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A literature review based on the potential of use of RAP (Reclaimed Asphalt Pavement) in the base and subbase layers of flexible pavements

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Review Article

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Abstract
The Brazilian Road transport mode accounts for approximately 65% of the freight transport matrix, playing a significant role in the productivity of all economic sectors. Therefore, the maintenance of road infrastructure impacts resource optimization, safety, and user comfort. This article reviews the use of Reclaimed Asphalt Pavement (RAP) as an aggregate in the base and sub-base layers of pavement, employing cementitious materials as a binder/stabilizer. The ProKnow-C method was used to identify articles for discussions in the systematic literature review (SLR). The results show that the resilient modulus (MR) increases with the higher RAP content in the mixtures, improving the load-bearing capacity of granular layers, while the California Bearing Ratio (CBR) decreases as the RAP content increases. However, treated RAP exhibits high-strength properties. As the RAP content increases, unconfined compressive strength decreases. Future investigations are needed to address durability, life cycle analysis (LCA), and economic feasibility.

1. Introduction

Globally, the transportation sector is responsible for 21% of total greenhouse gas emissions, with road transport accounting for 15% of total CO_2 emissions. Most of these emissions come from passenger vehicles, which contribute 45.1%, while 29.4% comes from freight transport. Figure 1 illustrates the CO_2 emissions from 2018, totaling 8 billion tons of CO_2 (Ritchie, 2020).

In a global context, when evaluating road quality, Brazil ranks 116th, with an average score of 3.0, where 1 corresponds to extremely underdeveloped and 7 to efficient by international standards. Figure 2 presents road quality; the study was conducted in 141 countries, with an overall average road quality score of 4.1 (Schwab, 2009).

The Brazilian Road transport mode accounts for about 65% of the country's freight transport matrix, playing a significant role in the productivity of all economic sectors. Therefore, the maintenance and preservation of road infrastructure directly impact resource optimization, user safety, and comfort. The main critical points that hinder traffic flow and increase accident risks include landslides, road erosion, potholes on driving lanes, and narrow or closed bridges (CNT, 2022).

The aim of this study is to investigate the feasibility of using Reclaimed Asphalt Pavement (RAP) in the base and sub-base layers of pavement as a substitute for natural aggregates.

The current national production of crushed stone is approximately 256 million tons per year, with 85% used in concrete production and 15% in road and pavement construction. Road paving requires around 5,500 m^3 of crushed stone and 2% of the total crushed stone as sand per kilometer, equating to about 9,500 tons per kilometer, while road maintenance requires 3,000 tons per kilometer (ABDI, 2012; IBRAM, 2022).

The crushed stone mining sector is characterized by pollution and environmental impact, contributing to the depletion of natural resources, deforestation, alteration and destruction of native vegetation, noise pollution, air pollution, and the decline of local fauna, among other issues. The production processes for crushed stone follow the steps outlined in Figure 3 (Monteiro & Silva, 2018; ABDI, 2012; IBRAM, 2022):

The previously mentioned environmental impacts can be measured through carbon dioxide emissions during the extraction, processing, and transportation of fine and coarse

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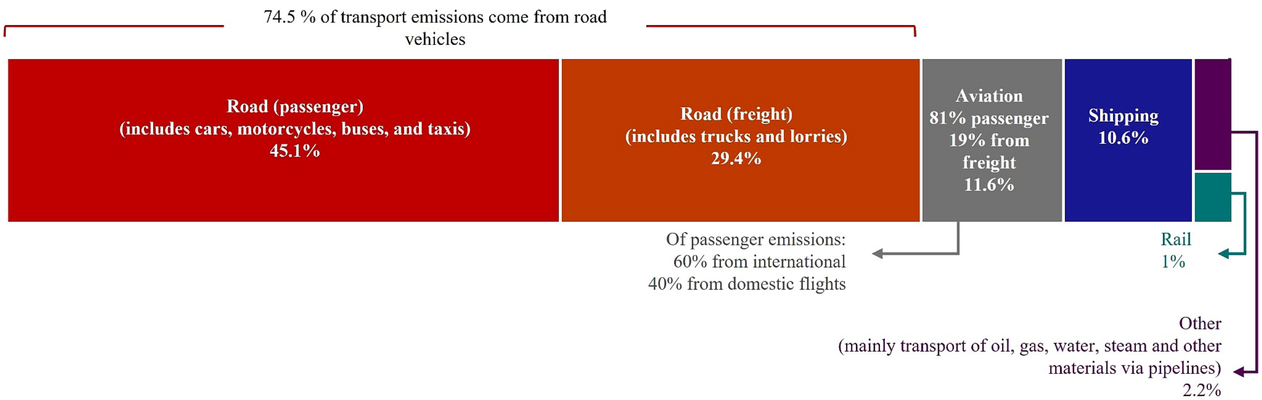

Figure 1. Global CO_2 Emissions by Transportation System. Adapted from Ritchie (2020).

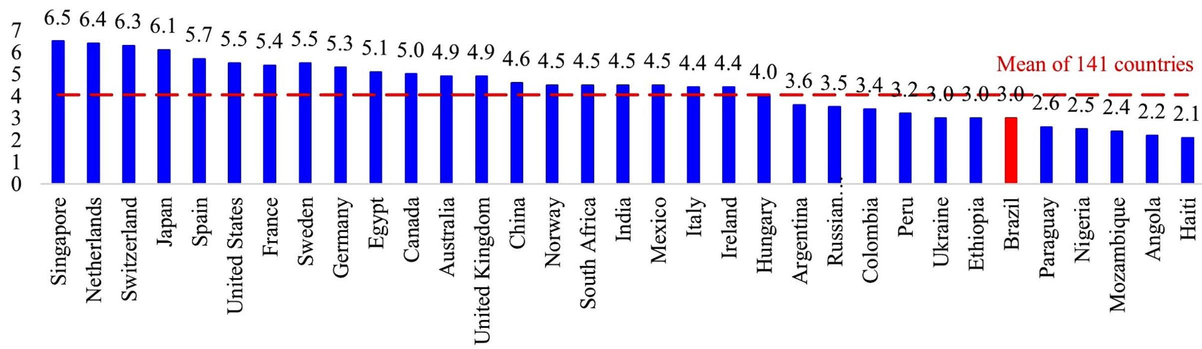

Figure 2. Road Quality – 2019. Adapted from Schwab (2009).

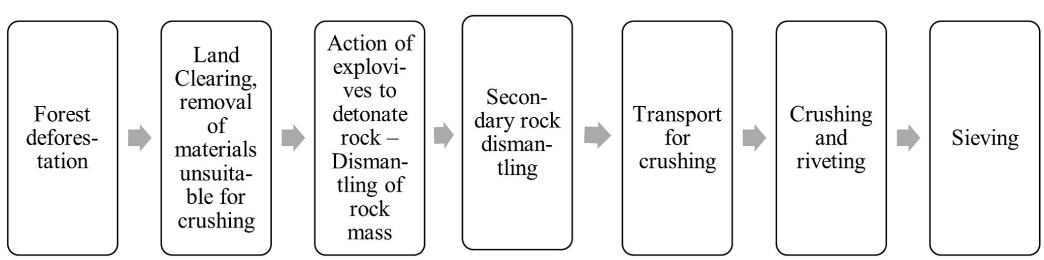

Figure 3. Crushed Stone Production (Monteiro & Silva, 2018; ABDI, 2012).

aggregates, Costa (2012) reports that producing one ton of fine aggregate emits 0.0861 tons of CO_2 and producing coarse aggregates emits 0.0858 tons of CO_2. The calculation of the data was conducted by considering the energy required for extraction and processing, as well as diesel fuel and electricity. For the transportation of materials, an average distance of 225 km for a round trip using a diesel-powered semi-truck was taken into account.

Alternative products can replace the use of natural aggregates in asphalt layers and the structural layers of pavements, such as RAP.

According to the National Asphalt Pavement Association (NAPA, 2020) 89.2 million tons of Reclaimed Asphalt Pavement (RAP) are used annually in the construction of new asphalt pavements in the United States. About 94% of RAP is utilized in new asphalt mixtures, while a small percentage is incorporated into granular layers. The net reduction in greenhouse gas emissions resulting from the use of RAP in asphalt mixtures from 2009 to 2019 was approximately 21.1 million tons of CO_2, which results in savings of approximately 44 million cubic meters in landfills.

The relevance of this study is linked to the significance and intensive use of the road transport mode, the exploitation of natural resources for the construction and maintenance of the road network, and the reduction of CO_2 emissions through the application of recycled materials in the base layer.

Reclaimed Asphalt Pavement (RAP) is a milled material generated from the removal of asphalt pavements for rehabilitation, resurfacing, or other maintenance activities. RAP is a graded aggregate coated with a layer of aged binder, which can be recycled and used in asphalt mixtures and other civil engineering applications (NAPA, 2020). RAP consists of 90% to 95% aggregate and 5% to 10% bitumen, with material recycling beginning in the 1970 (Plati & Cliatt, 2019).

Studies from different locations indicate the appropriate RAP contents for application in the pavement base layer. The permitted limits are shown in Table 1.

The Brazilian pavement recycling standard specifies that the base layer should contain a maximum of 50% Reclaimed Asphalt Pavement (RAP) with the addition of Portland cement. Additionally, the granulometric composition must comply with the ranges established in Table 2. The standard emphasizes that the aggregate used for the base must meet the following criteria: at least 95% of the material should pass through the 2” sieve; the percentage of fines passing the Nº 200 sieve (0.075 mm) should not exceed 15%; and it is desirable that at least 50% of the fraction passes through the Nº 4 sieve (4.75 mm) (DNIT, 2013).

Specific conditions are presented in Table 3, which can assist in engineering projects.

Using only RAP material in granular layers is a more sustainable alternative; however, the pavement’s functionality may be compromised due to permanent deformation, inadequate resistance characteristics, stiffness, and the variability in the composition of the material. The permanent deformation of RAP is 1.7 to 3 times greater compared to flexible base material due to its viscous properties (Khan & Puppala, 2023; George et al., 2021; Khan et al., 2023; Seferoğlu et al., 2018). However, reinforced or treated RAP exhibits high shear strength and stiffness properties, making it capable of withstanding traffic loads and consequently suitable for use in base and sub-base layers (Udomchai et al., 2021).

Table 1. RAP content limit for base layer (Lee et al., 2015; DNIT, 2013).

Jurisdiction	RAP content limit for base layer
Victoria	30%
New South Wales	15%
Tasmania	15%
Queensland	15%
South Australia	20%
Western Australia	10%
New Zealand	15%
USA / Canada	30% or more
Brazil	50%

The content for the use of RAP depends on the type of base, the quality of the RAP, and it must meet the project specifications.

2. Methods

This research presents a systematic literature review (SLR) based on studies, research, and the analysis of various articles related to the use of RAP (Reclaimed Asphalt Pavement) in the base and sub-base layers of flexible pavement.

2.1 Systematic analysis

The identification of articles for discussion was followed by a selection approach using the systematic literature review method the ProKnow-C (Knowledge Development Process – Constructivist).

Three databases in the field of Civil Engineering were defined in the Capes Portal, as well as, Scopus, Science Direct e Web of Science, where the search terms aligned with the research theme are the following keywords: base, subbase, layers, foundation, pavement, recycled asphalt pavement, RAP e cement.

The search was carried out in the eighth month of the year 2023, and the selection only included scientific articles from the last 10 years. The articles were filtered in the database and then extracted and inserted into the reference manager. Duplicate articles indexed in more than one database were

Table 2. Granulometric composition (DNIT, 2013).

Square mesh sieves		Percentage passing, by mass (%)		Design range tolerance (%)
ABNT	Aperture (mm)	I	II	
2”	50.800	100	100	-
1”	25.400	75 - 90	100	± 7
3/8”	9.500	40 - 75	50 - 85	± 7
Nº 4	4.750	30 - 60	35 - 65	± 5
Nº 10	2.000	20 - 45	25 - 50	± 5
Nº 40	0.425	15 - 30	15 - 30	± 2
Nº 200	0.075	5 - 15	5 - 15	± 2

Table 3. Specific conditions of base materials (DNIT, 2013, 2022).

Parameters	Base requirements	Reference
Simple compression strength	2.1 and 2.5 MPa	DNIT 167/2013 - ES
Diametrical compression tensile strength	0.25 and 0.35 MPa	DNIT 167/2013 - ES
Maximum expansion	0.50%	DNIT 141/2022-ES
ISC / CBR N ≤ 5 x 10^6	> 60%	DNIT 141/2022-ES
ISC / CBR N > 5 x 10^6	≥80%	DNIT 141/2022-ES
Abrasion for Los Angeles	< 55%	DNIT 141/2022-ES or DNIT 167/2013 - ES
Liquidity Limit	≤ 25%	DNIT 141/2022-ES
Plasticity Limit	≤ 6%	DNIT 141/2022-ES
Sand equivalent	> 30%	DNIT 141/2022-ES
Shape index	≥ 0.5	DNIT 167/2013 - ES
Lamellarity index	< 20%	DNIT 167/2013 - ES
Durability	< 12%	DNIT 167/2013 - ES

N: Equivalent Number of Standard Single Axle Operations of 80 kN Dual Wheels.

eliminated. 27 articles presented the title, abstract and text aligned with the research theme, which were selected for RSL to present the state of the art. One book chapter was included to assist in the evaluation of the results of the article portfolio.

3. State of the art

The properties of the base layer material significantly influence the stiffness of the layer. From the configuration in Figure 4, where a load (P) is applied to the pavement surface, generating a deflection (d), consequently causing strain due to tensile stresses (Et) in the lower region of the asphalt layer, leading to the formation of cracks. The load (P) is then transferred to the granular layer, and subsequently, the compressive deformations (Ec) are transferred to the top of the subgrade layer, causing shear in the subgrade. Therefore, the type of base layer used in flexible or semi-rigid pavement can affect its overall performance (Francois et al., 2019; Bernucci et al., 2008).

This section will present the mechanical properties that influence the performance of the base layer and the overall pavement structure.

3.1 Resilient modulus

The pavement layers are subjected to cyclic loads of varying intensities and different frequencies. The resilient modulus (MR) measures the recoverable deformation under repeated loading. This parameter is obtained through the dynamic triaxial test, which is used to calculate stresses and strains (Bernucci et al., 2008; Nokkaew, 2018).

The resilient modulus is the ratio of cyclic stress to recoverable deformation, indicating the material's ability to withstand load (Khan et al., 2023; Mousa et al., 2021).

The results of various studies have been compiled in Table 4 to illustrate the mechanical behavior of pavement structures containing different RAP mixtures applied in the base layers of pavements. The resilient modulus test is used

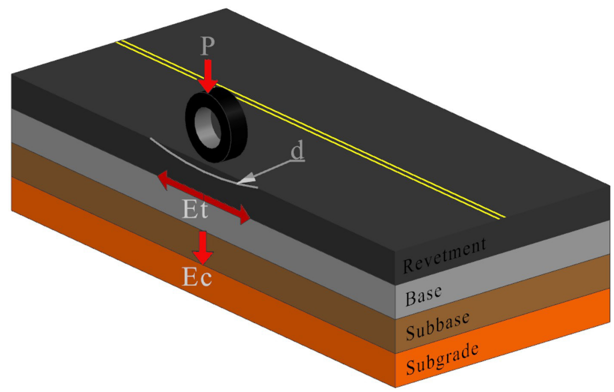

Figure 4. Stresses, Strains, and Displacement in Asphalt Pavement. Adapted from Franco (2007), Francois et al. (2019) and Bernucci et al. (2008). (P: load; Et: tensile stresses; d: deflection; Ec: compressive deformations).

during the detailed design phase and typically yields values ranging from 150 to 300 MPa for granular materials such as graded crushed stone (GCS), and from 5,000 to 10,000 MPa for chemically stabilized materials (DNER, 2006).

From the cyclic triaxial tests Francois et al. (2019) obtained the resilience modulus for bases stabilized with Portland cement, asphalt, calcium chloride, and geogrid. The chemically stabilized base with Portland cement exhibited the highest modulus at 818 MPa, followed by the asphalt sections at 294 MPa, calcium chloride at 262 MPa, and mechanically stabilized base with geogrid at 190 MPa. The Portland cement-stabilized base demonstrated the highest resilience modulus, confirming its suitability. In contrast, the geogrid showed the lowest resilience modulus, indicating that this material is not the most appropriate for resisting the cyclic stresses of flexible pavement.

The results for the base with 100% RAP material and the material with 50% RAP and 50% natural aggregate showed similar resilience modulus values to that of 100% natural aggregate, around 300 MPa, especially at increased confining pressures. This conclusion supports the inclusion of

Table 4. Approximate results of the Resilience Module of the bases with RAP.

Reference	Mixtures	MR (MPa)
Francois et al. (2019)	100% RAP	334
Francois et al. (2019)	100% RAP + Bitumen (3.62 l/m^2)	294
Francois et al. (2019)	100% RAP + $CaCl_2$ (3.40 lm^2)	262
Francois et al. (2019)	100% RAP + Cem. (17.4 kg/m^2)	818
Francois et al. (2019)	100% RAP + Geogrid	190
Mousa et al. (2021)	0% RAP + 100% NA	314
Mousa et al. (2021)	20% RAP + 80% NA	378
Mousa et al. (2021)	40% RAP + 60% NA	450
Mousa et al. (2021)	60% RAP+ 40% NA	500
Mousa et al. (2021)	80% RAP + 20% NA	630
Mousa et al. (2021)	100% RAP+ 0% NA	727
Nokkaew (2018)	100% RAP	480.3
Nokkaew (2018)	100% RMP	359.4
Nokkaew (2018)	100% NA	180.4

Legend: Natural aggregate (NA), Asphalt layer mixed with the underlying base layer (RMP) and Cement (Cem.).

RAP as a base material in the design of new pavements and rehabilitation projects, suggesting a sustainable perspective. (Plati & Cliatt, 2019).

Mousa et al. (2021), reports that the resilience modulus increases with the amount of RAP in the mixtures, surpassing the resilience modulus of natural aggregate. The addition of RAP to the mixture enhances the cohesion between particles due to the asphalt binder coating the RAP/aggregate, making the mixture stiffer. The mixtures with 0%, 20%, 40%, 60%, 80%, and 100% RAP achieved resilience modulus values of 314 MPa, 378 MPa, 450 MPa, 500 MPa, 630 MPa, and 727 MPa, respectively. When evaluating the samples using computed tomography, it is observed that natural aggregates have a higher air void content compared to samples containing RAP, suggesting that lower air voids may lead to higher resilience modulus values.

According to investigations conducted by Mousa et al. (2021) natural aggregates have resilience modulus values ranging from 161 to 361 MPa, while mixtures containing 20% to 100% RAP show resilience modulus values between 178 MPa and 461 MPa. This variation depends on the type of aggregate (geological origin, that is, inherent properties), the type of RAP, and the gradation of the materials.

RAP obtained from the milling of surface asphalt and RPM generated by the complete removal of the asphalt layer mixed with the underlying base layer was studied by Nokkaew (2018), according to the gradation distribution, both materials were classified as A-1-a; however, they exhibited different resilience modulus values. The RAP showed an MR of 480.3 MPa, while the RPM had a lower MR of 359.4 MPa. In comparison to crushed limestone, which is traditionally used for base construction, it can be stated that the recycled materials studied demonstrate a higher MR and can be used in base and sub-base layers, given that the MR of crushed limestone is 180.4 MPa.

Additionally, Nokkaew (2018) reports that pavement structures with RAP, after a 20-year simulation, exhibited lower longitudinal cracking at 949 cm/km, while RPM and crushed limestone showed 2,182 cm/km and 3,000 cm/km, respectively, against a normative value of 34,090 cm/km. Fatigue cracking (alligator cracking) was also lower for RAP aggregate at 0.5%, compared to 0.8% for RPM and 1.8% for crushed limestone, with a normative value of 25%. The plastic deformation of RAP was lower than that of crushed limestone, although RAP and RPM tend to develop higher plastic deformation under repeated loading. The International Roughness Index (IRI) for RAP, RPM, and crushed limestone was 220.8, 226.4, and 248.8, respectively, with a normative value of 244.3. Thus, these studied materials do not compromise pavement service life, and since RAP is derived from asphalt coating, it possesses high quality.

Chemically stabilized bases with cementitious materials exhibit higher resilience modulus values (Francois et al., 2019).

The resilience modulus increases with the amount of RAP in the mixture, surpassing the resilience modulus of natural aggregate (NA). Adding RAP enhances particle cohesion due to the asphalt binder coating the RAP/aggregate, resulting in a stiffer mixture (Euch Khay et al., 2015; Mousa et al., 2021; Nokkaew, 2018).

3.2 California Bearing Radio

The California Bearing Ratio (CBR) is a penetrometer test developed to assess the subgrade's potential for failure (plastic deformations) in roads. It is expressed as a percentage and defined as the ratio between the pressure needed to achieve a specific penetration of a piston into the test specimen and the pressure required to achieve the same penetration in a reference standard material (standardized crushed stone). The strength measured in the CBR test is an indirect response that combines both the cohesion and the friction angle of the material (Bernucci et al., 2008).

According to the Federal Highway Administration (FHWA), RAP has a CBR value of around 20% to 25%, which can reach values above 150% when mixed with approximately 60% natural aggregate (FHWA, 2016).

The results of several studies were grouped in Table 5 to show the mechanical behavior of pavement structures containing different RAP mixtures applied to the pavement base layers. The limits required by the DNIT (2022) are ISC / CBR $N \leq 5 \times 10^6$ with at least 60%, and ISC / CBR $N > 5 \times 10^6$ being greater than or equal to 80%.

The Limerock Bearing Ratio (LBR) test is a variant of the California Bearing Ratio (CBR) test. Generally,

Table 5. Approximate results of the California Support Index (CBR) of bases with RAP.

Reference	Mixtures	CBR (%)
Bleakley & Cosentino (2013)	100% RAP	30
Bleakley & Cosentino (2013)	0% RAP + 100% NA	162
Bleakley & Cosentino (2013)	25% RAP + 75% NA	99
Bleakley & Cosentino (2013)	50% RAP + 50% NA	55
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 1% emulsion CSS-1HF	127
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 2% emulsion CSS-1HF	105
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 3% emulsion CSS-1HF	107
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 1% emulsion SS-1H	106
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 2% emulsion SS-1H	103
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 3% emulsion SS-1H	100
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 1% Cem.	175
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 2% Cem.	288
Bleakley & Cosentino (2013)	50% RAP + 50% NA + 3% Cem.	396
Ayan et al. (2014)	100% Recycled Concrete	36
Ayan et al. (2014)	100% NA	32
Ayan et al. (2014)	50% Recycled Concrete + 50% RAP	29
Mousa et al. (2021)	0% RAP + 100% NA	85
Mousa et al. (2021)	20% RAP + 80% NA	65
Mousa et al. (2021)	40% RAP + 60% NA	45
Mousa et al. (2021)	60% RAP+ 40% NA	30
Mousa et al. (2021)	80% RAP + 20% NA	25
Mousa et al. (2021)	100% RAP+ 0% NA	15
Seferoğlu et al. (2018)	0% RAP + 100% NA	180
Seferoğlu et al. (2018)	10% RAP + 90% NA	149
Seferoğlu et al. (2018)	20% RAP + 80% NA	140
Seferoğlu et al. (2018)	30% RAP + 70% NA	90
Seferoğlu et al. (2018)	30% RAP + 70% NA + 1% Cem.	205
Seferoğlu et al. (2018)	30% RAP + 70% NA + 2% Cem.	320
Seferoğlu et al. (2018)	30% RAP + 70% NA + 3% Cem.	380
Seferoğlu et al. (2018)	40% RAP + 60% NA	80
Seferoğlu et al. (2018)	40% RAP + 60% NA + 1% Cem.	140
Seferoğlu et al. (2018)	40% RAP + 60% NA + 2% Cem.	150
Seferoğlu et al. (2018)	40% RAP + 60% NA + 3% Cem.	280
Seferoğlu et al. (2018)	50% RAP + 50% NA	50
Seferoğlu et al. (2018)	50% RAP + 50% NA + 1% Cem.	85
Seferoğlu et al. (2018)	50% RAP + 50% NA + 2% Cem.	180
Seferoğlu et al. (2018)	50% RAP + 50% NA + 3% Cem.	185
Seferoğlu et al. (2018)	60% RAP + 40% NA	45
Seferoğlu et al. (2018)	60% RAP + 40% NA + 1% Cem.	80
Seferoğlu et al. (2018)	60% RAP + 40% NA + 2% Cem.	130
Seferoğlu et al. (2018)	60% RAP + 40% NA + 3% Cem.	145
Seferoğlu et al. (2018)	100% RAP + 0% NA	31
Seferoğlu et al. (2018)	100% RAP + 0% NA + 1% Cem.	65
Seferoğlu et al. (2018)	100% RAP + 0% NA + 2% Cem.	80
Seferoğlu et al. (2018)	100% RAP + 0% NA + 3% Cem.	140

specifications require a minimum LBR of 100% (equivalent to a CBR of 80%) for base layer materials. To facilitate analysis, we will convert the LBR results obtained by Bleakley & Cosentino (2013).

The test with 100% natural aggregate (NA) without chemical stabilization achieved an average CBR of 130%. The mixture of 25% RAP with 75% natural aggregate without chemical stabilization achieved an average CBR of 79%, while the mixture of 50% RAP with 50% natural aggregate without chemical stabilization achieved an average CBR of 42%. The mixtures of 50% RAP with 50% natural aggregate stabilized with 1%, 2%, and 3% CSS-1HF emulsion achieved CBR values of 102%, 84%, and 86%, respectively. The mixtures of 50% RAP with 50% natural aggregate stabilized with 1%, 2%, and 3% SS-1H emulsion achieved CBR values of 85%, 82%, and 80%, respectively. The mixtures of 50% RAP with 50% natural aggregate stabilized with 1%, 2%, and 3% Portland cement achieved CBR values of 140%, 230%, and 317%, respectively. Only mixtures with 50% or more natural aggregate have the potential to achieve a CBR above 80%, with the most promising results obtained using Portland cement for chemical stabilization (Bleakley & Cosentino, 2013).

A study conducted by Ayan et al. (2014) examined the performance of 100% recycled materials for untreated sub-base layers. Natural aggregate (NA) samples were compared with samples of recycled concrete aggregate (RCA) and samples with a 50% RAP and 50% RCA blend. The CBR values obtained were 32%, 47%, and 29%, respectively. It was observed that during compaction RCA particles broke down into smaller particles more readily compared to NA and RAP. A significant difference between RCA and RAP properties is that the bitumen-coated aggregates in RAP create a more flexible material, which is less prone to breakage during compaction compared to RCA. Samples with a 50% RAP and 50% RCA blend achieved a CBR value of 29%, which falls below the minimum requirement (CBR < 30%) for unbound sub-base applications. However, a treatment applied to this blend could potentially improve the material's performance for such applications.

In line with other literature, Mousa et al. (2021), report that the California Bearing Ratio (CBR) significantly decreases with the increasing amount of RAP in mixtures for base and sub-base layers. This reduction may be attributed to decreased friction between the aggregates due to the bitumen coating on the aggregate grains. The mixtures containing 0%, 20%, 40%, 60%, 80%, and 100% RAP yielded CBR values of 85%, 65%, 45%, 30%, 25%, and 15%, respectively. Based on these CBR results, the authors conclude that up to 60% RAP can be utilized in sub-base layers, while only 20% RAP is suitable for base layers.

Seferoğlu et al. (2018) also observed that as the concentration of RAP increased, the CBR value decreased. Tests were conducted with natural aggregates and RAP. The mixtures that presented a CBR lower than 120% were stabilized with 1%, 2%, and 3% cement. The mixtures with 100% natural aggregate, 10% RAP, 20% RAP, and 30% RAP had CBR values of 180%, 149%, 140%, and 90%, respectively. Table 5 illustrates the other results obtained in the research. The mixture with 100% RAP had a CBR of 31%, which is insufficient for use as a base layer. However, with the addition of 1%, 2%, and 3% cement, the CBR values increased to 65%, 80%, and 140%, respectively. Thus, it is possible to create a base layer with 100% RAP, provided it receives appropriate treatment to meet normative requirements.

The SP-CS (gravelly sands and clay) and GW-GC (gravelly soil with clays) soils were mixed with 0%, 20%, 40%, and 60% RAP. Without any treatment, it was observed that the mixtures decreased the CBR value with the increase of RAP. The CBR values obtained for SP-CS/RAP were 30%, 25%, 20%, and 18%, while the values for GW-GC/RAP were 83%, 63%, 51%, and 46%. It can be concluded that 60% RAP reduces the CBR by half, and from 40% RAP, the rate of CBR reduction approaches a constant value (Ghanizadeh et al., 2018).

The CBR significantly decreases with the increase in the amount of RAP in the mixtures for base and sub-base layers. This reduction may be due to the decreased friction between the aggregates caused by the asphalt binder coating the aggregate grains (Mousa et al., 2021; Seferoğlu et al., 2018; Ghanizadeh et al., 2018).

3.3 Unconfined compressive strength

Unconfined compressive strength (UCS) is a test that involves applying axial loading to a cylindrical specimen of cohesive soil using a simple press (Bernucci et al., 2008).

The results of several studies were grouped in Table 6 to show the mechanical behavior of pavement structures containing different RAP mixtures applied to the pavement base layers. The limits required by the DNIT (2013) for unconfined compressive strength at 7 days range between 2.1 MPa and 2.5 MPa.

Euch Khay et al. (2015) added a content of 6% Portland cement with 100%, 75%, 50%, 25%, and 0% RAP, achieving unconfined compressive strength at 7 days of 5.85 MPa, 6.75 MPa, 8.30 MPa, 10.55 MPa, and 12.50 MPa, respectively, and at 28 days of 8.35 MPa, 9.95 MPa, 11.30 MPa, 14.70 MPa, and 18.05 MPa. As the RAP content increased, the compressive strength decreased. The indirect tensile strength was around 11 to 12% of the compressive strength, while the flexural strength was about 13% to 19% of the compressive strength. In pavement layer structures, a minimum curing period of 7 days is recommended.

When analyzing the compressive stresses in bases stabilized with Portland cement, bitumen, calcium chloride, and geogrid, it is observed that the bituminous section and the one containing geogrid exhibited similar compressive deformation at the top of the subgrade layer, subjected to similar impacts regarding susceptibility to wheel track

Table 6. Approximate results of unconfined compressive strength of bases with RAP.

Reference	Mixtures	UCS (MPA)
Euch Khay et al. (2015)	100% RAP + 6% Cem. + 0% NA	5.85
Euch Khay et al. (2015)	75% RAP + 6% Cem. + 25% NA	6.75
Euch Khay et al. (2015)	50% RAP + 6% Cem. + 50% NA	8.30
Euch Khay et al. (2015)	25% RAP + 6% Cem. + 75% NA	10.55
Euch Khay et al. (2015)	0% RAP + 6% Cem. + 100% NA	12.50
Fedrigo et al. (2017)	20% RAP + 80% Recycled gravel + 2% Cem. (modified)	2.50
Fedrigo et al. (2017)	50% RAP + 50% Recycled gravel + 2% Cem. (modified)	2.80
Fedrigo et al. (2017)	20% RAP + 80% Recycled gravel + 4% Cem. (modified)	4.80
Fedrigo et al. (2017)	50% RAP + 50% Recycled gravel + 4% Cem. (modified)	4.50
Fedrigo et al. (2017)	20% RAP + 80% Recycled gravel + 4% Cem. (intermediary)	3.10
Fedrigo et al. (2017)	50% RAP + 50% Recycled gravel + 4% Cem. (intermediary)	3.90
Fedrigo et al. (2017)	20% RAP + 80% Recycled gravel + 6% Cem. (intermediary)	5.50
Fedrigo et al. (2017)	50% RAP + 50% Recycled gravel + 6% Cem. (intermediary)	5.10
Pratikso et al. (2017)	100% RAP + 1.5% Cem.	1.18
Pratikso et al. (2017)	100% RAP + 3% Cem.	1.58
Pratikso et al. (2017)	100% RAP + 4.5% Cem.	2.01
Pratikso et al. (2017)	100% RAP + 6% Cem.	2.57
Pratikso et al. (2017)	100% RAP + 7.5% Cem.	3.44
Ungureanu et al. (2020)	100% RAP + 3.5% Cem.	1.44
Ghanizadeh et al. (2018)	0% RAP + 100% soil (SP-SC) + 3% Cem.	2.76
Ghanizadeh et al. (2018)	20% RAP + 80% soil (SP-SC) + 3% Cem.	2.55
Ghanizadeh et al. (2018)	40% RAP + 60% soil (SP-SC) + 3% Cem.	2.26
Ghanizadeh et al. (2018)	60% RAP + 40% soil (SP-SC) + 4% Cem.	2.43
Ghanizadeh et al. (2018)	0% RAP + 100% soil (GW-GC) + 3% Cem.	3.61
Ghanizadeh et al. (2018)	20% RAP + 80% soil (GW-GC) + 3% Cem.	3.43
Ghanizadeh et al. (2018)	40% RAP + 60% soil (GW-GC) + 3% Cem.	2.23
Ghanizadeh et al. (2018)	60% RAP + 40% soil (GW-GC) + 5% Cem.	2.26
Kasu et al. (2020)	100% NA + 2.5% Cem.	2.60
Kasu et al. (2020)	100% NA + 5% Cem.	5.00
Kasu et al. (2020)	100% NA + 7.5% Cem.	7.50
Kasu et al. (2020)	100% NA + 10% Cem.	11.62
Kasu et al. (2020)	80% NA + 20% RAP + 2.5% Cem.	2.50
Kasu et al. (2020)	80% NA + 20% RAP + 5% Cem.	4.80
Kasu et al. (2020)	80% NA + 20% RAP + 7.5% Cem.	7.20
Kasu et al. (2020)	80% NA + 20% RAP + 10% Cem.	10.60
Kasu et al. (2020)	60% NA + 40% RAP + 2.5% Cem.	2.00
Kasu et al. (2020)	60% NA + 40% RAP + 5% Cem.	4.50
Kasu et al. (2020)	60% NA + 40% RAP + 7.5% Cem.	7.00
Kasu et al. (2020)	60% NA + 40% RAP + 10% Cem.	9.20
Kasu et al. (2020)	40% NA + 60% RAP + 2.5% Cem.	1.23
Kasu et al. (2020)	40% NA + 60% RAP + 5% Cem.	3.20
Kasu et al. (2020)	40% NA + 60% RAP + 7.5% Cem.	6.00
Kasu et al. (2020)	40% NA + 60% RAP + 10% Cem.	8.50
Adresi et al. (2019)	0% RAP+ 65% NA+ 30% Sand + 5% Filler + 3% Cem. (Saturated 25 °C 7 days)	3.50
Adresi et al. (2019)	0% RAP+ 65% NA+ 30% Sand + 5% Filler + 3% Cem. (Dry 50 °C 7 days)	5.00
Adresi et al. (2019)	40% RAP+ 20% NA+ 40% Sand + 0% Filler + 3% Cem. (Saturated 25 °C 7 days)	4.50
Adresi et al. (2019)	40% RAP+ 20% NA+ 40% Sand + 0% Filler + 3% Cem. (Dry 50 °C 7 days)	3.50
Adresi et al. (2019)	60% RAP+ 0% NA+ 40% Sand + 0% Filler + 3% Cem. (Saturated 25 °C 7 days)	4.00
Adresi et al. (2019)	60% RAP+ 0% NA+ 40% Sand + 0% Filler + 3% Cem. (Dry 50 °C 7 days)	3.00
Adresi et al. (2019)	80% RAP+ 0% NA+ 0% Sand + 20% Filler + 3% Cem. (Saturated 25 °C 7 days)	1.50
Adresi et al. (2019)	80% RAP+ 0% NA+ 0% Sand + 20% Filler + 3% Cem. (Dry 50 °C 7 days)	1.30
Adresi et al. (2019)	0% RAP+ 65% NA+ 30% Sand + 5% Filler + 5% Cem. (Saturated 25 °C 7 days)	7.50
Adresi et al. (2019)	0% RAP+ 65% NA+ 30% Sand + 5% Filler + 5% Cem. (Dry 50 °C 7 days)	8.40

Table 6. Continued...

Reference	Mixtures	UCS (MPA)
Adresi et al. (2019)	40% RAP+ 20% NA+ 40% Sand + 0% Filler + 5% Cem. (Saturated 25 °C 7 days)	5.30
Adresi et al. (2019)	40% RAP+ 20% NA+ 40% Sand + 0% Filler + 5% Cem. (Dry 50 °C 7 days)	4.00
Adresi et al. (2019)	60% RAP+ 0% NA+ 40% Sand + 0% Filler + 5% Cem. (Saturated 25 °C 7 days)	4.40
Adresi et al. (2019)	60% RAP+ 0% NA+ 40% Sand + 0% Filler + 5% Cem. (Dry 50 °C 7 days)	3.00
Adresi et al. (2019)	80% RAP+ 0% NA+ 0% Sand + 20% Filler + 5% Cem. (Saturated 25 °C 7 days)	3.60
Adresi et al. (2019)	80% RAP+ 0% NA+ 0% Sand + 20% Filler + 5% Cem. (Dry 50 °C 7 days)	2.00
Adresi et al. (2019)	0% RAP+ 65% NA+ 30% Sand + 5% Filler + 7% Cem. (Saturated 25 °C 7 days)	9.50
Adresi et al. (2019)	0% RAP+ 65% NA+ 30% Sand + 5% Filler + 7% Cem. (Dry 50 °C 7 days)	10.00
Adresi et al. (2019)	40% RAP+ 20% NA+ 40% Sand + 0% Filler + 7% Cem. (Saturated 25 °C 7 days)	5.90
Adresi et al. (2019)	40% RAP+ 20% NA+ 40% Sand + 0% Filler + 7% Cem. (Dry 50 °C 7 days)	5.00
Adresi et al. (2019)	60% RAP+ 0% NA+ 40% San+ 0% Filler + 7% Cem. (Saturated 25 °C 7 days)	4.90
Adresi et al. (2019)	60% RAP+ 0% NA+ 40% Sand + 0% Filler + 7% Cem. (Dry 50 °C 7 days)	3.60
Adresi et al. (2019)	80% RAP+ 0% NA+ 0% Sand + 20% Filler + 7% Cem. (Saturated 25 °C 7 days)	3.60
Adresi et al. (2019)	80% RAP+ 0% NA+ 0% Sand + 20% Filler + 7% Cem. (Dry 50 °C 7 days)	2.00
Goldoni et al. (2023)	20% RAP+ 38% NA + 42% Gravel + 2% Cem.	1.60
Goldoni et al. (2023)	20% RAP+ 38% NA + 42% Gravel + 4% Cem.	3.30
Goldoni et al. (2023)	20% RAP+ 38% NA + 42% Gravel + 6% Cem.	8.30
Goldoni et al. (2023)	45% RAP+ 33% NA + 22% Gravel + 2% Cem.	1.80
Goldoni et al. (2023)	45% RAP+ 33% NA + 22% Gravel + 4% Cem.	4.00
Goldoni et al. (2023)	45% RAP+ 33% NA + 22% Gravel + 6% Cem.	7.50
Goldoni et al. (2023)	70% RAP + 30% NA + 2% Cem.	1.80
Goldoni et al. (2023)	70% RAP + 30% NA + 4% Cem.	4.40
Goldoni et al. (2023)	70% RAP + 30% NA + 6% Cem.	5.60

deformation in flexible pavements. In contrast, the compressive deformations for the sections with $CaCl_2$ and Portland cement were lower than those obtained for the untreated 100% RAP control section, indicating that these sections had a positive impact on the entire section's ability to resist wheel track rutting (Francois et al., 2019).

The statistical analysis conducted by Noulmanee et al. (2021) indicated that the type of aggregate and the water/cement ratio influence the compressive strength. The lower the water/cement ratio, the higher the compressive strength of the layer. Regarding the type of aggregate, three types were studied: (1) lateritic soil, (2) RAP and crushed stone, and (3) RAP with crushed stone and lateritic soil. The RAP with crushed stone tended to produce the highest compressive strength value among the three materials, while the lateritic soil produced the lowest compressive strength value.

Fedrigo et al. (2017) emphasizes that strength is not the only property to consider when designing mixtures for base layers. Some mixtures, although they exhibit acceptable strength values, may fail due to cracking from shrinkage or erosion. When using RAP with crushed stone and varying cement contents of 2%, 4%, and 6% with different compaction energies, it was concluded that increasing the cement content raises the unconfined compressive strength but also increases the brittleness of the mixtures, making them more susceptible to cracking. However, it is important to highlight that a greater compaction effort can offset the use of low cement contents, thereby reducing costs and the risks of shrinkage cracking.

Like other authors, Pratikso et al. (2017) highlight the influence of cement content in mixtures and curing time. A variation of 1.5% to 7.5% cement, with increments of 1.5%, was tested with 100% RAP, resulting in strengths of 1.18 MPa, 1.58 MPa, 2.01 MPa, 2.57 MPa, and 3.44 MPa at 7 days. The cement levels that meet the UCS requirements for base layers are between 6% and 7.5%.

One of the important factors in gaining strength is curing. Mixtures with 100% RAP stabilized with 3.5% hydraulic binder using Portland cement clinker achieved unconfined compressive strengths of 1.44 MPa, 2.22 MPa, and 3.22 MPa at 7, 28, and 60 days, respectively (Ungureanu et al., 2020). Therefore, UCS increases with longer curing times, (Ungureanu et al., 2020; Ghanizadeh et al., 2018) other researchers have drawn similar conclusions.

A percentage of 0%, 3%, 4%, 5%, and 6% cement is added to two mixtures: SP-CS soil (gravelly sands and clay) with RAP and GW-GC soil (gravelly soil with clay) with RAP, maintaining a fixed soil/RAP ratio. The UCS of the treated material increases with the increase in cement content; increasing the cement by 1% while keeping RAP constant results in an average strength increase from 376 kPa to 410 kPa for the SP-CS and GW-GC soils, respectively. Conversely, when the cement content is fixed and the percentage of RAP in the mixtures is increased, the UCS decreases. The reason for this reduction in strength is that the asphalt coating around the RAP material decreases the friction between the aggregates (Ghanizadeh et al., 2018).

The Portland Cement Association suggests that the UCS should be greater than 2100 kPa at 7 days; lower values reduce the pavement's load-bearing capacity, and thus less than 3% cement leads to low strength. Comparing the UCS results for the two soils, it can be concluded that the base treated with 0% and 20% RAP containing GW-GC soil is approximately 793 kPa higher than samples containing SP-SC soil, while the UCS value for the base treated with 60% RAP containing SP-SC soil is about 405 kPa higher than samples containing GW-GC soil. It is concluded that at higher levels of RAP, the effect of cement on increasing UCS is greater for the base treated with SP-SC compared to the base treated with GW-GC soil (Ghanizadeh et al., 2018).

Various studies report that UCS decreases with an increase in RAP content and increases with the amount of cement. This behavior was also reported by Kasu et al. (2020). The bituminous film on the RAP aggregate consists of a hydrophobic material that is chemically incompatible with the hydrophilic cement paste, which results in lower strength in the transition zone at the interface between the aggregate and the cement paste. This conclusion is consistent with other literature. In the experiments, the percentages of cement varied from 2.5% to 10% with increments of 2.5%. Five sample types were produced: 100% natural aggregate with and without cement treatment, 80% natural aggregate plus 20% RAP, 60% natural aggregate plus 40% RAP, and 40% natural aggregate plus 60% RAP. The results obtained ranged from 1.23 MPa to 11.62 MPa. After a statistical study, the author revealed that the optimal mixture concerning strength and durability contains 30% RAP and 70% natural aggregate for all cement dosages. It was suggested that for an economical design, mixtures should have a UCS greater than 1.75 MPa to be applied in sub-base layers, greater than 4.5 MPa for base layers, and greater than 7 MPa for rigid pavement bases.

In order to increase the recycling rate of RAP, Adresi et al. (2019) studied its mechanical properties. Due to the inadequate grading of RAP, percentages of natural aggregate, sand, and filler were added to the RAP aggregate to achieve a well-graded material. The obtained mixtures were stabilized with 3%, 5%, and 7% cement. The results show that the increase in cement content significantly increases the strength of the mixture. The UCS of samples with 5% cement was approximately three times higher than that of samples with 3% cement. The results presented for the mixtures with 5% cement and variations of 0%, 40%, 60%, and 80% RAP were 7.5 MPa, 5.3 MPa, 4.4 MPa, and 3.6 MPa, respectively, with failure occurring after 7 days of curing under saturated conditions at 25 °C. Under dry conditions at 50 °C, the results were 8.4 MPa, 4 MPa, 3 MPa, and 2 MPa. The UCS values were higher for the mixtures without RAP tested at a temperature of 50 °C compared to those tested at 25 °C.

Goldoni et al. (2023) investigates the feasibility of using high RAP (Reclaimed Asphalt Pavement) contents in base layers stabilized with cementitious materials. In mixtures containing 70% RAP and 30% stone dust with 2%, 4%, and 6% cement, the UCS (Unconfined Compressive Strength) values were approximately 1.8 MPa, 4.4 MPa, and 5.6 MPa, respectively. The author highlights those mixtures with 70% RAP and 30% stone dust have lower packing density, resulting in lower strength compared to mixtures composed of 20% RAP, 38% stone dust, supplemented with gravel, and those with 45% RAP, 33% stone dust, also supplemented with gravel. The UCS values for these gravel-included mixtures, with additions of 2%, 4%, and 6% cement, are approximately 1.6 MPa, 3.3 MPa, 8.3 MPa, and 1.8 MPa, 4 MPa, 7.5 MPa, respectively. This led the author to conclude that the RAP content does not have a significant influence on the mechanical behavior of the mixtures. However, the results indicate that increasing cement content enhances mechanical strength, particularly for mixtures with lower RAP content.

3.4 Reflections from literature

Table 7 presents the strength values of different RAP mixtures from various countries, which meet the requirements of the Brazilian standard DNIT (2013). Strength values below the standard are subject to pathologies that may appear prematurely in the pavement, compromising its durability, while excessively high strength values may lead to increased costs during implementation.

Table 7. Unconfined compressive strength of bases with RAP.

Reference	Mistures	UCS (MPa)
Fedrigo et al. (2017)	20% RAP + 80% Recycled gravel +2% Cem. (modified)	2.50
Fedrigo et al. (2017)	50% RAP + 50% Recycled gravel +2% Cem. (modified)	2.80
Pratikso et al. (2017)	100% RAP + 4.5% Cem.	2.01
Ghanizadeh et al. (2018)	0% RAP + 100% soil (SP-SC) + 3% Cem.	2.76
Ghanizadeh et al. (2018)	20% RAP + 80% soil (SP-SC) + 3% Cem.	2.55
Ghanizadeh et al. (2018)	40% RAP + 60% soil (SP-SC) + 3% Cem.	2.26
Ghanizadeh et al. (2018)	60% RAP + 40% soil (SP-SC) + 4% Cem.	2.43
Ghanizadeh et al. (2018)	40% RAP + 60% soil (GW-GC) + 3% Cem.	2.23
Ghanizadeh et al. (2018)	60% RAP + 40% soil (GW-GC) + 5% Cem.	2.26
Kasu et al. (2020)	80% NA + 20% RAP+ 2.5% Cem.	2.50

The mix designs will depend on the characteristics of the materials; however, Tables 4, 5 and 6 present previous studies that can contribute to the theoretical foundation of future research and provide technical support for the development of highway pavement projects. The optimal cement content range for RAP-containing mixtures is between 2.5% and 5%.

Few studies address the long-term behavior of RAP applied in base layers; generally, research focuses on strength parameters and does not present durability results.

From an environmental perspective, few studies have been conducted on the application of recycled materials in base and sub-base layers of asphalt pavements, as well as studies on life cycle analysis (LCA).

Cost analyses of base layers with cement-treated RAP are rarely studied.

4. Conclusion

The study reviews the effects of recycled materials, as well as RAP (Reclaimed Asphalt Pavement) as a material for the base and sub-base layers of flexible pavements. Based on the results, the following conclusions were drawn:

a) The addition of RAP and chemical stabilization improves the load-bearing capacity of the granular layers, resulting in a significant increase in the stiffness of the base layer;
b) The resilience modulus increases with the amount of RAP in the mixtures;
c) The CBR (California Bearing Ratio) significantly decreases with the increase in the amount of RAP in the mixtures; however, reinforced or treated RAP exhibits high-strength properties, making it suitable for supporting traffic loads and, consequently, its applicability in the base and sub-base layers;
d) As the RAP content increases, the compressive strength decreases. The reason for the reduction in strength is that the asphalt surrounding the RAP material decreases the friction between the aggregates;
e) Although the topic has been explored in the academic field, there are gaps that need to be researched, such as durability, life cycle assessment (LCA), and economic viability.

Finally, the SLR (literature review) shows that the results of incorporating RAP as an aggregate for the base and sub-base layers of flexible pavements are promising.

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Declaration of interest

The authors have no conflicts of interest to declare.

Authors' contributions

Emiliane Karolina Gonçalves dos Santos Braga Santana: conceptualization, investigation, methodology, validation, visualization, writing-original draft, writing – review & editing. Júnia Nunes de Paula: project administration, supervision, writing – review & editing.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was translated with the assistance of generative artificial intelligence (GenAI) by ChatGPT, with the aim of translating the text from Portuguese to US English. 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 assistance of GenAI.

List of symbols and abbreviations

d	deflection
BGS	Simple graded gravel
$CaCl_2$	Calcium chloride
CBR	California Berring Ratio
CO_2	Carbon dioxide
CSS-1H	Cationic asphalt emulsion
DNER	Departamento Nacional de Estradas de Rodagem
DNIT	Departamento Nacional de Infraestrutura de Transportes
GW-GC	Rocky soil with clays
LBR	Limerock Bearing Ratio
LCA	life cycle analysis
MR	Resilience module
N	number of repetitions of a standard axis
NA	Natural aggregate
P	load
RAP	Reclaimed Asphalt Pavement
RPM	Asphalt layer mixed with the underlying base layer
SP-CS	Soil with Stony Sand and Clay
SS-1H	Anionic asphalt emulsion
SRL	Literature review
UCS	Unconfined compressive strength
Ec	compressive deformations
Et	tensile stresses

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