymers, can be used to increase soil flexibility. These modifications aim to reduce plastic deformations, extend fatigue life, and improve both flexibility and elasticity. Moreover, several countries are advancing technologies to incorporate ground tire rubber into soil stabilizers, addressing these durability challenges while also reducing environmental liabilities (Pinheiro, 2004).

A commonly used additive in soil stabilization is a synthetic polymer. Polymer stabilizers are typically vinyl acetates or acrylic copolymers suspended in an emulsion by surfactants. These polymers enhance the soil's deformation capacity while preserving or even increasing its overall stability. Acting as a binding agent, synthetic polymers improve the cohesion between soil particles, which makes the soil more malleable and flexible under stress. This enhanced flexibility allows the stabilized soil to better withstand mechanical loads and environmental factors, such as temperature fluctuations and moisture variations, thereby reducing the risk of cracks and structural failure. Additionally, polymer stabilization can lead to more durable pavements and infrastructure, extending the lifespan of the soil application while requiring less frequent maintenance.

Iyengar et al. (2013) evaluated the potential of polymer binders to stabilize pavement subgrades in Qatar. According to the author, results demonstrate that the polymer binders modify the Qatari subgrade soils, resulting in more favorable engineering properties. For example, the compressive strengths of the polymer-stabilized soils are superior to those of the unstabilized soils and those stabilized using Portland cement.

Tingle et al. (2007) studied the chemical and physical bonding mechanisms associated with selected nontraditional stabilizers. They observed that polymer (a typical polyethylene vinyl acetate copolymer) stabilizers coat soil particles and form physical solid bonds. Polar components in the polymer may adsorb strongly onto soil particle surfaces, promoting adhesion.

Tingle and Santoni (2003) conducted a laboratory evaluation of the stabilization of clay soil with polymer emulsions using polyethylene vinyl acetate copolymer. Newman et al. (2005) report the use of polymer emulsions for sand stabilization.

Qingquan, Qing and Zhijing (2004) report the study of non-standard sterilizers on the base course of rural roads. The stabilizer in liquid form was observed to contain long-chain high polymers, and each polymer connects with the surrounding soil through the bridge of its long chain to establish a net-shape structure. Under such net-shape structures, the stabilized soil gains stable strength because this process is in one direction and cannot return to its original status.

Newman and Tingle (2004) studied the action of six polymer emulsions for soil stabilization: Acrylic vinyl acetate copolymer; Polyethylene-vinyl acetate copolymer; Acrylic copolymer; Polymeric Proprietary Inorganic Acrylic Copolymer; Acrylic vinyl acetate copolymer; and Acrylic polymer. They observed that all of the additives improved retained wet strength and toughness, and the soil additives they employed increased unconfined compressive strength.

Polymeric stabilization can be used in soils of different particle sizes and is effective in stabilizing both granular and fine soils (Rezende, Marques and Cunha, 2015). The characteristics optimized after the stabilization processes are increased durability and reduced expansion of the base layer.

According to Soliz (2007), the stabilization established with the use of polymers is based, in most cases, on the efficiency of the additive in repelling water and providing the soil with a cohesive portion through polymerization. Polymerization can be understood as a form of cementation, where the polymer acts to flocculate the soil structure, increasing its resistance to shear.

According to Khatami and O'Kelly (2013), the crosslinking process connects polymer chains through chemical reactions, whether ionic/electrostatic or covalent bonds; hydrogen bonding (strong polar attraction) and Van Der Waals forces (physical absorption), creating a comprehensive network in the soil matrix. These reactions strengthen the entire polymeric structure, improve mechanical resistance, and reduce permeability.

Researchers have conducted various studies (Al-khanbashi and El-Gamal, 2003; Hernández et al., 2005; Zandieh and Yasrobi, 2010; Khatami and O'Kelly, 2013; Garcia, Valdes and Cortes, 2015; Barreto, Repsold and Casagrande, 2018; Okonta, 2019) on the use of polymers in soil stabilization, aiming to improve mechanical properties. However, the literature lacks studies investigating soil flexibility with the addition of polymers, making it necessary to develop research that includes this assessment.

Polymer stabilization, unlike other chemical stabilization techniques, may be used in any type of soil and particle size and is effective in stabilizing fine and granular soils. Based on this assumption, this study proposes to study the stabilization of soils with polymers, as this technique works by improving the mechanical properties of the soil and reducing the deterioration of road layers.

2. MATERIALS AND EXPERIMENTAL DETAILS

2.1. Materials

2.1.2. Polymers

The present study discusses the association of followed polymers: DirtGlue Industrial polymer, TerraDry, and PolyCure. The company VIAENCOSTA Engenharia Ambiental® provides all of them. The functions of those polymers are:

- DirtGlue Industrial polymer is an acrylic polymer binder employed to adhere the soil particles together and form a composite structure.
- TerraDry is a water-proofing agent employed to reduce the water sensitivity of soil particles, especially in soils containing significant levels of clays or silts. It functions to hydrophobize the soil surface and resist water intrusion.
- PolyCure served as a catalyst, accelerating the drying process while promoting early strength development.

According to the provider, the ideal ratio for the polymeric mixture is 7% DirtGlue Industrial polymer, 6% PolyCure, and 2% TerraDry by weight. In this research, DirtGlue Industrial polymer was used at concentrations of 1%, 3%, and 5%, while the proportions of the other polymers were adjusted to maintain the recommended ratio.

Table 1 describes the contents of the polymer association utilized in this research.

Table 1: Contents of polymer association.

DirtGlue Industrial polymer (%)	TerraDry (%)	PolyCure (%)	Total contents of Polymer association (%)
1	0.29	0.86	2.2
3	0.86	2.57	6.4
5	1.43	4.29	10.7

2.1.3. Soils

Three (3) different soils with the following TRB classification were studied: Soil 1 (A-2-6), Soil 2 (A-5) and Soil 3 (A-2-4). Table 2 summarizes the geotechnical properties of these soils.

Table 2: Physical properties of research soils.

Properties	Soil 1	Soil 2	Soil 3	Standard method
Passing 2.0 mm sieve (%)	96.34	100.00	99.98	ABNT- NBR 7181/1984 (ABNT, 1984d)
Passing 0.42 mm sieve (%)	37.29	98.30	74.79	ABNT- NBR 7181/1984 (ABNT, 1984d)
Passing 0.074 mm sieve (%)	11.12	68.81	12.98	ABNT- NBR 7181/1984 (ABNT, 1984d)
Liquid limit (%)	34.22	49.25	NL	ABNT- NBR 6459/1984 (ABNT, 1984a)
Plastic limit (%)	23.81	40.82	NP	ABNT- NBR 7180/1984 (ABNT, 1984c)
Plastic index (%)	10.41	8.43	NP	ABNT- NBR 7180/1984 (ABNT, 1984c)
Specific Gravity	2.655	2.602	2.703	ABNT- NBR 6508/1984 (ABNT, 1984b)

2.1.4. Common stabilizers

To provide a reference point, soil samples were also stabilized with conventional chemical agents (cement and lime).

Based on TRB classification, cement was selected for granular soils, while lime was applied to clayey and silty soils.

The cement dosage was determined in accordance with the ABNT NBR 12253 (ABNT, 2012) standard, which specifies the requirements for determining the appropriate amount of Portland cement to stabilize soils for soil-cement layers by measuring the unconfined compressive strength (UCS) of cylindrical specimens. The Portland cement used was CP IV-32 RS, added at a 3% dosage to stabilize Soils 1 and 3.

The dosage for determining the required lime content for physicochemical stabilization was carried out by the DNIT-ME 419 standard (DNIT, 2019). This method is based on the procedure proposed by Eades and Grim, which measures the pH of the soil with various lime contents, aiming to reach a pH of 12.4. The hydrated lime used was CH-1. A 3% content of hydrated lime was added as a stabilizer at Soil 2.

2.2. Testing Program

The stabilization effect of polymers on soil was analyzed through the results of (i) compaction, (ii) California Bearing Ratio (CBR), (iii) Unconfined Compressive Strength (UCS), (iv) Resilient Modulus (*RM*), and (*v*) Deterioration Test.

All tests were conducted at optimum moisture content and maximum dry density conditions. For each test, three specimens were molded under consistent conditions, adhering to acceptance criteria with a molding moisture content within ±0.5% of the optimum moisture and a compaction degree between 98% and 102% of the maximum dry density obtained in the compaction test.

2.2.1. Compaction test

The compaction test was conducted using Intermediate Proctor energy (13kgf.cm/cm^3) in accordance with the DNIT-ME 164 (DNIT, 2013) standard. The soil was compacted in five equal layers, with 26 blows per layer. Five tests with increasing moisture contents were performed to establish the material's compaction curve. The optimum moisture content (OMC) and the maximum dry bulk density (MDD) were determined based on the results.

2.2.2. California Bearing Ratio

The California Bearing Ratio (CBR) test followed the DNIT-ME 172 (DNIT, 2016) standard. The samples were molded at the optimum condition obtained from the compaction test. After manual compaction, the expansion test was done by applying a standard load to each mold and immersing the compacted soils in a water tank for 96 hours. The samples were air-cured for seven days before immersion for four days. It was monitored expansion using extensometers with periodic readings (initial and daily). After completing the expansion test, the mold was removed from the immersion tank and allowed to drain excess water for fifteen minutes. The CBR test used a universal testing machine and extensometers to measure penetration and piston pressure.

2.2.3. Unconfined compressive strength test

Each specimen used in the unconfined compressive test (NBR 12025 of ABNT, 1990) was compacted in a cylindrical mold 100 mm in diameter by 130 mm in height at OMC and MDD. After being molded, specimens with the addition of polymers were submitted to different conditions with air curing times of 7 and 28 days before rupture.

2.2.4. Resilient modulus test

The resilient modulus tests were done on specimens with a height of 200 mm and a diameter of 100 mm, with intermediate Proctor energy using a bipartite cylinder. The tests used the Material

Testing System machine with a closed-loop servo-hydraulic loading system. The applied load was measured using a load cell installed inside the triaxial cell. The axial displacement measurements used two linearly variable differential transducers (LVDTs) placed between the top platen and the base of the cell to reduce extraneous axial deformation compared to external LVDTs.

The resilient modulus testing was conducted following DNIT ME 134 (DNIT, 2018). According to this method, sample conditioning began with the application of 300 load cycles to minimize surface irregularities on the top and bottom, effectively reducing initial stages of permanent deformation. The procedure involved a series of 1800 cycles, applying a haversine-shaped load pulse under varying levels of confining and deviatoric stresses to evaluate the resilient modulus across different stress conditions. A load pulse duration of 0.1 seconds was applied, followed by a rest period of 0.9 seconds. Samples with polymer associations were air-cured for seven days prior to testing to ensure adequate stabilization.

2.2.5. Deterioration test

The Loaded Wheel Test (LWT) and Wet Abrasion Test Track (WTAT), commonly used in microsurfacing studies, were adapted based on modifications proposed by Duque No. (2004). To create a soil layer representative of the pavement base surface, the conventional molds used in the LWT and WTAT wear tests were modified. For the LWT, molds were fabricated with dimensions of 50.0 mm in height, 50.8 mm in width, and 381.0 mm in length. For the WTAT, molds measuring 300 mm in diameter and 50.0 mm in height were used. Loading conditions, equipment speeds, and contact surface types were maintained in accordance with ABNT standards (NBR 14746 (ABNT, 2014) and NBR 14841 (ABNT, 2002)) to ensure consistency with established protocols.

The LWT test follows the norm NBR 14841 as the "determination of asphalt excess and adhesion of sand" by the LWT machine. The WTAT test was performed according to NBR 14746, which determines loss by humid abrasion. This test, modified by Duque No. (2004), evaluates soil deterioration upon simulated traffic. Tests were performed with samples of soil polymer and reference samples of pure soil and stabilized with cement and lime. The samples for the LWT and WTAT tests were air-cured for seven days.

3. RESULTS

3.1. Compaction

The Standard Proctor compaction tests was used to observe changes imposed by adding the polymer association at optimum moisture content and maximum apparent dry density. Figure 1 presents the results for compaction tests and Table 3 presents the results of the compaction tests for the studied mixtures.

The results for the Standard Proctor compaction test showed that the addition of the polymeric association increased the maximum dry density for Soils 1, 2 and 3.

The reduction of optimum moisture content for all soils was possibly caused by Terradry, which reduces the sensitivity of water's action on soil particles.

Baghini et al. (2014) conducted a comprehensive study on the effects of a road base layer's type and amount of Portland cement and carboxylated styrene-butadiene emulsion (Tylac 4190). Their findings show that the Standard Proctor compaction test has a clear relationship between the increase in cement content and the changes in optimum water content and maximum dry density.

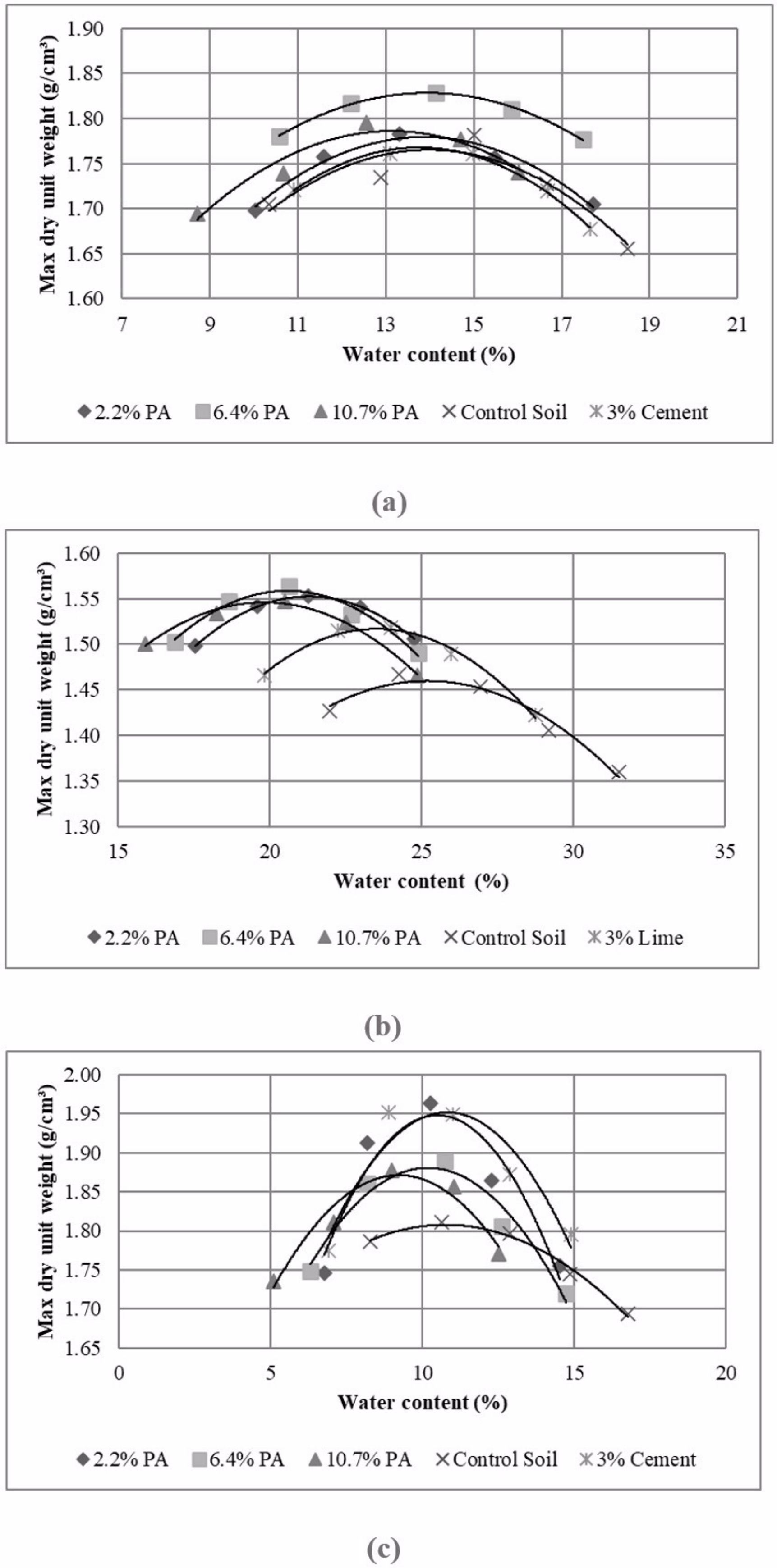

Figure 1. Compaction curves for mixtures of soil additives for Soil 1 (a), Soil 2 (b) and Soil 3 (c).

Table 3: Compaction tests for mixtures of soil additive.

	Soil 1		Soil 2		Soil 3	
Additive	**OMC (%)**	**MDD (g/cm³)**	**OMC (%)**	**MDD (g/cm³)**	**OMC (%)**	**MDD (g/cm³)**
Pure	15.00	1.782	24.24	1.467	10.64	1.811
2.2%	13.30	1.782	21.26	1.553	10.26	1.963
6.4%	14.30	1.829	20.64	1.564	10.72	1.889
10.7%	12.57	1.795	20.51	1.548	8.97	1.878
Reference Samples (Cement/lime)	13.09	1.761	23.99	1.518	8.88	1.952

Sariosseiri and Muhunthan (2009) studied the use of Portland cement to modify and stabilize soils in Washington, USA. They generally observed that as cement content increased, the optimum water content increased, while the maximum dry unit weight decreased. They found that changes in compaction characteristics were significant at lower percentages of cement, whereas the changes in compaction characteristics of treated soils were minimal at higher percentages.

Adding 3% cement by weight to Soil 1 did not significantly change the performance for this test. The results show that adding cement to the Soil 3 sample increases its maximum dry density and reduces its optimum moisture content.

Elsharief et al. (2013) studied lime stabilization of tropical soils for road construction. Adding lime to three tropical soils increased their maximum dry density and reduced their optimum moisture content.

The results indicate that the addition of lime to the Soil 2 sample increases its maximum dry density while reducing its optimum moisture content.

3.2. California bearing ratio

Table 4 shows the results of CBR tests for the studied samples.

Table 4: California Bearing Test for mixtures of soil additive.

	California Bearing Test (%)					
Additive	**Soil 1**	**σ**	**Soil 2**	**σ**	**Soil 3**	**σ**
Pure	5	2	3	1	4	2
2.2% Polymers	14	5	7	3	23	3
6.4% Polymers	33	6	31	6	45	5
10.7% Polymers	43	9	41	3	135	16
References samples (Cement/lime)	27	2	3	1	107	17

σ: Standard deviation

In CBR results, adding the polymer association to all soils gradually increased CBR values as the polymer content increased, reaching values 3200% higher with the addition of 10.7% polymer composition to Soil 3. A possible explanation is the addition of DirtGlue Industrial polymer, which increased soil density and soil-bearing capacity. Additionally, Terradry, which reduces water sensitivity, also helped increase CBR values because the samples are saturated, which typically reduces bearing capacity.

There was a significant increase in CBR values of Soil 1 and 3 to reference samples. Adding cement to Soil 3 resulted in higher CBR values than the composition with a 6.4% polymer association. This fact may occur due to the presence of cement, which enhances the soil's stiffness and thus hinders the penetration of the piston.

According to the state-of-the-art report on lime stabilization by the Transportation Research Board (TRB, 1987), the CBR is inappropriate for characterizing the strength of cured soil-lime mixtures. It can only be used as a comparison and has little practical significance or meaning as a measure of strength or stability other than as a relative indicator test. Adding 3% of lime at weight at Soil 2 shows a small increase.

The standard DNIT ES-098/2007 (DNIT, 2007) sets criteria, based on CBR values, for using soils in granular base layers according to the traffic (number of ESALs) the pavement must withstand during its service life. For a road with low traffic volume, corresponding to ESALs < 10^6, DNIT allows using a base layer with a minimum CBR of 40%. For 10^6 < ESALS < 5×10^6, a CBR equal to or greater than 60% is required. Above 5×10^6, a minimum CBR value of 80% is necessary. These criteria provide practical guidance for pavement design and construction, based on the strength and stability of the soil.

While the CBR test may not fully represent the dynamic nature of the loads on pavements, it offers significant advantages. Its simplicity, lack of need for complex calculations, and global recognition make it a valuable tool in the technical field. The CBR test provides results that are recognized worldwide and offer insights into the material type, particularly for low and medium-traffic roads (Barros, 2003; Narzary and Ahamad, 2018; Attah, Okafor and Ugwu, 2020; Guilherme, 2023), providing a sense of reassurance about its validity.

Therefore, the addition of the polymer association significantly increased the CBR values. Soil 3, with a 10.7% polymer addition, is suitable for heavy traffic base requests (N > $5\text{x}10^6$). Similarly, Soils 1 and 2, both with a 10.7% polymer composition, and Soil 3 with a 6.4% composition, are suitable for light traffic pavement bases. This information, derived from the CBR test, provides confidence in the selection of soils for different traffic volumes.

DNIT ES-139/2010 (DNIT, 2010) establishes a 20% CBR value in the subbase. Thus, all soils studied with an addition of 6.4% and Soil 3 with 2.2% polymer association can be in the subbase.

3.3. Unconfined compressive strength test

The unconfined compression test, a widely used laboratory test, has practical applications in pavement and soil stabilization. The unconfined compression strength, often used as an index to quantify soil improvement due to treatment, is a valuable tool for engineers and researchers (Sariosseiri and Muhunthan, 2009). In this study, the samples were subjected to air-curing, which probably exceeded the stabilizing effect; the suction was partly responsible for the increased resistance. Table 5 shows the results obtained on the UCS test.

The results showed that UCS values increased with the polymer combination content, reaching values 658% higher for Soil 3 at 28 days of dry curing than pure soil. Data shows that UCS increases with varying curing times across all soil samples. The increase in UCS occurs because of the DirtGlue Industrial polymer acting on soil particles to adhere to and form a composite structure. A possible explanation for the increase of UCS with prolongation of cure time was the action of PolyCure, which aims to catalyze the action of DirtGlue Industrial polymer.

Sariosseiri and Muhunthan (2009) studied UCS tests on three soil types. They found that adding small percentages of cement improved the unconfined compressive strength of ML-CL soil. In contrast, they used higher percentages of cement to improve ML and SP-SM soils. Cement treatment significantly increased the unconfined compressive strength in all soils.

Table 5: Unconfined Compressive Strength for mixtures of soil additive.

	Unconfined Compressive Strength for mixtures of soil (MPa)											
	Soil 1				Soil 2				Soil 3			
	Air cure (days)											
Additive	7	σ	28	σ	7	σ	28	σ	7	σ	28	σ
Pure	0.21	0.01	-	-	0.37	0.06	-	-	0.36	0.01	-	-
2.2% Polymers	0.30	0.03	0.35	0.06	0.50	0.08	0.57	0.02	1.19	0.06	1.42	0.22
6.4% Polymers	0.37	0.07	0.46	0.07	0.74	0.08	0.96	0.04	1.89	0.05	1.94	0.25
10.7% Polymers	0.43	0.05	0.55	0.05	0.90	0.09	1.28	0.22	2.31	0.19	2.37	0.29
Reference Samples (Cement/lime)	0.39	0.06	-	-	0.64	0.03	-	-	1.51	0.31	-	-

σ: Standard deviation.

The samples stabilized with cement showed substantial gains in Unconfined Compressive Strength (UCS), with Soil 3 exhibiting a remarkable 408% increase upon the addition of 3% cement. This finding highlights the effectiveness of cement as a stabilizing agent, particularly in enhancing soil strength. According to Baghini et al. (2014), the UCS improvement associated with cement addition is attributed to the hydration process, wherein cement hydration products fill the soil's pore spaces. This pore-filling action enhances the structural stiffness by creating numerous rigid bonds within the soil aggregate matrix, effectively reducing porosity and increasing particle cohesion. This binding effect not only boosts the soil's load-bearing capacity but also improves its durability, making cement stabilization an effective method for achieving long-lasting soil strength in various geotechnical applications.

For the lime-stabilized soil samples, the maximum increase was 173% for Soil 2 with the addition of 3% lime, a lower value than the same soil with the addition of 6.4% and 10.7% for the polymers at 7 and 28 days of curing.

Kumar et al. (2022) observed an increase in the Unconfined Compressive Strength (UCS) following treatment with polymer emulsion (synthetic vinyl copolymers) across all curing periods. The UCS of the soil improved with both extended curing time and higher polymer emulsion dosages. This increase in strength was attributed to a combination of suction development, induced by moisture evaporation in the soil samples, and the particle bonding created by the polymer emulsion.

3.4. Resilient Modulus Test

This research used two classic mathematics models related to the Resilient Modulus: confining stress (σ_3) and deviation stress (σ_d), as described in Equations 1 and 2, respectively.

$$RM = k_1 \times \sigma_3^{k2} \tag{1}$$

$$RM = k_1 \times \sigma_d^{k2} \tag{2}$$

- *RM*: resilience modulus
- σ_d: deviation stress
- σ_3: confining stress;
- *k*: modeling parameters numerically define each model.

A third model that uses stress of confinement and deviation with *RM* represents the Compound Model. Equation 3 describes the compound model used in this study.

$$RM = k_1 \times \sigma_3^{k2} \times \sigma_d^{k3} \quad (3)$$

Table 6 includes the parameters modeling and determination coefficients obtained for the three models used in this research for Soil 1, 2 and 3, respectively, stabilized and without stabilizers.

Table 6: Determination coefficients obtained for Soil 1, 2 and 3.

	$RM = k_1 \times \sigma_3^{k2}$			$RM = k_1 \times \sigma_d^{k2}$			$RM = k_1 \times \sigma_3^{k2} \times \sigma_d^{k3}$			
Soil 1	k_1	k_2	R^2	k_1	k_2	R^2	k_1	k_2	k_3	R^2
Pure	385	0.11	0.54	313	0.05	0.14	414	0.19	-0.08	0.69
2.2%	374	-0.05	0.06	328	-0.13	0.47	426	0.21	-0.27	0.80
6.4%	544	0.03	0.01	417	-0.08	0.19	635	0.31	-0.29	0.88
10.7%	717	0.08	0.19	560	-0.01	0.01	810	0.27	-0.19	0.80
3% Cement	460	-0.02	0.01	378	-0.12	0.37	545	0.27	-0.30	0.86
	$RM = k_1 \times \sigma_3^{k2}$			$RM = k_1 \times \sigma_d^{k2}$			$RM = k_1 \times \sigma_3^{k2} \times \sigma_d^{k3}$			
Soil 2	k_1	k_2	R^2	k_1	k_2	R^2	k_1	k_2	k_3	R^2
Pure	136	-0.25	0.72	176	-0.20	0.71	144	-0.11	-0.15	0.84
2.2%	271	-0.10	0.18	250	-016	0.69	319	0.18	-0.28	0.89
6.4%	632	0.08	0.27	450	-0.00	0.00	709	0.27	-019	0.98
10.7%	593	0.04	0.03	438	-0.08	0.15	732	0.37	-0.33	0.85
3% Lime	462	-0.06	0.08	413	-0.12	0.56	545	0.19	-0.24	0.88
	$RM = k_1 \times \sigma_3^{k2}$			$RM = k_1 \times \sigma_d^{k2}$			$RM = k_1 \times \sigma_3^{k2} \times \sigma_d^{k3}$			
Soil 3	k_1	k_2	R^2	k_1	k_2	R^2	k_1	k_2	k_3	R^2
Pure	673	0.13	0.47	526	0.06	0.14	707	0.20	-0.07	0.54
2.2%	1987	0.45	0.88	1048	0.29	0.54	2306	0.51	-0.01	0.92
6.4%	1114	0.21	0.68	955	0.19	0.90	1030	0.03	0.19	0.91
10.7%	1852	0.36	0.78	1321	0.31	0.85	1909	0.20	0.22	0.92
3% Cement	2670	0.32	0.95	1644	0.18	0.50	2919	0.40	-0.07	0.98

The experimental data show significant dispersion related to each stress variable, indicating that none of these variables can fully describe the behavior. The compound model (Equation 3) demonstrated superior fits, with coefficients of determination (R^2) equalling or exceeding 0.80 in nearly all cases.

A compound model for samples stabilized by adding polymeric association better explained the relation between the stress of confinement, the stress of deviation, and *RM*. Farias (2023) and Farias, Araújo and Rodrigues (2023) obtained similar results when lateritic soils stabilized with hydraulic binders were analyzed.

In Brazil and worldwide, there is a recognized consensus on the importance of employing parameters associated with mechanistic-empirical methods to ensure the quality and durability of paving works. The robustness of this approach is supported by its widespread acceptance. Material suitability is evaluated by determining the resilient modulus of samples through repeated load triaxial tests, a method validated as effective in various studies (Guimarães, Motta and Castro, 2018; Alnedawi, Nepal and Al-Ameri, 2019).

Figure 2 shows the values of the average Resilient Modulus for the mixtures of soil-polymer - additives.

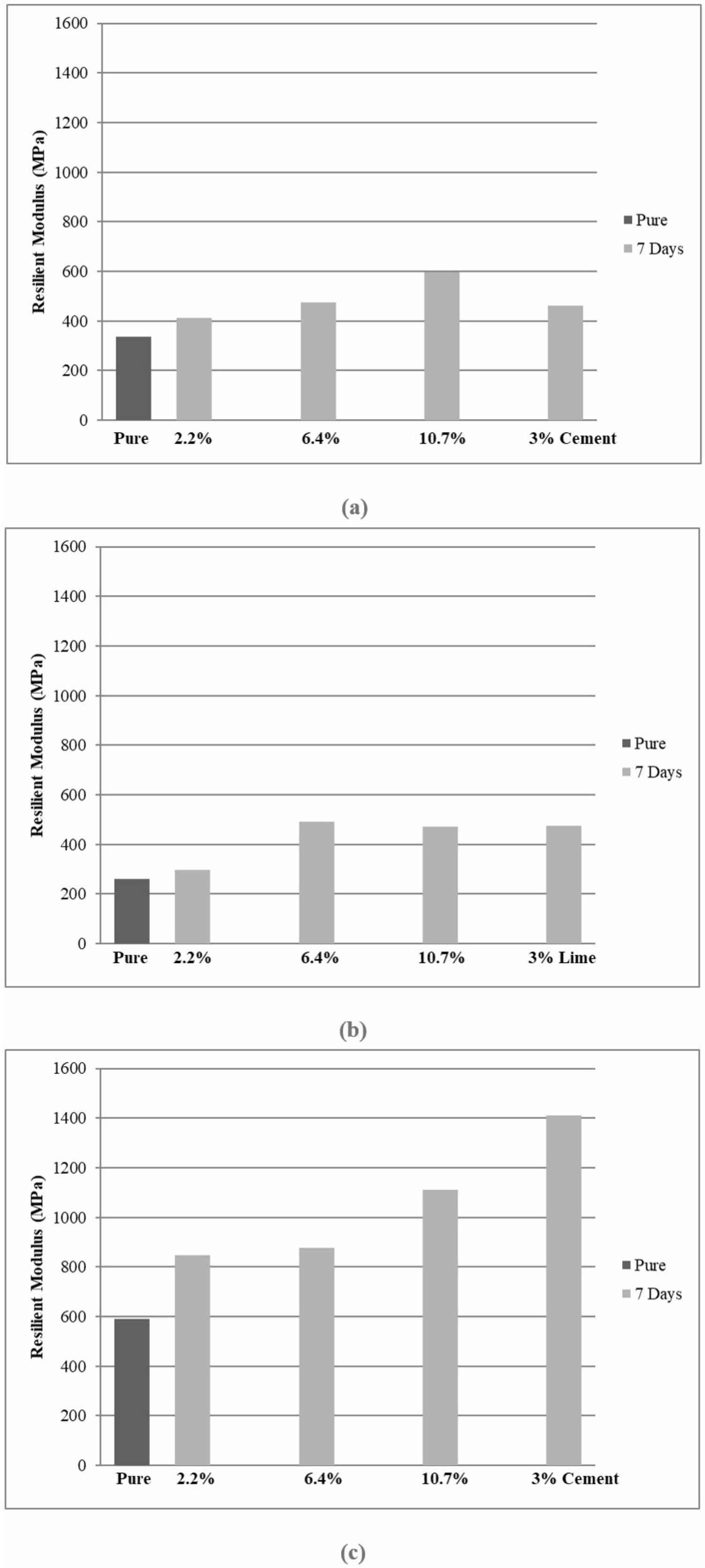

Figure 2. Resilient Modulus of soil additives for Soil 1 (a), Soil 2 (b) and Soil 3 (c).

The results indicate a consistent increase in the Resilient Modulus across all soils as the polymer content rises, demonstrating the effectiveness of the polymer association in enhancing soil performance. This improvement is primarily due to the action of the DirtGlue Industrial polymer, which acts as a powerful binding agent by creating chemical and physical bonds among soil particles that boost cohesion and reduce plastic deformation under repeated loading. By bonding particles together, DirtGlue Industrial polymer reinforces the soil matrix, increasing both stiffness and resistance to deformation, which is reflected in the higher Resilient Modulus and improved resistance to resilient deformation. This binding effect not only strengthens the soil structure but also promotes a more uniform stress distribution within the sample, which is essential for maintaining structural integrity under variable load conditions. Consequently, the polymer-modified soils exhibit enhanced resilience, making them well-suited for applications requiring long-term durability and stability under dynamic loads, such as in road pavements and other critical infrastructure projects.

The addition of 3% cement led to a substantial increase in the Resilient Modulus, surpassing the values achieved by adding the polymer association to Soil 3. The chemical reactions initiated by the cement in the soil, particularly through hydrated cement, result in the formation of strong chemical bonds between the surface of the hydrated cement grains and the soil.

Macedo (2004) found values of 2000 MPa at Resilient Modulus by adding 3% of cement at A-2-4 soil with seven days of cure. The values were five times superior to pure soil. Farias (2023) found that CPs with lateritic fine soil stabilized with lime indicated much higher average values (approximately 80%) than those molded with natural soil. These results corroborate Silva (2016), who found that for LG soil with lime, an MR value is 54% higher than the MR of the natural soil. For sandy soil, incorporating cement promoted a considerable increase in the resilient modulus values (an increase of almost 200%). Cement also increased MR for stony soil, although with a more discreet evolution (approximately 20%).

Kumar et al. (2022) investigated the effect of polymer emulsion treatment on the resilient properties of a sandy soil used in highway construction. The emulsion belongs to the family of synthetic vinyl copolymers. Results showed that the addition of polymer emulsion increased the resilient modulus of the soil in the early curing periods, specifically after 6 hours (0 days) and 3 days. However, after a 7-day curing period, the resilient modulus values of both untreated and polymer-emulsion-treated soil were nearly identical, suggesting that the polymer's effect may be more pronounced during short-term curing.

3.5. Deterioration test

Adding polymer to soils improves durability by making the soil resistant to the detrimental effects of water and increasing cohesion. Deterioration tests try to simulate the action of traffic coatings on non-pavement bases. LWT is conducted to evaluate permanent deformation (or "sinking") in wheel tracks. It is essential to determine the resistance of the soil to continuous and heavy traffic, simulating real-world conditions. WTAT evaluates the amount of particulate matter that is released from the soil surface under simulated traffic conditions. This test is important to understand how the addition of polymers helps to reduce dust emissions by keeping the surface stable and coherent.

Figure 3 presents the LWT test results for the soil and mixtures. Throughout the test, the soil condition was visually monitored. In certain instances, indicators of failure, such as cracks, significant corrugations, excessive soil displacement, and pronounced deformations, were observed, prompting an immediate cessation of the test.

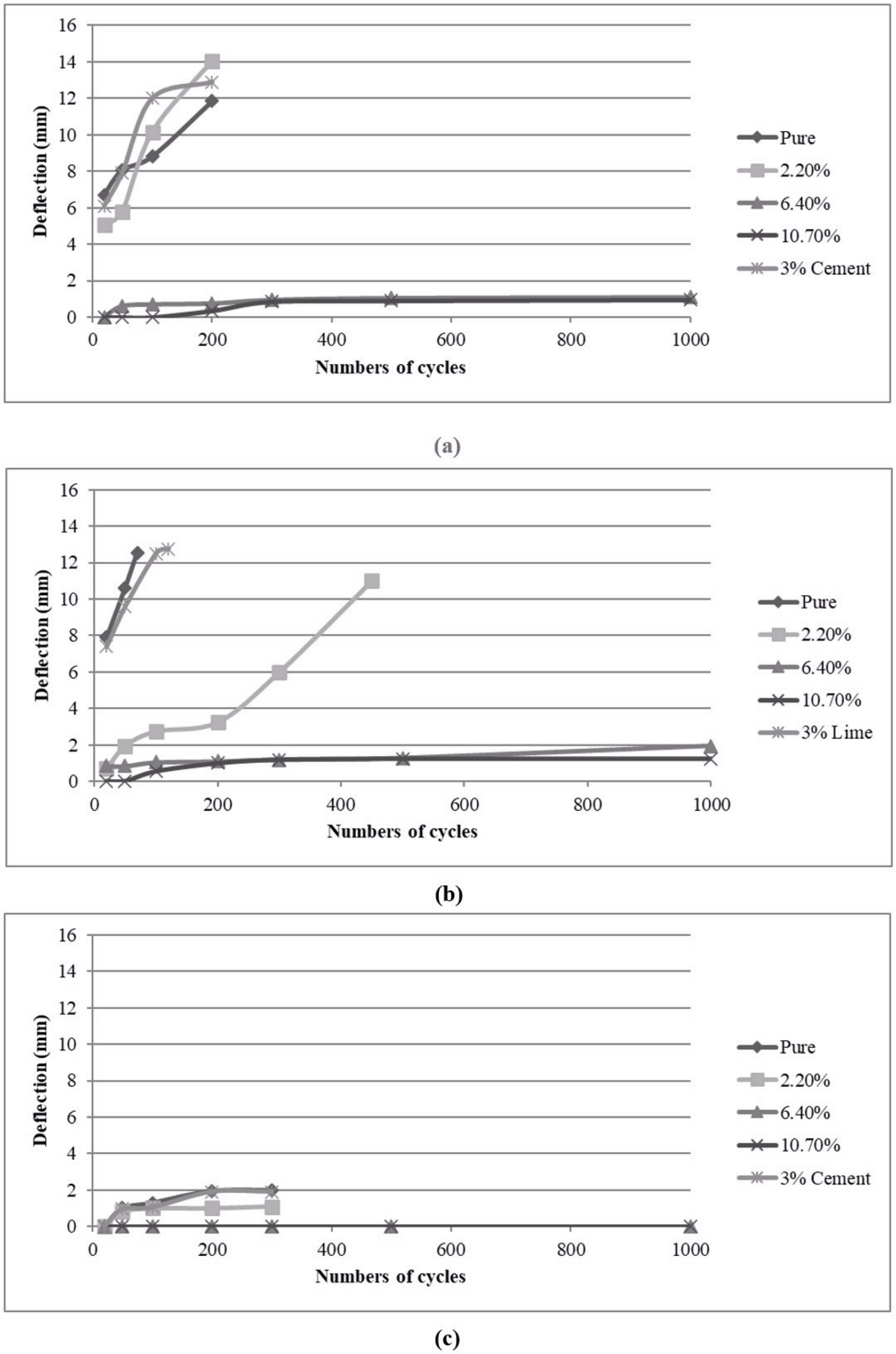

Figure 3. The LWT test results with pure soil vs mixture of soil with additives: Soil 1 (a), Soil 2 (b) and Soil 3 (c).

Miceli Jr. (2006) studied the addition of asphalt emulsion to an LWT test. Results showed that the addition decreased the deterioration of the soil studied. Lucena (2012) studied wastewater sludge as a stabilizer. Samples with the addition supported 800 cycles and reduced the maximum deformation by 33%.

The addition of the polymer combination proved efficient in deterioration analysis using the LWT test. For all soils, adding 6,4% and 10,7% of polymeric association reduced the wheel track deterioration, so samples supported the action of the maximum recommended cycle for this test. Reference samples showed lower deterioration than the pure soil but, could not support the wear of all cycles.

The permanent deformation test should be correlated with triaxial equipment to ensure a more accurate assessment of the soil's mechanical properties and behavior under various loading conditions. Additionally, as described by Miceli Jr. (2006), it is essential to consider the application of laboratory-to-field correlation factors, which help bridge the gap between controlled laboratory conditions and actual field performance. These factors are crucial for adjusting laboratory results to better reflect in situ conditions, ensuring that permanent deformation specifications are more reliable for practical applications in pavement design and analysis.

Figure 4 illustrates the results obtained from the WTAT test.

Miceli's Jr. (2006) findings, which revealed that emulsion did not enhance resistance to abrasion by the WTAT test, and Lucena (2012) discovery of a 70% reduction in mass loss with the addition of sludge, are significant contributions to our understanding of soil treatments.

The results obtained in the test WTAT showed that polymer addition reduced degradation for all soils. Soil 1 gradually decreased according to the increase in polymer association content. This reduction was also observed for the addition of cement. However, that reduction was less than found with the addition of 10.7% polymer association.

For Soil 2, continuous wear reduction was observed, attributed to the clay soil's low-wear surface.

Soil 3 gradually decreased as the polymer content increased, reaching a reduction of 1450% for adding 10.7% of the polymer combination compared to pure soil.

The reference sample obtained reduced degradation but not more than the addition of 2.2% polymer association for Soil 3.

3.6. Challenges in the use of polymers

Patented liquid chemical products, diluted and applied on-site, stabilize soil in highway projects. Although they are an attractive alternative for treating soils with high sulfate content and reducing transportation costs, the effectiveness of these products is only sometimes validated by independent field or laboratory evaluations (Rauch et al., 2002).

One obstacle to using polymers is determining the application rates for different soil types, as the rates recommended by manufacturers often need to be more effective. Specific tests are necessary to identify appropriate application rates (Onyejekwe and Ghataora, 2014).

The cost of polymer stabilization is another significant factor limiting its widespread application. Currently, the market prices for major polymers are significantly higher than traditional stabilizers like cement and lime. According to Chang, Im and Cho (2016), for an equal unit (1 ton) of soil treatment, the cost of materials at current prices for the use of xanthan gum becomes uneconomical compared to conventional cement mixing, being 37% more expensive (xanthan gum treatment: USD 13.5/ton of soil; cement: USD 9.85/ton of soil).

Cheng (2022) notes that, considering 2022 market values, the material cost for one unit of soil treatment (1ton) with biopolymer is 140% higher than conventional cement mixing, with biopolymer treatment priced at 30 USD/ton of soil and cement at 12.5 USD/ton of soil. However, biopolymer-treated soil becomes significantly more competitive when CO_2 emission trade-offs are taken into account.

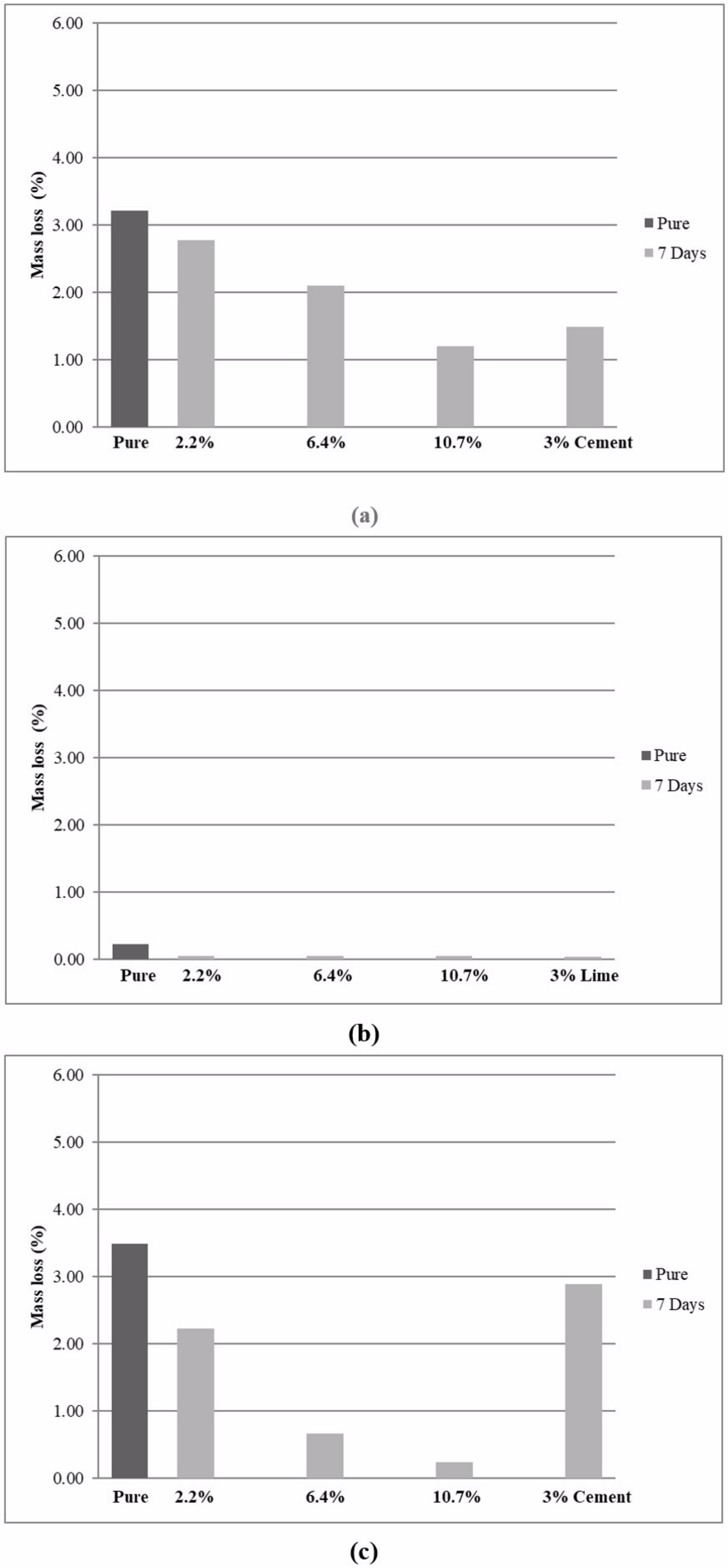

Figure 4. The WTAT test results with pure soil x mixture of soil with additives:
Soil 1 (a), Soil 2 (b) and Soil 3 (c).

Therefore, the application of polymers in soil stabilization faces several challenges. It is crucial that future research is undertaken to promote the widespread use of polymers in soil stabilization. This includes the establishment of standard testing protocols, evaluation of the in-situ properties of polymer-stabilized soils, addressing durability issues, and a more in-depth examination of the stabilization mechanisms (Huang et al., 2021).

4. CONCLUSIONS

This study highlights the substantial potential of polymer association for soil stabilization in road pavements, offering a groundbreaking approach to road engineering.

The action of DirtGlue Industrial polymer, employed to adhere soil particles, and TerraDry, used to reduce the water sensitivity of the polymer association, raised the mechanical strength in terms of CBR, UCS, and *RM* and decreased degradation results at WTAT and LWT.

The analysis of the mechanical performance and wear resistance results suggest that adding the polymer combination can effectively stabilize soils.

Those results indicate that the polymeric association, with 6,4% and 10,7%, changed geotechnical properties and could be used for road construction with light to heavy traffic.

However, it is crucial to highlight that the lack of systematically and independently published research, inconsistent labeling of polymers in the market, the absence of appropriate performance evaluation standards, and the variation in application rates recommended by suppliers are significant obstacles that urgently need to be addressed for the widespread and reliable adoption of these materials. Additionally, the high cost of polymers, their biodegradability, and the moisture sensitivity of polymer-stabilized soils are critical factors that may restrict their use if not adequately addressed.

AUTHORS' CONTRIBUTIONS

Jonny Dantas Patricio: Project administration, Formal analysis, Funding acquisition, Conceptualization, Data curation, Writing – original draft, Investigation, Methodology, Software, Resources, Supervision, Validation, Visualization; John Kennedy Guedes Rodrigues: Project administration, Formal analysis, Funding acquisition, Conceptualization, Data curation, Writing – original draft, Investigation, Methodology, Software, Resources, Supervision, Validation, Visualization; Lêda Christiane de Figueiredo Lopes Lucena: Project administration, Formal analysis, Funding acquisition, Conceptualization, Data curation, Writing – original draft, Investigation, Methodology, Software, Resources, Supervision, Validation, Visualization; Manoel Leandro Araújo e Farias: Project administration, Formal analysis, Funding acquisition, Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Investigation, Methodology, Software, Resources, Supervision, Validation, Visualization; Ana Maria Gonçalves Duarte Mendonça: Project administration, Formal analysis, Resources, Visualization; Leonardo Rodrigues Guedes: Formal analysis, Funding acquisition, Investigation, Software, Resources, Visualization; Hillary de Oliveira Marinho: Funding acquisition, Investigation, Visualization; Paulo Germano Tavares Marinho Filho: Project administration, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Resources, Visualization; Ana Letícia Feitosa de Macêdo: Project administration, Formal analysis, Funding acquisition, Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Investigation, Methodology, Software, Resources, Supervision, Validation, Visualization.

CONFLICTS OF INTEREST STATEMENT

Nothing to declare.

USE OF ARTIFICIAL INTELLIGENCE-ASSISTED TECHNOLOGY

This work was prepared with the assistance of Generative Artificial Intelligence (GenAI) ChatGPT with the aim of to assist in translation and improve the quality of the text. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

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