Available online at www.CivileJournal.org

Civil Engineering Journal

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

Vol. 9, No. 09, September, 2023

Sustainable Use of Recycled Asphalt Pavement in Soil Stabilization

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Received 29 June 2023; Revised 09 August 2023; Accepted 22 August 2023; Published 01 September 2023

Abstract

This study addresses unused recycled asphalt pavement (RAP) incorporated into sedimentary soil from the Guabirotuba Formation in Curitiba, Southern Brazil. Different percentages of RAP, ranging from 0% to 80% by weight, were mixed with the pure soil, with and without the addition of pozzolanic Portland cement. Tests were conducted to evaluate the mixtures' compaction properties, mechanical strength, and expansion after curing for up to 28 days. The results showed that adding RAP improved the mixtures' unconfined compressive strength (qu) and splitting tensile strength (qt). Up to 60% RAP, the qu increased by 260 kPa, and the qt increased by 340 kPa compared to the pure soil. The California Bearing Ratio (CBR) tests demonstrated an 18.62% improvement when 80% RAP was added to the untreated soil. In addition, the RAP also reduced the expansion of the compacted blends, with values decreasing from 1.19% to 0.88% with 80% RAP replacement. The expansion value was further reduced to 0.86% when the cement was added. The cement-soil-RAP compacted blends showed suitability for subgrade reinforcement, meeting the criteria of expansion <1% and CBR> 2%. Additionally, 3% cement and 40% RAP mixtures were suitable as a sub-base layer, with expansion <1% and CBR > 20%. The results provide valuable insights into utilizing RAP as an alternative material in soil improvement techniques employing the novelty porosity-to-cement index.

Keywords: Recycled Asphalt Pavement; Soil Improvement; Strength; Porosity-Cement.

1. Introduction

The Guabirotuba Formation (GF), located in Curitiba, Paraná (Southern Brazil), covers an area of approximately 3000 km². It comprises loosely consolidated banks of clays, fine carbonate, arcosian sands, and gravel deposits. The clayey and silty layers are generally massive, ranging from gray to greenish-gray colors, with an average thickness of around 40 m. When excavated, the soil belonging to the GF can become potentially unstable, leading to accidents during excavations. Clayey soils are characterized by high consistency (stiff to hard), high expansion, and low bearing capacity [1]. Therefore, stabilizing GF soils has been the subject of several studies (e.g., [2–4]) by adding stabilizers such as lime and cement, construction waste, and crushed glass. Although research has shown improvement in GF soils through these studies, incorporating recycled asphalt pavement (RAP) residues has not yet been investigated.

Traditional pavement restoration methods in Brazil often fail to meet expected performance standards, are costly, and cause environmental liabilities [5]. A similar situation arises for new structures, where pavement design frequently leads to high thicknesses of asphalt layers, increasing the risk of permanent deformations (wheel path rutting, plastic deformations, corrugation, and slippage) or shear failures (especially surface-initiated cracks, known as "top-down

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http://dx.doi.org/10.28991/CEJ-2023-09-09-016

cracking"). Consequently, the trend in countries with advanced pavement technology is the incorporation of artificially cemented layers in conjunction with flexible overlays, creating semi-rigid pavements [6]. Indeed, deep pavement recycling with the addition of Portland cement becomes an attractive alternative for structurally restoring highways in Brazil. This technique creates a rigid base layer and aims at material reuse, thereby reducing costs and environmental liabilities [7, 8]. Given the considerable volume of milled asphalt waste generated, this approach provides a sustainable solution, promoting the reuse of materials and minimizing environmental impact. Recent studies have included, in addition to cement, other sustainable materials. For example, Nhieu et al. [9] replaced cement with natural rubber latex for stabilizing recycled concrete aggregate as a pavement base material. The authors concluded that natural rubber latex can be used for ground improvement based on resilient and unconfined compressive tests. In another study conducted by Maghool et al. [10], incorporating natural rubber latex into pavement material against drying and wetting cycles, the mixes replacement cement by latex proved satisfactory for use in paving. Recently, studies included waste, glass, and plastics in RAP stabilization soil [10] and polymers [11].

The RAP material combines old petroleum asphalt cement (named "CAP" in Brazil) and aggregate obtained through pavement milling. The properties of milled material depend on the road type, the aggregate used in the mixture, the type of milling machine employed, the exposure time of the pavement to weather conditions, and the CAP content [2]. The cold in-place recycling of pavements is an in-situ technique for the structural and functional rehabilitation of pavements that allows the reuse of the existing pavement structure by adding a stabilizing agent. Unlike hot in-place recycling, which is limited to asphalt material, cold in-place recycling enables the reuse of both asphalt layers and base or even sub-base layers. Pires et al. [3] analyzed the viability of using pure and stabilized (mechanically, granulometrically, and chemically) milled material in flexible pavement layers. It has been determined through laboratory tests that a composition of 70% milled material and 30% natural aggregate yields satisfactory results. The milled material was sourced from two different highways, and in both cases, the 70/30 composition improved the California Bearing Ratio (CBR) values. The CBR value of the milled material from the first highway was 56%, with the addition of 30% aggregate. Similarly, a CBR value of 68% was achieved using the milled material from the second highway with the same 30% aggregate addition.

Several studies have demonstrated the effectiveness of incorporating RAP to improve the strength and performance of problematic soils. Suddeepong et al. [4] researched the use of cement and RAP in stabilizing crushed stones. The study found that the California Bearing Ratio (CBR) values using only crushed stone were higher than those using RAP, with values of 90.40% versus 56.40%. Adding RAP to crushed stone reduced the CBR values, and the highest CBR value (85.10%) was achieved with a composition of 80% crushed stone and 20% RAP. In another study, Miao et al. [12] investigated mixtures with and without milled material at different temperatures (40°C, 22°C, and 5°C). Their findings revealed that the use of finely graded milled material reduced the potential for pavement rutting, and this was attributed to the presence of asphalt in the fine particles, which boosted the mixture's cohesion.

The study by Adhikari et al. [13] focused on analyzing the pavement's base and sub-base layers using RAP, geopolymer, and soil. Two types of soils were studied and classified as A-7-5 and A-7-6 by the TRB methodology. For soil A-7-5, the tests showed an unconfined compressive strength value of 2.57 MPa without adding RAP. However, when 15% RAP was added, the value increased to 4.68 MPa. The same behavior was observed in soil A-7-6, with values of 0.68 MPa without RAP and 1.62 MPa with the addition of 15% RAP. Hasan et al. [14] analyzed different amounts of milled material mixed with fine soil collected from a highway subbase. It was observed that the resilient modulus increased with the addition of milled material. For the pure soil, the resilient modulus was 180 MPa, and there was an increase in modulus with all RAP additions. A resilient modulus of 300 MPa was achieved by adding 75% milled material. Suebsuk et al. [15] studied the addition of RAP and cement to a lateritic soil composition consisting of 53% sand, 25% silt, 20% clay, and 2% gravel. When assessing the compaction of the soil+RAP mixtures, the mixture with 50% RAP addition achieved the highest dry density, with a value of 21.90 kN/m^3, and the lowest optimum moisture content, with a value of 6.40%. Finally, Hasan et al. [14] studied milled material in hot asphalt mixtures. The tests showed that the samples containing milled material experienced 15% less permanent deformation and were less susceptible to the formation of ruts in the pavement.

Hence, Curitiba, its metropolitan region, and the existing literature must have comprehensive studies focusing on soil improvement using various cementitious agents and recyclable materials like reclaimed asphalt pavement (RAP). Within this context, the primary objective of this study is to assess the mechanical behavior of sedimentary soil obtained from the Guabirotuba geological formation. The soil is stabilized and treated with small percentages of cement, with curing periods lasting up to 28 days. The study examines the influence of incorporating RAP and varying soil/RAP ratios on several fundamental properties, including unconfined compressive strength, tensile strength via diametral compression, California Bearing Ratio (CBR), and expansion. The research involved conducting laboratory tests. The outcomes of this research will provide valuable insights into determining the optimal cement/RAP dosage for future engineering projects with similar soil types. These findings will enhance the understanding of soil improvement techniques and facilitate the implementation of sustainable practices in construction and infrastructure development.

2. Experimental Program

The experimental program was divided into three stages, each serving a specific purpose in the study:

First, the characterization of soil, RAP, and Portland cement: In the first stage, various tests were performed to characterize the soil, recycled asphalt pavement (RAP), and Portland cement. These tests included analyzing the particle size distribution of the soil and RAP, following the Brazilian standard NBR 7181 [16]. Determining the Atterberg soil limits according to Brazilian standards NBR 7180 [17] and NBR 6459 [18] provides essential information about the soil's plasticity and moisture content. Measuring the specific gravity of soil and RAP particles using ASTM D854 [19] helps assess their density. Estimating the cement particles' specific gravity per the Brazilian standard NBR 16605 [20] also provides insight into their density. The bitumen content in RAP is evaluated based on the DNER/ME 53 [21] method, as bitumen is a crucial component in asphalt. Assessing the compaction properties of the soil and soil-RAP-cement mixtures at an intermediate energy/effort, as defined by the Brazilian standard NBR 7182 [22]. Compaction tests aim to calculate the curves and determine the maximum dry unit weight and the optimum water content of the soil and compacted blends.

The second stage comprises the soil-RAP specimen molding, curing, and testing. In the second stage, the focus was on preparing and examining specimens composed of soil and RAP mixtures. The following tests were conducted: Molding the specimens and subjecting them to compression tests to measure their simple compression strength. Diametral compression tests were performed to determine the specimens' tensile strength.

Finally, California Bearing Ratio (CBR) and Expansion Tests. The third stage involved conducting California Bearing Ratio (CBR) and expansion tests on the soil and soil-RAP mixtures. These tests are essential for evaluating the materials' load-bearing capacity and potential for expansion under specific conditions.

The experimental program flowchart is shown in Figure 1. In addition, the materials and methodology used are described as follows:

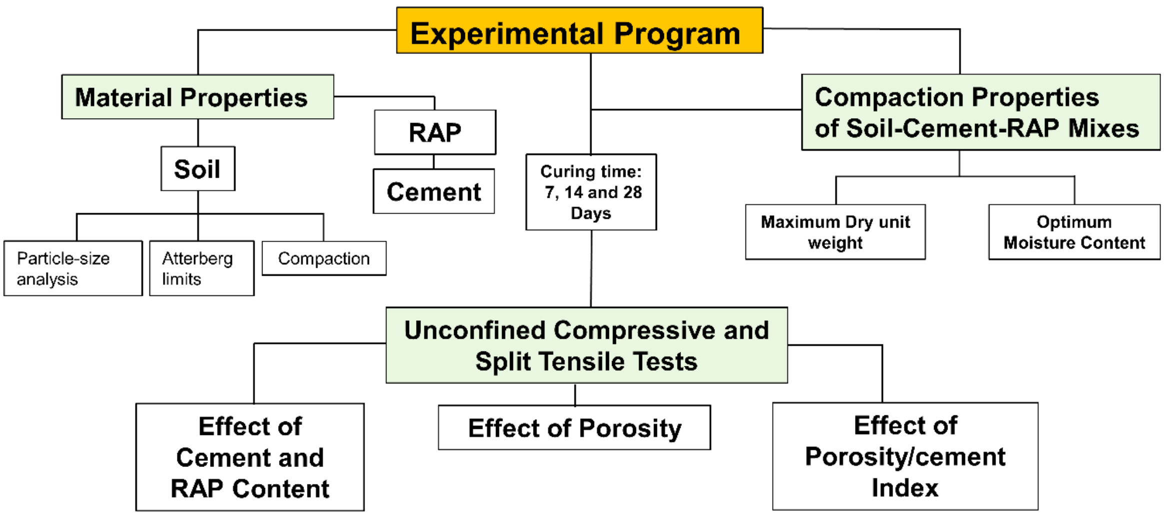

Figure 1. Experimental Program of Flowchart

2.1. Materials

The soil used in this research was obtained from the first layer of the Guabirotuba Formation. The sample was collected near the UTFPR Campus in Curitiba, Paraná, with geographic coordinates of 25°26'42.10" S and 49°21'17.26" W. At the time of collection, the soil had a hygroscopic moisture content of 40%. The study used milled material sourced from the BR-277/PR highway, specifically the section between São José dos Pinhais and Paranaguá in Paraná. The material was generated due to the cold milling process, which involved removing the pavement's surface layer for replacement. This routine maintenance practice was conducted on the road, and the milled material was transported and stored in metal drums. The RAP material was initially loosened using a rotating drum. Figure 2-a shows a photo of the RAP collection site, and Figure 2-b shows the soil collection site. In addition, Figure 3 presents a map of the location of soil and RAP sample collection in Southern Brazil.

(a) (b)

Figure 2. Photos of the raw materials collection sites (a) Photo of the RAP collection site. (b) Photo of the soil collection site

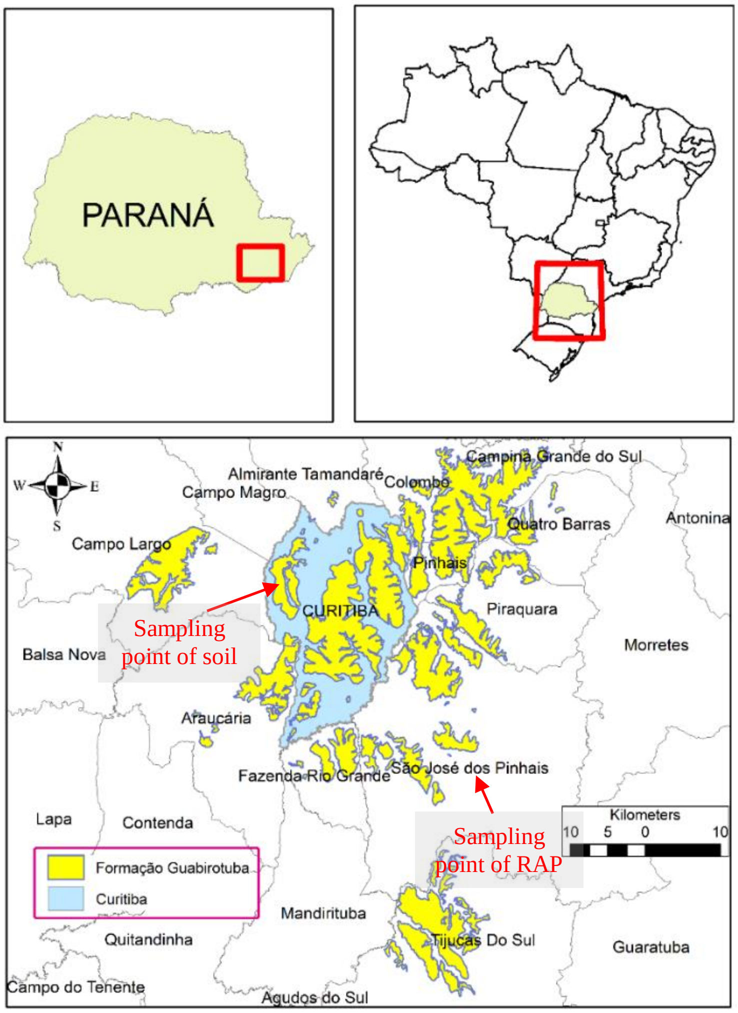

Figure 3. Location of soil and RAP samples collection in Southern Brazil

The soil and RAP physical characterization test results are presented in Table 1 and Figure 4. The grain size distribution curves of the soil and RAP are shown in Figure 4. The soil consists of 7.5% coarse sand, 8.5% medium sand, 11% fine sand, 34% silt, and 39% clay. The clay component (particle diameter < 0.002 mm) is the most significant constituent of the soil (see Table 1). The RAP is composed of 57.5% gravel particles and 42.5% sand. The soil chemical composition was measured using X-ray Fluorescence (XRF). The soil primarily comprises a weight of 48.5% silicon dioxide, 42.2% aluminum oxide, 5% sulfur oxide, 1.8% potassium oxide, 1.3% iron oxide, and less than 1% titanium oxide. In the test regarding the bitumen content in the RAP, a content of 4.64% of Asphalt Cement (petroleum asphalt) was found in the material. Additionally, the density of the RAP was calculated as 2.51.

Table 1. Physical properties of soil and RAP (Recycled Asphalt Pavement)

Property	Value	
	Soil	*RAP*
Liquid Limit (*LL*), %	47.8	-
Grain Specific Gravity (Gs)	2.69	2.51
Plasticity Index (*IP*), %	5.8	Non-plastic
Plastic Limit (*LP*), %	42	-
Clay (0.002 mm)	39	-
Silt (0.002 mm-0.06 mm), %	34	-
Fine Sand (0.06 mm-0.2 mm), %	11	4
Medium Sand (0.2 mm-0.6 mm), %	8.5	12
Coarse Sand (0.6 mm-2 mm), %	7.5	26.5
Fine Gravel (2 m-6 mm), %	-	37.5
Coarse Gravel (6 mm-20 mm), %	-	20
Effective Diameter (D_{50}), mm	0.006	2.6
Coefficient of Uniformity Cu	42.9	8.75
Coefficient of Curvature Cc	0.21	1.21
SUCS Classification	ML (silty clay)	SW (clean sand)
Activity, A [A=IP/(%< 0.002 mm)]	0.15	-
Color	Red	Black

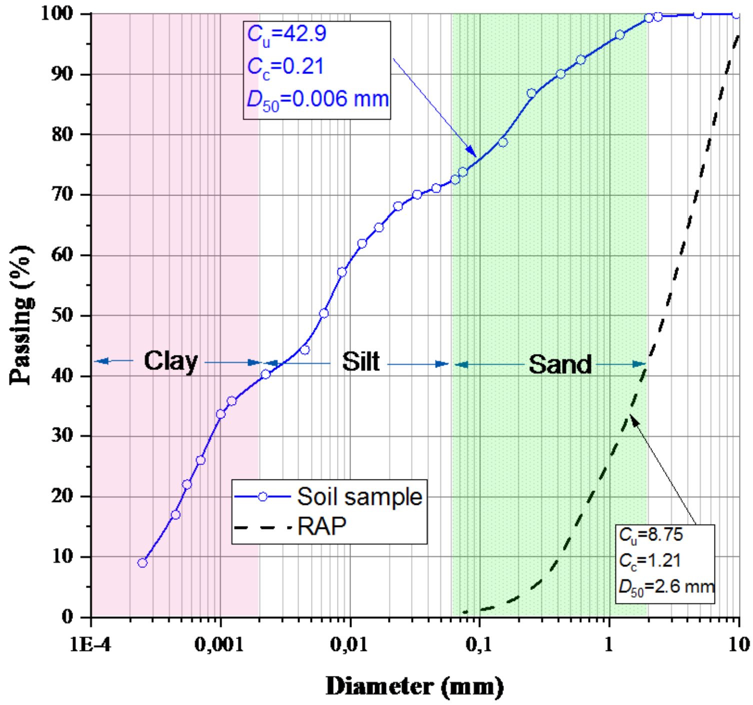

Figure 4. Soil's and RAP's grain size distribution curves

Portland cement CP II-F32 was used as a stabilizing agent. The cement was chosen due to its easy availability in the local market, and it was purchased in 20 kg bags. The density of the cement was calculated to be 3.03 g/cm³. The axial compressive strength at 7 and 28 days of curing was determined to be 30 MPa and 35 MPa, respectively. Distilled water was used for the specimen molding and soil characterization tests, following the specifications outlined in the standards. Distilled water is free from impurities and helps to prevent undesired reactions [23].

2.2. Definition of Mixtures, Compaction Tests, and Curing Times

RAP contents of 20%, 40%, 50%, 60%, and 80% were used relative to the soil dry mass. Furthermore, 3% of cement was added as a stabilizer. To study the cement addition effects on the mechanical strength of RAP-cement mixtures, curing times of 7, 14, and 28 days were investigated.

After establishing RAP's and cement's contents as well as curing times, compaction tests were conducted on each mixture to determine the compaction points (i.e., maximum dry unit weight - γd-max and optimum moisture content-ωo) at an intermediate Proctor energy level according to NBR 7182 [22]. Due to the material retained on sieves (2 inches) in the RAP, a more extensive mold with dimensions of 15.20×17.77 cm was necessary. The intermediate compaction energy level was used for the Proctor test, pursuant to the guidelines established by DNIT [24], which dictate that sub-base layers must be compacted with at least an intermediate energy level.

2.3. Test Specimens Molding and Mechanical Strength Tests

Specimens measuring 100 mm in height and 50 mm in diameter for the unconfined compression and splitting tensile tests were molded. The soil was oven-dried at 100±5°C, and portions were mixed with lime. Dry RAP and Portland cement (if applicable) were incorporated based on the soil dry weight, as indicated in Table 2. The aim was to achieve a homogeneous mixture of soil, RAP, and cement. The optimum moisture content, determined from compaction tests, guided the addition of water. The mixing procedure used distilled water and was completed in less than 10 minutes to minimize a premature cement-water reaction. Specimens were statically compacted in three layers using a stainless-steel mold under the compaction conditions outlined in Table 2. The necessary material weight for each sample was calculated to ensure the desired density. The process entailed manual molding, assisted by a hydraulic press.

Table 2. Compaction points' definition

Mixture	Without Cement		With 3% Cement	
	$\gamma_{d\text{-}max}$ (g/cm^3)	ω_o (%)	$\gamma_{d\text{-}max}$ (g/cm^3)	ω_o (%)
Soil (Control)	1.45	25.70	1.53	22.20
80%Soil+20%RAP	1.58	22.30	1.71	20.80
60%Soil+40%RAP	1.68	18.70	1.69	16.40
50%Soil+50%RAP	1.68	16.80	1.85	10.90
40%Soil+60%RAP	1.78	13.80	1.91	9.70
20%Soil+80%RAP	1.86	11.00	1.53	22.20

CBR (California Bearing Ratio) tests were conducted using samples with a diameter of 152 mm and a height of 114.3 mm. The compaction process followed the NBR 9895 [25] standard, employing a 63.5 mm spacer and the standard Proctor energy (5 layers with 12 blows in each layer). After compaction, a perforated plate with a plunger and an annular disc with a 5-pound overload were placed on top of the specimen. A dial gauge attached to an extensometer holder was positioned on the perforated plate's stem to measure readings before and after 96 hours, during which the specimen was immersed. Following the immersion period, the specimen was removed, and a penetration resistance test was performed using a standard piston. Three samples were compacted for each mixture, and the average of the results from both the swelling and penetration phases were recorded.

The procedures for the unconfined compression test and the split tensile test followed the NBR 5739 [26] and NBR 7222 [27], respectively. An automatic press with calibrated rings for axial load with 10 kN capacity was used for both tests. The tests were conducted using an automated system that measured the applied force with a resolution of 3.5 N and the deformation with a sensitivity of 0.01 mm. The testing speed was set to 1.30 mm/min.

3. Results and Discussions

3.1. Soil-RAP-cement Mixtures Compaction Tests

As shown in Figure 5, adding RAP to soil increased the dry unit weight of the soil-RAP mixture and decreased optimum moisture content. The higher the percentage of RAP, the higher the dry unit weight and the lower the optimum moisture content. The addition of reclaimed asphalt pavement (RAP) material leads to an increase in dry unit weight and a decrease in optimum moisture content due to a granulometric stabilization of the mixture, increasing its specific weight. Additionally, since the RAP material is covered with asphalt binder, it results in lower water absorption by the material. This phenomenon was repeated in the mixtures when 3% cement was used, as shown in Figure 6. It is observed that the inclusion of cement results in a minor reduction in the optimum moisture content, as shown in Figure 6. The composition containing 60% reclaimed asphalt pavement (RAP) material exhibits slightly decreased moisture content compared to the cement-free blend. The most substantial reduction in optimum moisture content was found in the 40/60 (soil/RAP material) mixture, which was 2.90%.

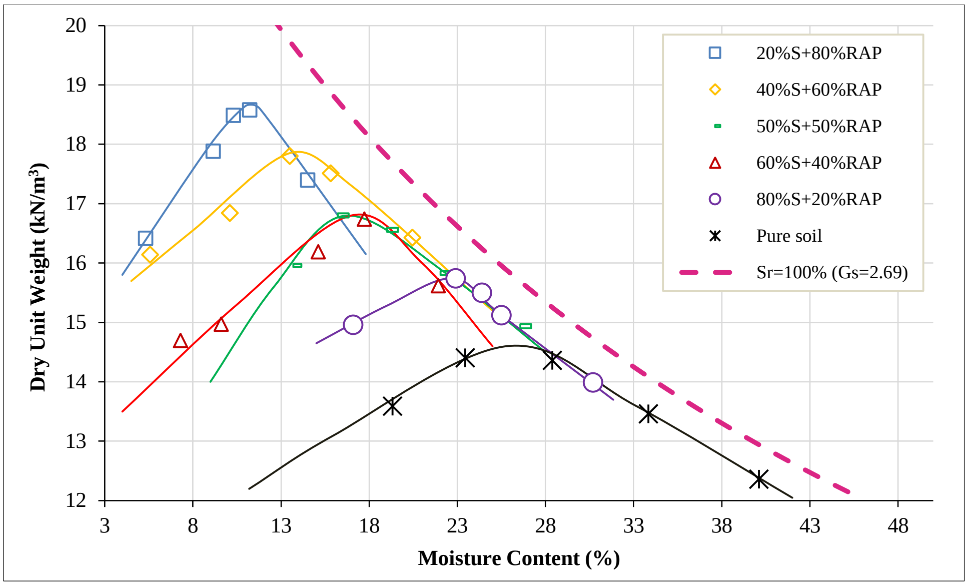

Figure 5. Compaction curves of soil and soil-RAP mixtures at an intermediate energy level

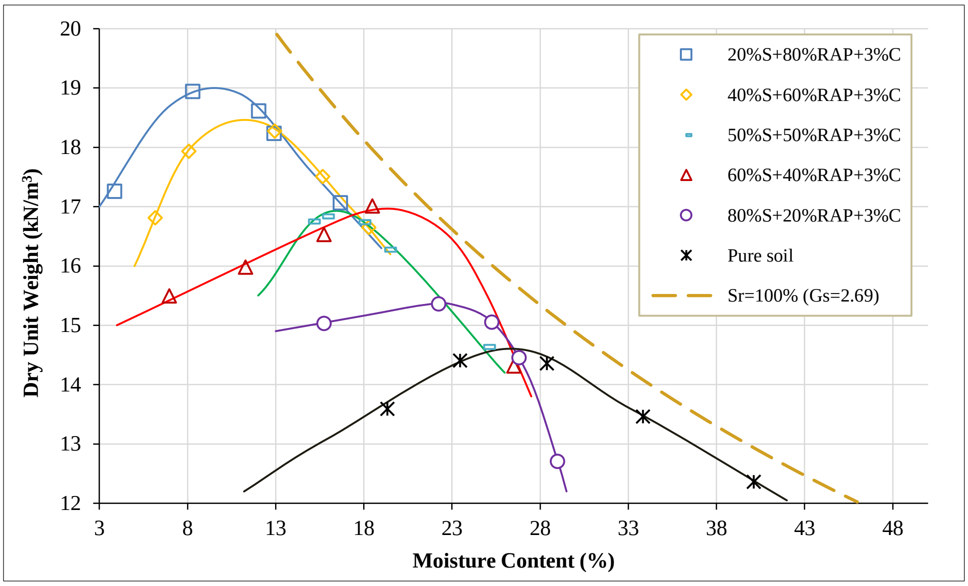

Figure 6. Compaction curves of soil and soil-RAP-3% cement mixtures at an intermediate energy level

3.2. Soil-RAP Mixtures' Unconfined Compressive Strength

Based on the data presented in Figure 7, including RAP in the mixture increases the compressive strength values up to a maximum of 60% RAP addition, where the values reached 371.82 kPa. However, there was a reduction in the strength values for higher increments beyond this threshold. The unconfined compressive strength of the pure soil was approximately 259 kPa lower than the value obtained with a 60% RAP addition to the mixture. The mixtures that used cement in their composition showed substantial gains with curing days, as shown in Figure 7.

Compared to pure soil, the unconfined compressive strength values increase by adding reclaimed asphalt pavement (RAP) material to the mixture. Incorporating 60% RAP material resulted in a maximum increase (about 259 kPa) in the unconfined compressive strength, reaching a value of 371.82 kPa against 112.57 kPa for the pure soil. However, adding 80% RAP material decreased strength, as evidenced by the unconfined compressive strength value of 194.44 kPa. In all compositions, there was an increase in unconfined compressive strength with the increase in curing days. The composition with 40% soil, 60% reclaimed asphalt pavement (RAP) material, and 3% cement achieved the highest unconfined compressive strength values at all curing times. It reached a value of 2,502.08 kPa at 28 curing days.

The results of the unconfined compressive strength tests were compared with the minimum values stipulated by the Texas Department of Transportation [28] for sub-base (0.35 MPa) and base (0.70 MPa) materials. The findings indicate that the mixtures without cement, specifically those comprising 40% soil and 60% reclaimed asphalt pavement (RAP) material composition that reached values of 0.37 MPa, would be suitable for a sub-base layer. Regarding the mixtures with cement, all the studied proportions could be used as a sub-base layer. From 60% RAP material addition, it could already be used as a base layer.

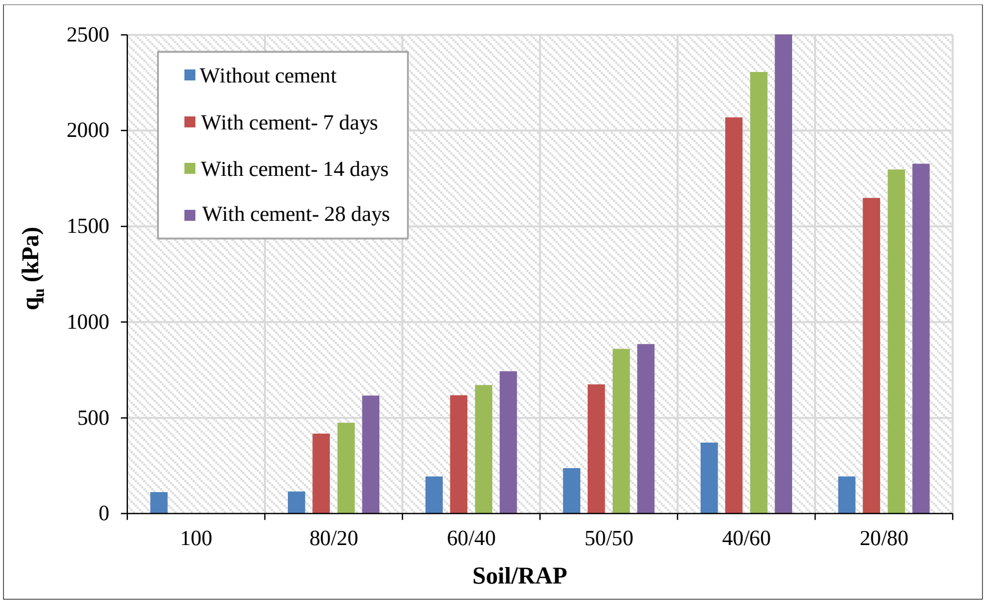

Figure 7. Influence of curing time and cement on the unconfined compressive strength of soil-RAP mixtures

According to DNIT 143 [24], which deals with soil-cement mixtures, the sample must exhibit a minimum strength of 2.1 MPa after seven curing days for its use as a base layer. Although none of the specimens met this requirement, the sample with 60% reclaimed asphalt pavement (RAP) material and 3% cement demonstrated the highest proximity to the minimum threshold, with 2.07 MPa. The samples with 60% and 80% RAP material additions and 3% cement meet the required specifications and can be used as base and sub-base layers.

3.3. Split Tensile Strength of Soil-RAP Mixtures

In Figure 8, the split tensile strength results show that the values increase as the percentage of reclaimed asphalt pavement (RAP) material in the mixture grows. The composition with 60% RAP material and 40% soil presented the highest value of 48.18 kPa. Increasing the RAP material to 80% decreased strength to 20.47 kPa, indicating that the ideal composition occurs with 60% RAP material. The split tensile strength (q_t) values increased with the addition of reclaimed asphalt pavement (RAP) material. The pure soil sample showed the lowest q_t value (10.23 kPa), while the maximum value of 48.18 kPa was obtained by adding 60% RAP material without cement. However, q_t values decreased when more RAP material was added, presenting values of 20.47 kPa with 80% RAP. A similar trend was observed in cement mixtures, with the highest strengths achieved by adding 60% RAP material, reaching values of 348.37 kPa after 28 curing days. However, q_t values decreased with a higher addition of RAP material, with values of 272.47 kPa at 28 curing days being obtained when 80% RAP was added.

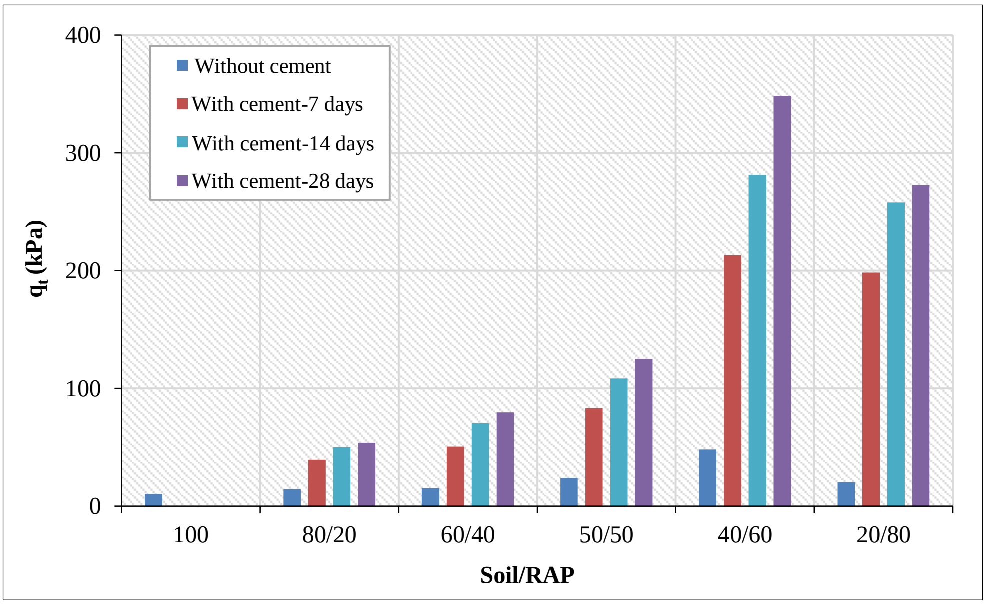

Figure 8. Influence of curing time and cement on the splitting tensile strength of soil-RAP mixtures

3.4. California Bearing Ratio (CBR) Index and Expansion of soil-RAP Mixtures

Figure 9 presents the California Bearing Ratio (CBR) index results for soil-RAP mixtures with and without the addition of cement. The data reveals that adding reclaimed asphalt pavement (RAP) material increased the CBR values. A more significant growth in CBR values was observed between 40% and 50% of RAP material, with a rise of approximately 5% in CBR values. The CBR value for the pure soil was 3.52%, and the maximum value of 18.62% was obtained by adding 80% RAP material.

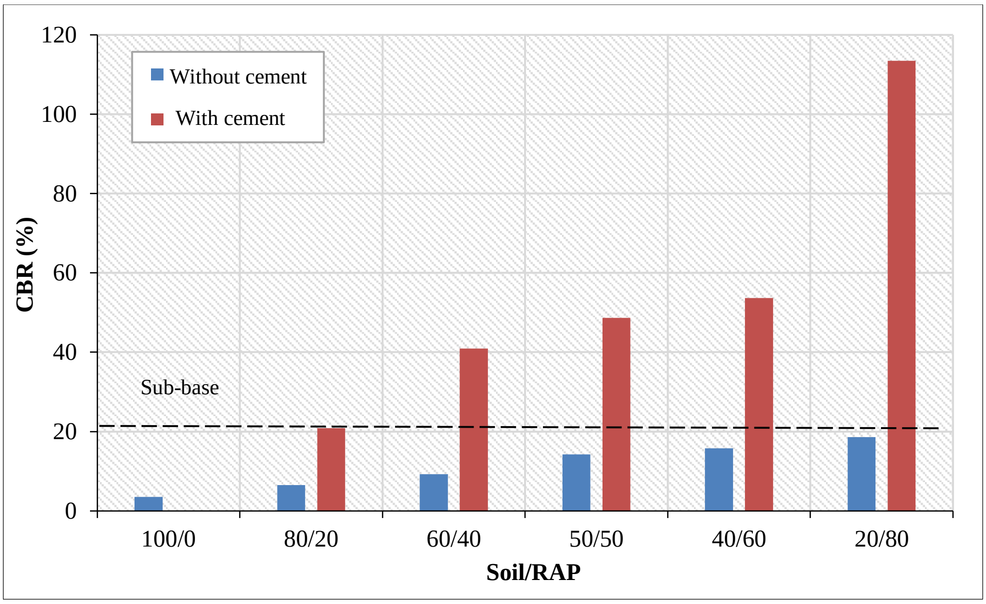

Figure 9. Influence of cement and RAP on the CBR of soil-RAP mixtures

The increase in CBR values co-occurred with increased reclaimed asphalt pavement (RAP) material. The lowest value was observed when adding 20% RAP material, with a CBR value of 20.85%. Conversely, the highest CBR value of 113.43% was achieved by adding 80% RAP material. However, in the case of the highest percentage of RAP material used in the mixtures, the increase in CBR values was disproportionate compared to the behavior observed in other combinations. This could be attributed to the increased stiffness achieved due to the use of cement and the higher proportion of RAP material, which was 80%.

The highest variation in CBR tests occurred in the composition with 20% soil and 80% addition of reclaimed asphalt pavement (RAP) material, representing the composition with the highest amount of RAP material. In this case, mixtures without cement had a CBR value of 18.62%. In comparison, mixtures with cement presented a CBR value of 113.43%, approximately six times higher than the values of the same composition without the use of cement. The other compositions showed more linear variations, with CBR values ranging from three to four times higher than the mixture without cement. This increase due to the use of cement was also observed by Edeh et al. [29].

The values of expansion for the mixtures are presented in Figure 10. Adding reclaimed asphalt pavement (RAP) material decreased the expansion values compared to the pure soil composition. When comparing the compositions with 100% soil and with the highest proportion of RAP material, which is 80%, there was a 26% decrease in the expansion of the mixture. The expansion value for the pure soil was 1.19%, while the composition with 80% RAP material had an expansion value of 0.88%.

The inclusion of 20% and 80% reclaimed asphalt pavement (RAP) material in mixtures resulted in the smallest expansion values of 0.89% and 0.86%, respectively, compared to cement-free mixes, which reduced approximately 26% in expansion values. When analyzing the reduction in expansion values between the compositions with the lowest and the highest proportion of RAP material, there was a reduction of around 3% in the values. These outcomes suggest that the addition of cement, in this case, has a more substantial influence on the expansion values of the mixtures, making them almost equal in terms of expansion.

An expansion limit of ≤ 1% is required to use the material for subgrade reinforcement. The soil in question does not meet these requirements initially. However, with the addition of 40% of reclaimed asphalt pavement (RAP) material, the expansion value reaches 0.92%, making it suitable for subgrade reinforcement, provided that its CBR is higher than the CBR of the existing subgrade layer. These results are consistent with the findings of Schlögel et al. [30] in their study. It is important to note that adding RAP material alone did not meet the minimum values for use in pavement sub-base layers.

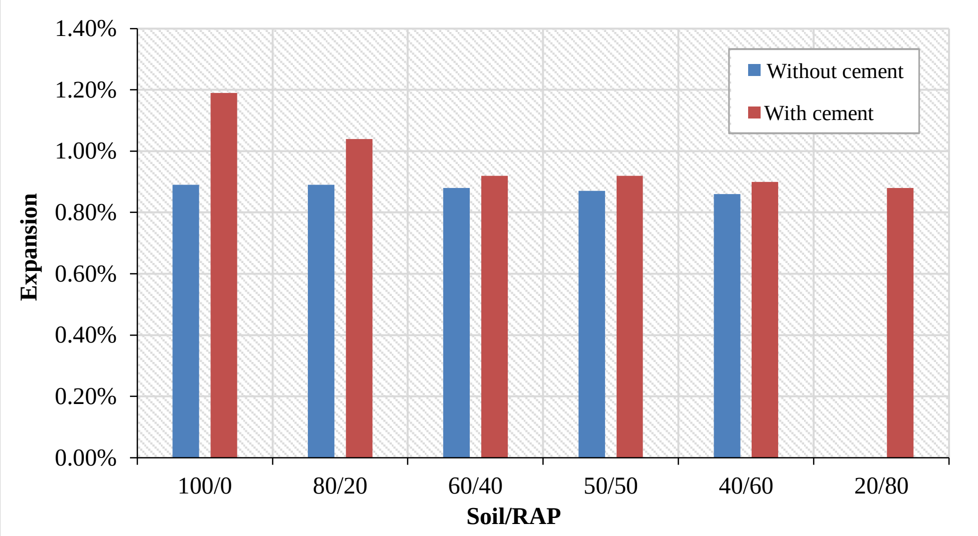

Figure 10. Influence of cement and RAP on the expansion of soil-RAP mixtures

For the mixtures with the addition of cement, it was possible to meet the requirements for CBR and expansion, starting by adding 40% of reclaimed asphalt pavement (RAP) material, making them suitable for use as a sub-base layer. Initially, considering only the CBR of the mixtures, all compositions without cement were suitable for subgrade use. When considering the mixtures with the addition of cement, they can serve as a sub-base layer. Upon evaluating the CBR, the 20/80 mix achieved a CBR of 113.43%, making it suitable for base material, provided it meets other established prerequisites.

According to DNIT-ES 139 [31], using mixtures as a sub-base layer requires the application of intermediate energy levels during testing for compaction. The conducted tests satisfied this requirement. On the other hand, the DNIT -ES 141 [32], which outlines specifications for the granularly stabilized base, stipulates the requirements for CBR depending on the calculated N-value for the section. If the N-value exceeds 5×10^6, a minimum CBR of 80% is required. If it is equal to or less than the mentioned N-value, the CBR must be equal to or greater than 60%. The expansion must not exceed 0.5% in either case.

3.5. Empirical Relationships between Unconfined Compressive Strength, Splitting Tensile Strength, and CBR

Figure 11 shows the empirical relationship between compression and tension. The splitting tensile values equate to about 14% of the unconfined compressive strength, with the tension/compression ratio values ranging between 0.10 and 0.17. According to Diambra et al. [33], for artificially cemented sandy soils, the existence of a tension/compression ratio (q_t/q_u) is independent of the curing time and is primarily governed by the tensile strength ratio (or frictional properties) of the cement. Baldovino et al. found that the q_t/q_u value ranged from 0.15 to 0.17 for silts from the Guabirotuba Formation stabilized with high early-strength Portland cement [34] and that the q_t/q_u value depends on the moisture content during molding or compaction and varies between 0.136 and 0.159 for silty-sandy soil from the same formation improved with cement [35]. These findings indicate that the tension/compression relationship of the soil-cement-RAP mixtures falls within the range of values reported in the literature.

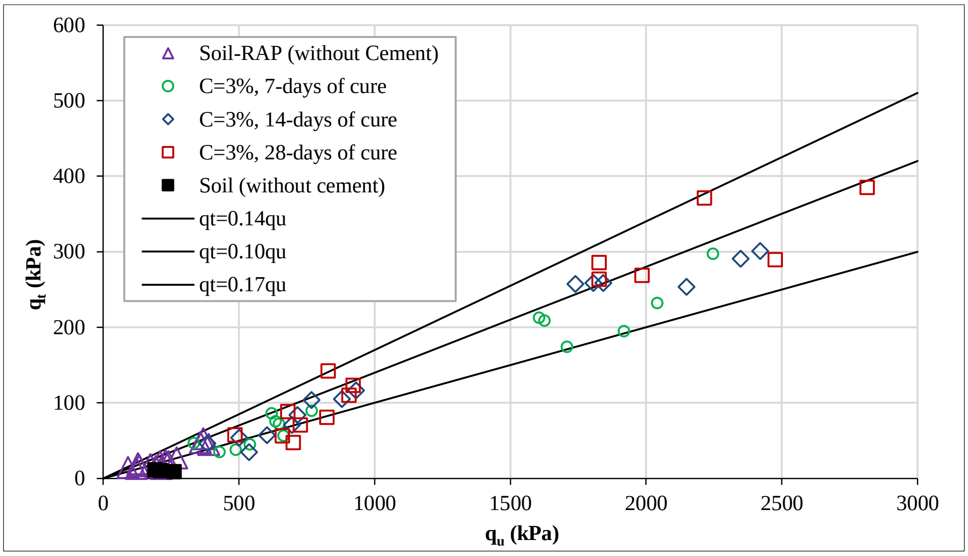

Figure 11. Empirical relationship between unconfined compression and split tensile strength

In Figure 12, the relationship between CBR and unconfined compression is calculated. The CBR values for soil-RAP without cement and soil stabilized with cement both equate to 7% of the unconfined compression value. The CBR value may also be influenced by the tension/compression ratio of the mixtures (q_t/q_u=0.14). As a result, CBR can alternatively be calculated as 50% of the splitting tensile strength value.

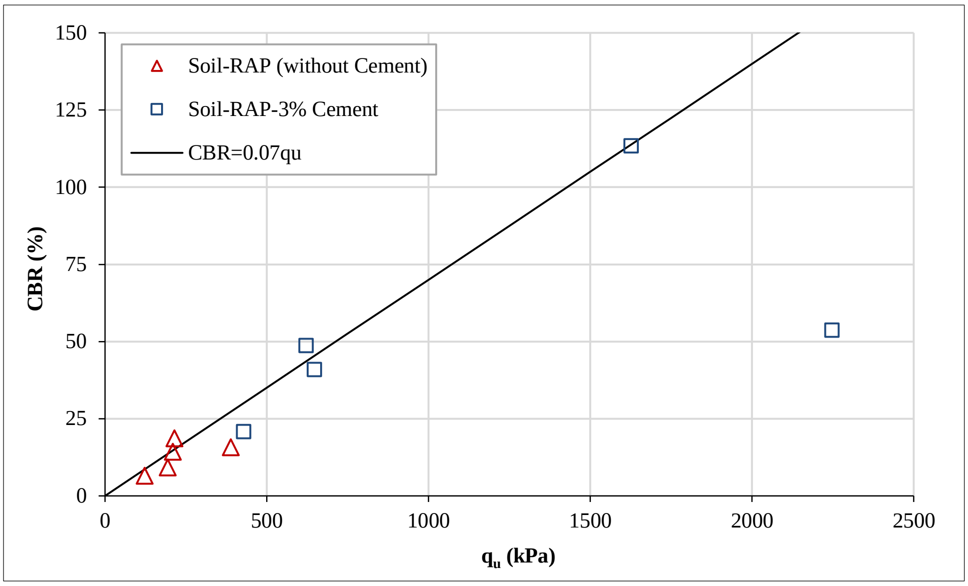

Figure 12. Empirical relationship between unconfined compression and CBR

3.6. Application of the Porosity/Cement

Figure 13 correlates the relationship between the porosity/cement index (η/C_{iv}) and the unconfined compressive strength (q_u) and split tensile strength (qt) of compacted soil-cement-RAP mixtures for curing periods between 7 and 28 days, using 3% of cement. The calculation of η/C_{iv} is detailed in studies conducted by Baldovino et al. [36] and Arrieta Baldovino et al. [37]. It is noted that the most effective way to depict the correlation between the two parameters (η/C_{iv} e q_u-q_t) was through a power function. The determination coefficients, ranging between 0.91 and 0.96, indicate the efficiency of the porosity/cement relationship in predicting the evolution of unconfined compression and split tensile strength for each curing time. The decrease in η/C_{iv} ratio increased both q_u and q_t, meaning that, as the voids in the mixtures decreased (increase in compacted density), the amount of cement powder added to the soil increased.

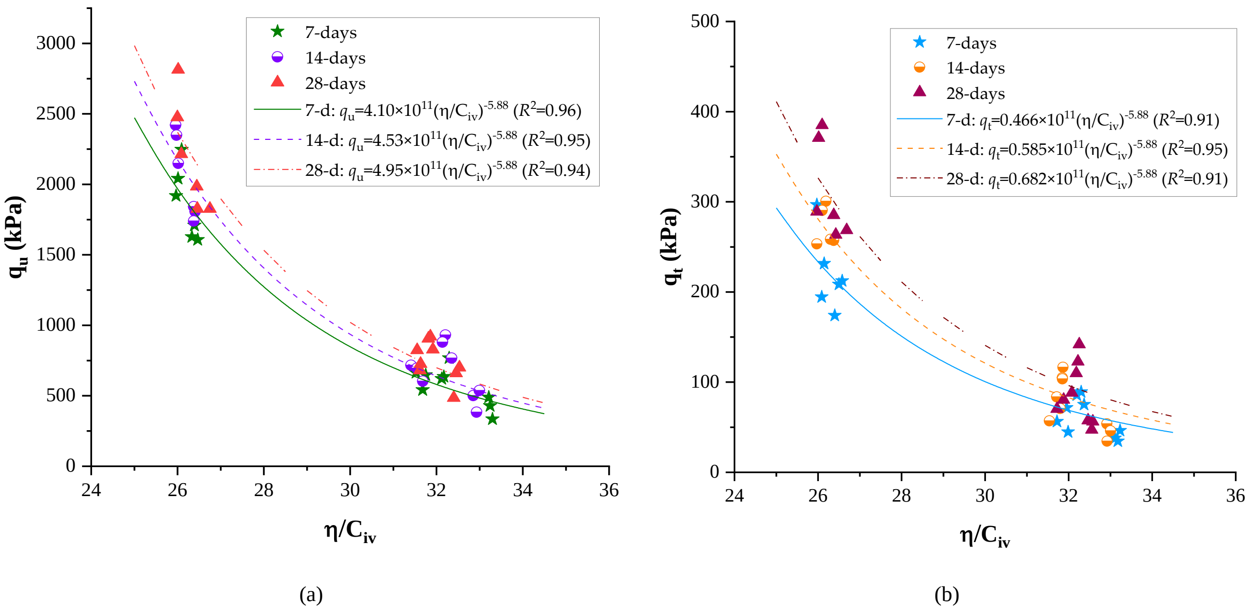

Figure 13. The porosity/cement ratio influences unconfined compressive strength (a) and split tensile strength (b)

The equations governing the unconfined compression for 7, 14, and 28-day curing periods are, respectively:

$$q_u=4.10\times10^{11}\left[\frac{\eta}{C_{iv}}\right]^{-5.88} \quad (R^2=0.96) \tag{1}$$

$$q_u=4.53\times10^{11}\left[\frac{\eta}{C_{iv}}\right]^{-5.88} \quad (R^2=0.95) \tag{2}$$

$$q_u=4.95\times10^{11}\left[\frac{\eta}{C_{iv}}\right]^{-5.88} \quad (R^2=0.94) \tag{3}$$

The equations that determine the split tensile strength after 7, 14, and 28 curing days are as follows:

$$q_t=0.466\times10^{11}\left[\frac{\eta}{C_{iv}}\right]^{-5.88} \quad (R^2=0.91) \tag{4}$$

$$q_t=0.585\times10^{11}\left[\frac{\eta}{C_{iv}}\right]^{-5.88} \quad (R^2=0.95) \tag{5}$$

$$q_t=0.682\times10^{11}\left[\frac{\eta}{C_{iv}}\right]^{-5.88} \quad (R^2=0.91) \tag{6}$$

An equation can be derived to estimate the unconfined compressive strength and split tensile strength for any curing time based on the porosity and cement volumetric content present in the samples, using the η/C_{iv} relationship shown in Figure 13. This is because the lime content, soil percentage, and dry unit weight of compaction are directly involved in the η/C_{iv} relationship. If Equations 1 to 6 are divided by the expression $10^{11}[\eta/C_{iv}]^{-5.88}$, a constant is obtained that increases with curing time for both q_u and q_t. The evolution of unconfined compressive strength and split tensile strength from 7 to 28 curing days is depicted in Figure 14. As the curing time increases, the values of q_u and q_t also rise, suggesting a potential growth with a determination coefficient value of R^2=0.99. Therefore, dosage equations for q_u and q_t can be proposed using the η/C_{iv} relationship and curing time (t). The dosage expressions for q_u and q_t are shown in Equations 7 and 8, respectively.

$$q_u=[3.1577t^{0.1355}]\times10^{11}\,(\eta/C_{iv})^{-5.88} \quad (R^2=0.99) \tag{7}$$

$$q_t=[0.3044t^{0.2485}]\times10^{11}\,(\eta/C_{iv})^{-5.88} \quad (R^2=0.99) \tag{8}$$

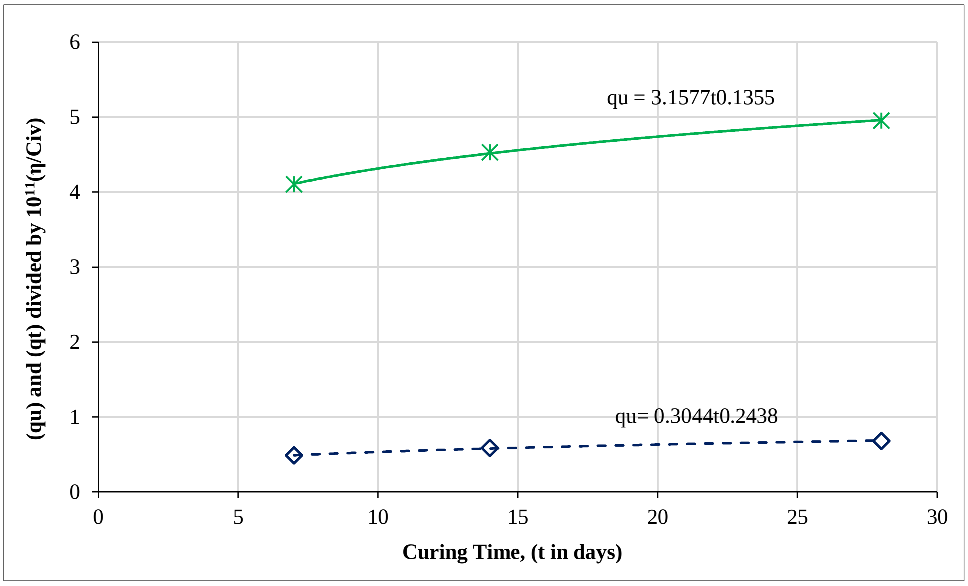

Figure 14. Dosage equations to estimate the unconfined compressive and split tensile strength

These results highlight the significance of porosity and volumetric cement content as critical influencers of soil-cement-RAP mixtures' mechanical behavior and strength properties. Engineers and researchers can accurately predict and fine-tune the strength characteristics of the stabilized mixtures due to the molding process if these variables are carefully controlled and monitored throughout the process. It is essential to point out that the proposed method's applicability and dependability extend beyond the specific molding situations and soil/RAP ratios considered in this study, demonstrating its broad usefulness. As a result, the established methodology shows promise for practical engineering applications, as it enables estimating the mechanical strength of soil-cement-RAP mixtures.

However, additional research and validation are required to investigate the potential of porosity and volumetric cement content as predictive variables under various soil types, cementitious materials, and environmental conditions.

It is possible to improve the robustness and applicability of the proposed approach by conducting the abovementioned investigations. These investigations will provide valuable insights for designing and constructing soil-cement-RAP mixtures, particularly for pavement applications [11]. The use of Portland cement as a stabilizing agent is employed because, even in small quantities, it significantly increases strength. In this context, milled asphalt pavement waste is proposed for soil improvement, aiming to provide a proper disposal method. However, the utilization of milled asphalt waste in cement stabilization lacks a consolidated dosage methodology, preventing the establishment of a standardized procedure to predict pavement performance [9]. The main advantages of using milled material and the recycling technique are economic, environmental, and logistical benefits. These include cost reduction through material transportation and reuse, substituting the need for virgin aggregates. Additionally, it reduces construction time and operational impacts, allowing for a quicker rehabilitation of pavement layers. Finally, the present research demonstrates the benefits of recycled RAP with low cement additions (3-5%) to enhance a soil layer for pavement construction.

4. Conclusions

This research aimed to analyze the influence of incorporating milled material into sedimentary soil from the Guabirotuba Formation and adding milled RAP material and cement to this soil to assess its suitability for different pavement layers. Based on the experimental program and the analysis of the results, the following conclusions were drawn:

- Adding milled material to the soil significantly increased the dry unit weight of the mixture, indicating improved compaction. Compositions without cement showed an approximate 28% increase compared to pure soil. The inclusion of reclaimed asphalt pavement (RAP) led to a reduction in the optimum moisture content. Compositions without cement experienced a 12% decrease compared to pure soil.
- The soil's unconfined compressive strength increased with the addition of RAP. Incorporating 60% RAP resulted in a significant 230% increase compared to pure soil. Compositions with cement exhibited similar behavior, with the highest strength achieved at a 60% milled material addition.
- The soil's split tensile strength increased with the inclusion of RAP and cement. Adding 60% RAP resulted in a substantial 370% increase compared to pure soil. The highest split tensile strength was achieved with a 60% milled material addition at 28 curing days.
- Adding RAP to the soil decreased expansion and increased the California Bearing Ratio (CBR), indicating improved stability and load-bearing capacity.
- Based on the findings, a specific composition of 60% RAP and 3% Portland cement demonstrated optimal results in split tensile strength and unconfined compressive strength, indicating its suitability for pavement applications, specifically as a sub-base layer.
- The porosity/cement ratio was valuable for estimating tensile and compressive strength evolution in soil-RAP-cement mixtures at different curing times. The dosage equations developed using this ratio showed an excellent correlation between the porosity/cement ratio and compressive and tensile strength values. These equations provide a practical tool for predicting the strength properties of soil-RAP-cement mixtures based on their porosity and cement content.

5. Declarations

5.1. Author Contributions

Conceptualization, D.L. and J.A.B.; methodology, D.L. and R.I.; validation, J.A.B., D.L., and R.I.; formal analysis, D.L.; investigation, D.L.; resources, J.A.B. and R.I.; data curation, R.I.; writing—original draft preparation, J.A.B.; writing—review and editing, R.I.; visualization, D.L.; 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

Finance Code 001 of the Coordenacão de Aperfeiçoamento de Pessoal de Nivel Superior - Brasil (CAPES) partially funded this study.

5.4. Acknowledgements

The authors would like to acknowledge the valuable support received from the Federal Technological University of Paraná, the Coordination for the Improvement of Higher Education Personnel (CAPES) under Financing Code 001, the

National Council for Scientific and Technological Development (CNPq), and the Araucária Foundation of Paraná in Brazil. Their support and funding have been instrumental in the successful execution of this research project.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

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