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Influence of Curing Time on the Mechanical Behavior of Cold Recycled Bituminous Mix in Flexible Pavement Base Layer

Lisley Madeira Coelho [1,*,†], Rafael Pereira Kox [1,†], Antônio Carlos Rodrigues Guimarães [1], Rafael Travincas [2] and Sergio Neves Monteiro [2]

[1] Department of Fortification and Construction, Military Institute of Engineering-IME, Praça General Tibúrcio, 80, Urca, Rio de Janeiro 22290-270, Brazil; rafaelkox@gmail.com (R.P.K.); guimaraes@ime.eb.br (A.C.R.G.)
[2] Department of Materials Science, Military Institute of Engineering-IME, Praça General Tibúrcio, 80, Urca, Rio de Janeiro 22290-270, Brazil; rafael.travincas@ime.eb.br (R.T.); snevesmonteiro@gmail.com (S.N.M.)
* Correspondence: madeiralisley@gmail.com
† These authors contributed equally to this work.

Abstract: This study examined the mechanical behavior characteristics of cold recycled emulsified asphalt bases with RAP 76% and emulsified asphalt 3%, in different cure time, i.e., 0, 7, 14 and 28 days and evaluated in terms of the resilient modulus (RM) and permanent deformation (PD) based on repeated load triaxial tests. The results demonstrated that in the first 7 days, the RM increased by 80% compared to the freshly compacted material and after this period, the subsequent increases were not as significant, ranging, from 10.9% to 19.4%, that shows that initical cure time significantly influences the RM behavior of the mixtures. However, the mixtures showed considerable permanent deformations, even after 28 days of curing. This indicates that the use of asphalt emulsion, with prolonged curing, improves the mechanical properties of the mixture but does not entirely resolve the issue of permanent deformation in cold reclaimed asphalt mixture (CRAM). The plastic deformation behavior observed in the triaxial tests must be taken into account when designing pavements containing RAP and asphalt emulsion.

Keywords: cold reclaimed asphalt mixture (CRAM); base layer; curing time; triaxial repeated load tests

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1. Introduction

The present concern about using natural resources has been relevant in developing new, more sustainable road pavement projects. A sustainable pavement reduces the environmental impact during its construction [1]. One possible approach is incorporating residual materials into the composition of asphalt pavements. This reduces the exploitation of natural resources and decreases the amount of discarded waste [2].

Various studies have investigated the use of alternative waste materials in construction both in Brazil and internationally. Fly ash has been studied for its benefits in construction applications [3,4]. Iron ore residues are another material under exploration [5,6], as are various slags, which have been evaluated for their properties and potential uses [7–11]. Calcined clay has also been examined for its suitability in construction [12,13]. Construction and demolition waste (CDW) has been shown to have significant potential [14,15], while ground tire rubber has been studied for its performance characteristics [16–18]. Additionally, reclaimed asphalt pavement (RAP) is frequently cited in research for its application in pavement materials [19–23], as also, aspects related to rejuvenation agents are also frequently mentioned when discussing RAP [24–27]. These materials are commonly investigated for their potential to improve and performance in sustainability construction practices.

However, it is crucial that these waste materials provide the layers with adequate mechanical behavior to withstand the traffic loads they will be subjected to. Therefore, the total or partial replacement of virgin aggregates with waste materials is evaluated both in the laboratory and in the field through experimental sections. Using the Brazilian mechanistic-empirical method for flexible pavements, which employs the MeDiNa software for computational analysis, the performance of granular materials is primarily assessed through resilient modulus (RM) and permanent deformation (PD) tests in dynamic triaxial tests. These tests apply mathematical models to estimate their behavior [28].

Specifically for the use RAP in base layers, stabilization with asphalt emulsions in cold-mix asphalt plants has been preferentially adopted. However, many of the mechanical behavior analyses of these materials have been conducted using typical tests for hot-mix asphalt mixtures. Some cases of failure have already been reported, with plastic deformation observed in these layers shortly after the release of vehicle traffic. This was observed during a technical inspection carried out on a stretch of the Fernão Dias highway (BR-381 highway), in the interior of São Paulo/Brazil, where the samples used in this study were collected.

Cold recycled asphalt mixtures (CRAMs) typically consist of RAP, virgin aggregates (for gradation adjustment), stabilized with bituminous binder (asphalt emulsion or foamed asphalt), and active filler such as ordinary Portland cement (OPC) or hydrated lime. Despite the use of asphalt and active filler, which increase the mixture's cohesion and stiffness, CRAMs are generally used as base layers due to their low abrasion resistance under heavy traffic loads, especially during the initial curing period. Therefore, a hot mix asphalt layer is usually placed on top of the CRAM [29].

The mechanical behavior of CRAMs is a topic of debate, with some studies considering them as unbound granular materials with higher cohesion [30,31], while others suggest that exhibit characteristics similar to asphalt mixtures with viscoelastic properties [32–34]. For exemple, Meocci et al. [35] pecimens were produced by means of a gyratory compactor (GC) or produced by marshall compactador [36], evaluated by indirect tensile strength (ITS) test [37], and for indirect tensile stiffness modulus (ITSM) test [38]. Unger [39] also evaluated a cold recycled asphalt mixture using 100% RAP with asphalt recycling emulsifying agent as a new pavement base layer, using similar evaluation methods. In contrast, Bessa et al. [40], Allah et al. [41] and Kuchiishi et al. [42], molded the specimens with modified Proctor (resulting in lower specimen compaction) and tested them using a triaxial configuration.

In general, the use of RAP as a base layer material is a sustainable rehabilitation technique that reduces costs. However, accurately characterizing its behavior is essential for ensuring its effectiveness. The performance of RAP depends on several factors, including the stress within the pavement layer structure [41,43] and the intrinsic properties of RAP, such as binder content, specific gravity, and parent rock [44]. These factors significantly affect the mixture's performance in terms of resilient modulus (RM) and permanent deformation (PD) test results, which in turn impacts the overall accuracy of pavement response predictions. Additionally, variability in mechanical properties can arise from factors such as particle size distribution, type of RAP, compaction method, type and content of active filler, and bitumen stabilizing agent [2,39,45–48].

Furthermore, Unger Filho et al. [39] observed that curing time, curing temperature and compaction in CRAMs with emulsified asphalt recycling agent do not follow a standardized protocol; therefore, it is difficult to carry out a more in-depth comparative analysis. This lack of standardization reinforces the need to understand the behaviour of these mixtures. In this context, Coelho et al. [23] concluded that the resilient modulus and PD based on repeated load triaxial tests can be considered predictive methods for the behavior of milled material in base layers. These tests provided initial data for interpreting the behavior of emulsified treated base, offering a potential solution to the challenges highlighted by Unger Filho et al. [39]. In addition, Medeiros et al. [49] also highlighted the importance of using repeated load triaxial tests to evaluate the mechanical behavior of emulsion-stabilized soil in real-world scenarios.

Despite the potential of CRAMs, there is still a significant gap in understanding how different curing times affect their mechanical behavior in repeated load triaxial tests. Most existing research still focuses on analysis in specific laboratory conditions and through specific tests of asphalt mixtures, which may not adequately reflect performance in real traffic conditions. Therefore, it is crucial to investigate the influence of curing times on the mechanical properties of CRAMs, especially with regard to resilience modulus and permanent deformation in repeated load triaxial tests, in order to guarantee adequate and long-lasting performance in paving base layers.

Therefore, the aim of this study is to evaluate the influence of different curing times on the behavior of CRAMs through resilient modulus (RM) and permanent deformation (PD) tests, in both repeated load triaxial tests, for application base layer.

2. Materials and Methods

Due to reports during a technical inspection carried out on a stretch of the Fernão Dias highway (BR-381), in the interior of São Paulo/Brazil, of plastic deformation occurring shortly after the release of traffic, in cold recycled asphalt mixtures in the base layer, a total of 500 kg of Cold Reclaimed Asphalt Pavement (CRAM), mixed in a cold pre-mix plant, was collected from a stretch of the base layer of the Fernão Dias highway, before it was applied to the pavement. The material was stored in plastic bags in the laboratory and kept at room temperature until the tests were carried out. Although the exact time between collection in the field and storage in the laboratory is not known, it is estimated to have been approximately 30 days.

2.1. Materials Characterizatian

The material used to produce the CRAM consisted of milled asphalt from the BR-381 highway. The stone dust was supplied and characterized by Arteris. The CP-II-F-32 cement and RL-1C asphalt emulsion were supplied and characterized by Stratura Asfaltos. Additive like 1% to 2% cement helps form a homogeneous mix [50]. The cement content below 1% is ineffective in early strength gain, and excess cement beyond 2.5% results in brittle nature in the mixes [40,50]. Hence, 1% of Ordinary Portland cement (OPC) was adopted to prepare the samples. In general, a value of 2 or 3% of asphalt emulsion has provided the best results for the different materials and gradations evaluated [2,39,51], Hence, 3% the emulsion was adopted to prepare the samples. The particle size composition of the CRAM was determined according to the standards of the Asphalt Academy [52] and the Southern African Bitumen Association (SABITA) [53], which provide guidelines on the particle size ranges for bitumen-stabilized bases. Figure 1 shows the visual aspect of the studied mixture. The CRAM composition used the following percentages: 76% RAP, 23% stone dust, 1% cement and 3% emulsion.

Figure 1. The visual aspect of the studied mixture.

Figure 2 presents the granulometric curve of the mixture, the individual curves of the materials, and the granulometric limits established by the Asphalt Academy [52] and

Sabita [53]. Stone dust was used in the composition to adjust the mixture's gradation. Table 1 shows the results of the characterization tests and the methodologies applied.

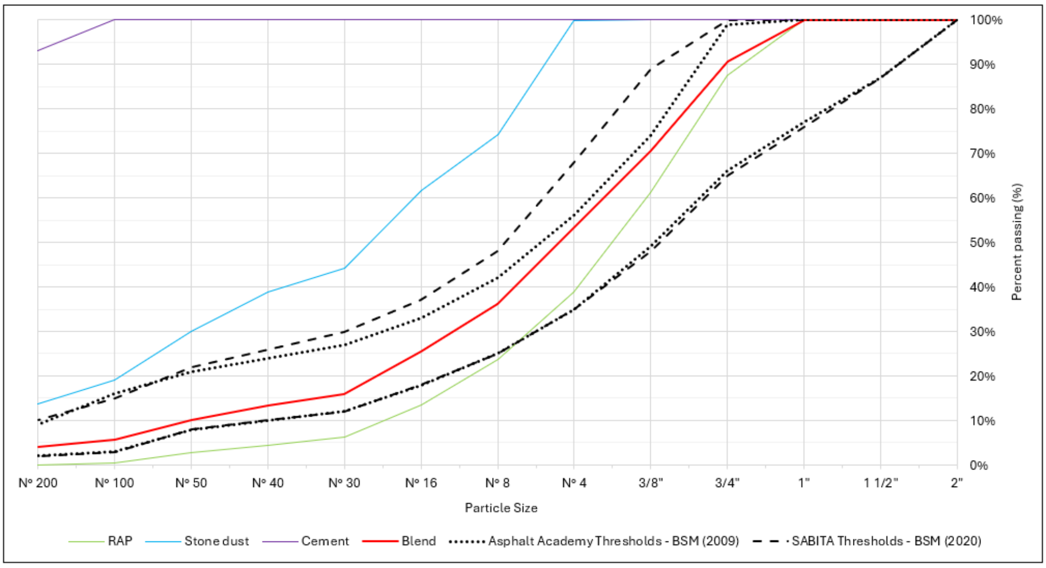

Figure 2. Granulometric curve of the mixture, the individual curves of the materials, and the granulometric limits established by the Asphalt Academy [52] and Sabita [53].

Table 1. Characterization of the stone powder used in the mixture.

Test	Brazilian Standard	Result	Unit
Methylene Blue	NBR 10235 [54]	1.5	mg/g
Sand Equivalent	NBR 12052 [55]	57.3	%
Water Absorption	NBR NM 30 [56]	0.1	%
Real Dry Specific Gravity	NBR NM 52 [57]	2.683	cm^3
Apparent Specific Gravity	NBR NM 52 [57]	2.679	cm^3

The analysis of Figure 2 highlights the importance of including stone dust and cement in adjusting the gradation of the mix, addressing the deficiency of fines in the RAP. Additionally, Table 2 presents the characterization results of the asphalt emulsion used in the study. As detailed in Table 2, the RL-1C type emulsion meets the specified normative limits.

Table 2. Characterization of the emulsion.

Test	Brazilian Standard	Unit	Specified	Result
Saybolt Furol Viscosity, 25 °C	NBR 14491 [58]	Seconds	Max. 70	21
Sedimentation, 5 days	NBR 6570 [59]	% mass	Max. 5.0	0.4
Sieve, 0.84 mm	NBR 14393 [60]	% mass	Max. 0.1	0
Particle Charge	NBR 6567 [61]	-	Positive	Positive
Dry Residue	NBR 14376 [62]	% mass	Min. 60	61
pH	NBR 6299 [63]	-	Max. 6.5	3.32

The CRAM compaction was performed in a tripartite cylindrical mold with a diameter of 100 mm and a height of 200 mm. Ten layers of 2 cm each were compacted, with 21 blows each, using modified compaction energy according to the DNIT [64] brazilian standard [64] to define the optimal water content to be added to the mixture. Table 3 presents the results of density and optimal moisture content.

Table 3. Proctor compaction test results.

Water Content (%)	1	3	5	7	9
Wet Density (g/cm^3)	1.59	1.97	2.05	2.08	2.06
Converted Density (g/cm^3)	1.84	1.91	1.95	1.94	1.89
Optimum Water Content (%)	5.6				
Maximum Dry Density (g/cm^3)	1.95				

According to the literature, the density values of CRAMs typically range between 1.8 g/cm^3 and 2.25 g/cm^3 [2,39,46]. This variation depends on the emulsion content, RAP content, amount of natural aggregate, and type of compaction. In this study, the density of CRAM was 1.95 g/cm^3, a value similar to the findings of Chakravarthi et al. [46] (1.8 g/cm^3 to 1.9 g/cm^3 in CRAMs containing 75% RAP). On the other hand, it differs from the results of Andrews et al. [2], who found slightly higher densities (2.20 g/cm^3, in samples with 75% RAP).

After establishing the design curve and determining the optimal moisture content for mixture, the specimens were compacted for the modulus of elasticity and permanent deformation tests in repeated load triaxial tests. The curing of the specimens was conducted outdoors at an average room temperature of 25 °C to simulate real-world conditions (see Figure 3) and were subjected to curing at the following time intervals:

- The curing times for the resilient modulus (RM) test were 0, 7, 14, and 28 days after compaction.
- For the permanent deformation (PD) test, the curing times were 0 days (0D) and 28 days (28D) after compaction.

Figure 3. CRAM sample in curing environment.

2.2. *Mechanical Analysis*

2.2.1. Resilient Modulus

After the storage period described in item 2, the compacted CRAM was subjected to the RM test. The test was conducted according to the standard test method of the DNIT 134 brazilian standard [65], using a dynamic triaxial testing machine (Owntec-MS-151). During the RM test, eighteen pairs of confining stresses (σ_3) and deviatoric stress (σ_d) were applied after the conditioning phase of the specimen. The load cycle lasted 1 s, with 0.1 s of load application and a frequency of 1 Hz. In the conditioning stage, the specimens were exposed to three sets of stresses and subjected to 500 load cycles for each set. Subsequently, they were subjected to 18 additional sets of stresses, with 100 load cycles for each set, totaling 3300 cycles per test. The applied stress values are presented in Table 4. Figure 4 shows the specimen molded inside the tripartite mold and in the dynamic triaxial equipment.

Table 4. Stress pairs for the resilient modulus test.

Conditioning Phase			
Par	σ_3 (KPa)	σ_d (KPa)	σ_3/σ_1
1	70	70	2
2	70	210	4
3	105	315	4
Loading Phase			
Par	σ_3 (KPa)	σ_d (KPa)	σ_3/σ_1
1		20	2
2	20	40	3
3		60	4
4		35	2
5	35	70	3
6		105	4
7		50	3
8	50	100	2
9		150	3
10		70	2
11	70	140	3
12		210	4
13		105	2
14	105	210	3
15		315	4
16		140	2
17	140	280	3
18		420	4

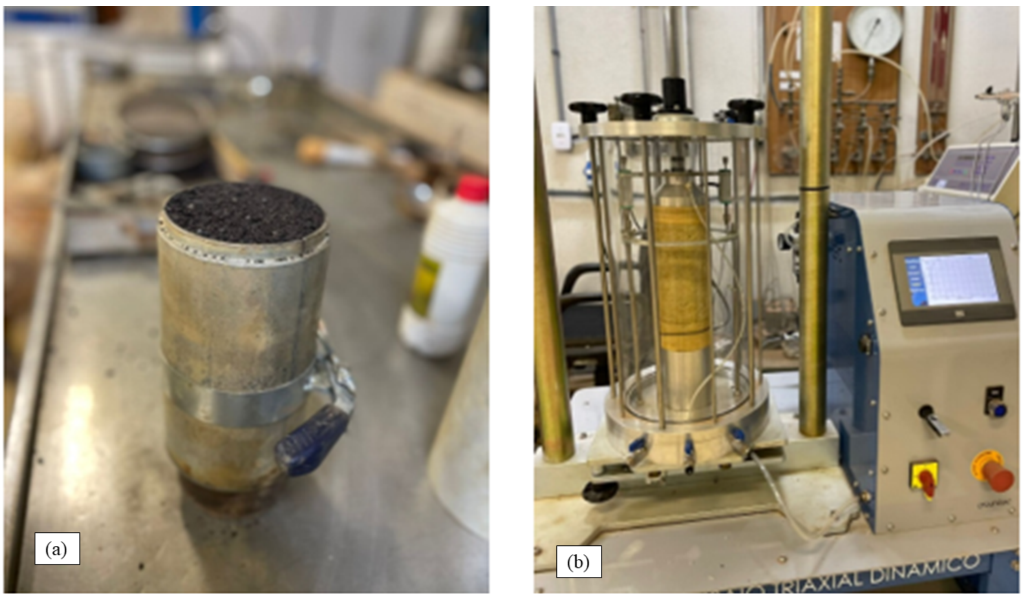

Figure 4. RM test. (**a**) The specimen molded inside the tripartite mold. (**b**) dynamic triaxial equipment.

RM is obtained from the results of the repeated load triaxial tests. It is defined as the ratio between the deviatoric stress (σ_d) and the resilient axial strain (Δr), as presented in Equation (1).

$$MR = \frac{\sigma_d}{\Delta r} \quad (1)$$

where:

- Δr: is the ratio of Δh to h_0. Δh is the maximum vertical displacement, and h_0 is the initial reference length of the cylindrical specimen.

For the results, the average of two specimens for each curing time was considered and analyzed using the MRCalc tool of the Systrain software. The aim was to determine the most appropriate model for the mixture's behavior during the triaxial test. The evaluation was based on the coefficient of determination to identify the model with the best fit to the experimental data.

2.2.2. Permanent Deformation (PD)

The DNIT regulates and describes the PD test of soils and granular materials using repeated load triaxial equipment, as established by the Brazilian standard DNIT 179 [66]. This test consists of applying many repeated load cycles to evaluate each specimen's behavior under different stress states. As previously described, the molding of the specimens for the PD test follows the same characteristics as the resilient modulus test and complies with the Brazilian standard DNIT 443 [64].

In Brazil, the model proposed by Guimarães [28] is used to predict the permanent deformation behavior of pavement materials. This model employs the results of the permanent deformation test in the repeated load triaxial equipment and uses multiple nonlinear regression techniques to determine its parameters. Although the Brazilian standard DNIT 179 [66] requires nine pairs of stresses to calculate these parameters, studies such as Lima et al. [67] highlight the feasibility of using at least six pairs. In the permanent deformation test of this research, each specimen was loaded with a previously established pair of stresses and subjected to 150,000 load repetitions in one cycle, considering a total of 6 pairs of stresses at an application frequency of 5 Hz. The pairs of stresses used in this study are detailed in Table 5.

Table 5. Selected stress pairs for the permanent deformation test.

Stress Pair	σ_3 (MPa)	σ_d (MPa)
1	0.04	0.12
2	0.08	0.08
3	0.08	0.16
4	0.08	0.24
5	0.12	0.12
6	0.12	0.24

The results were evaluated according to the Shakedown theory [28,68,69]. The Shakedown concept has been used to describe the behavior of many structures in engineering under cyclic or repeated loading. Therefore, according to the Shakedown Theory, there is a critical stress that separates stable from unstable conditions. It encompasses the concept that the growth of PD stabilizes gradually with the number of loading cycles only when the applied stress is low and that at high-stress levels, PD is likely to increase rapidly, resulting in progressive failure [70].

For the evaluation of accommodation, behavior levels are classified as Type A, B, C, or AB, improved in road pavement by Dawson and Wellner [68], Werkmeister [69], and also discussed by Motta and Guimarães [28]:

(A) Shakedown or Plastic Accommodation: In this behavior level, the material exhibits plastic deformations during a finite number of applications of the stress pair and, after the post-compaction period, responds entirely elastically. From this transition, where the material responds only elastically to the applied stresses, it is said that the material has entered shakedown.

(B) Intermediate Response Level: The material's behavior at this level shows high deformation during the first load cycles and, over the applications, tends to reduce its deformation and assume a more uniform rate. The number of cycles needed for the material to assume a constant deformation rate depends on the material's mechanical characteristics and the load application amplitude.

(C) Collapse: This is the level at which the response to load application is always plastic. The material deforms considerably with each applied load cycle, with no tendency for stabilization.

(AB) Shows significant initial deformations followed by plastic accommodation and was detected by Guimarães and Motta [28] for fine Brazilian soils.

The analysis of these behavior models can be observed in Figure 5.

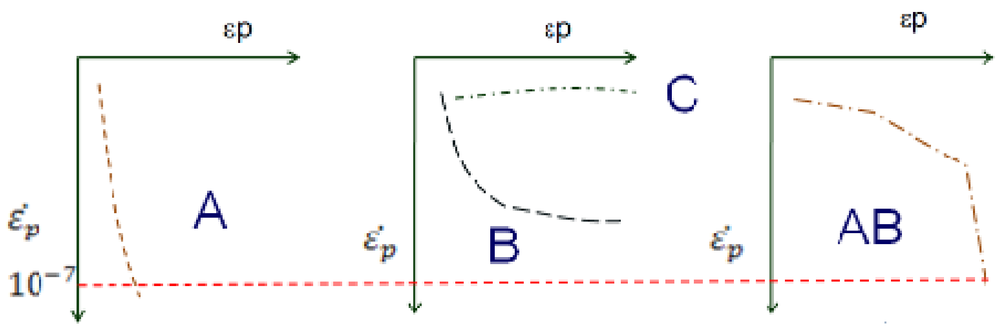

Figure 5. Diagram identifying the three levels of behavior in shakedown research (Adapted from DNIT 179) [66].

3. Results and Discussion

Resilient Modulus

Table 6, presents the average (3 replicates) RM data for the CRAM at each curing time the percentages in parentheses indicate the variation in results between the different curing times (7 days compared to 0 days, 14 days compared to 7 days, and 28 days compared to 14 days). This comparison highlights the progression of properties over time, providing a clearer understanding of the curing effects on the material. Especially in the final test sequences where the applied confining and deviator stresses are higher, this the material is dependent on the tension state.

It was observed that after a 7 day curing period, the stiffness of the cold-recycled mixtures increased by a minimum of 67.2% and a maximum of 92.7%, indicating that within the first seven days post-compaction, the material undergoes a substantial change in its resilient behavior.

This significant increase in stiffness after the initial curing can be attributed to hydration and stabilization processes, as observed in other studies. For instance, Brown and Needham [71] reported a significant increase in stiffness after adding cement to any asphalt emulsion, and Betti et al. [72] observed similar effects in foam-stabilized asphalt mixtures. These results underscore the importance of initial curing in developing the mechanical properties of cold-recycled mixtures.

Even though 1% cement was not used as a stabilizing agent in the mixture, it played a crucial role in enhancing the load-bearing capacity of CRAM during its initial stages. The using cement as an active filler accelerates the breakdown of the emulsion [72]. The hydration of cement compounds produces calcium silicate hydrate ($C_3S_2H_3$) and calcium hydroxide ($Ca(OH)_2$). The partially soluble calcium hydroxide then ionizes, producing calcium ions (Ca^{2+}) and hydroxide ions (OH^-). When using cationic asphalt emulsion, the negatively charged hydroxides surround the positively charged cationic asphalt droplets, neutralizing the emulsifying agent [73]. This process accelerates the coalescence of asphalt droplets and, consequently, the breakdown of the emulsion.

Table 6. Results obtained in RM tests by curing time.

Sequence	σ_3	σ_d	RM (MPa) (%)			
			0 Days	7 Days	14 Days	28 Days
1	0.02	0.022	115	213 (+85.8%)	210 (−1.4%)	225 (+7.1%)
2	0.02	0.042	122	217 (+77.8%)	233 (+7.4%)	231 (−0.9%)
3	0.02	0.062	131	245 (+87.1%)	247 (+0.8%)	255 (+3.2%)
4	0.035	0.037	175	293 (+67.2%)	336 (+14.7%)	390 (+16.1%)
5	0.035	0.072	188	345 (+83.6%)	385 (+11.6%)	416 (+8.1%)
6	0.035	0.107	199	371 (+86.7%)	392 (+5.7%)	428 (+9.2%)
7	0.05	0.052	226	411 (+81.7%)	479 (+16.5%)	532 (+11.1%)
8	0.05	0.103	242	447 (+84.3%)	502 (+12.3%)	651 (+29.7%)
9	0.05	0.153	251	483 (+92.7%)	521 (+7.9%)	659 (+26.5%)
10	0.07	0.073	278	493 (+77.2%)	628 (+27.4%)	818 (+30.3%)
11	0.069	0.143	293	527 (+79.9%)	603 (+14.4%)	837 (+38.8%)
12	0.069	0.213	305	554 (+81.4%)	620 (+11.9%)	772 (+24.5%)
13	0.105	0.108	377	646 (+71.3%)	798 (+23.5%)	894 (+12.0%)
14	0.105	0.213	386	715 (+85.2%)	753 (+5.3%)	936 (+24.3%)
15	0.105	0.319	398	713 (+79.2%)	792 (+11.1%)	915 (+15.5%)
16	0.14	0.144	448	779 (+73.9%)	845 (+8.5%)	1029 (+21.8%)
17	0.14	0.284	464	826 (+77.9%)	898 (+8.7%)	1029 (+14.6%)
18	0.14	0.424	464	825 (+77.8%)	862 (+4.5%)	1042 (+20.9%)

The composite model was adopted in this study due to its adequate coefficient of determination and simplicity, as shown in Equation (2). Additionally, this model was chosen because it is the one incorporated in the Brazilian mechanistic-empirical pavement design method (MeDiNa) for characterizationrelated to the stiffness of subgrade soils and granularmaterials [67,74–77]. For the Compound model, coefficient k_2 referring to theconfining stress action has higher impact on the RM value tothe detriment of coefficient k_3 related to the deviator stress. However, the fact that the coefficient k_3 has a positive valueindicates that, by increasing the deviator stress, an increasein the resilient modulus occurs.

$$RM = k_1 \cdot \sigma_3^{k_2} \cdot \sigma_d^{k_3} \quad (2)$$

The regression parameters are presented in Table 7 with thevalues of the coefficient of determination (R^2) and the value of the linear resilient modulus, for each curing time, that is, the average of theRM values obtained at each stress pair after performingthe mathematical modeling. Furthermore, Figure 6 shows the mixture's resilient behavior as a function of curing time, deviator stress, and confining stress applied during the tests.

The influence of curing time after 7 days is also reflected in the average RM presented in Table 7, where, within the first 7 days, the parameter showed an 80% increase compared to the material tested immediately after compaction. Although RM increased in the subsequent tests after the initial 7-day curing period, the increases were not significant, ranging from 10.9% to 19.4% compared to the previous curing time.

Table 7. Composite Model Parameters.

Curing Time	k_1	k_2	k_3	RM Medium (MPa)	R^2
0	1531.6	0.56	0.08	281	0.996
7	2752.46	0.56	0.08	506 (+80.1%)	0.992
14	2825.28	0.56	0.04	561 (+10.9%)	0.974
28	3743.49	0.60	0.04	670 (+19.4%)	0.935

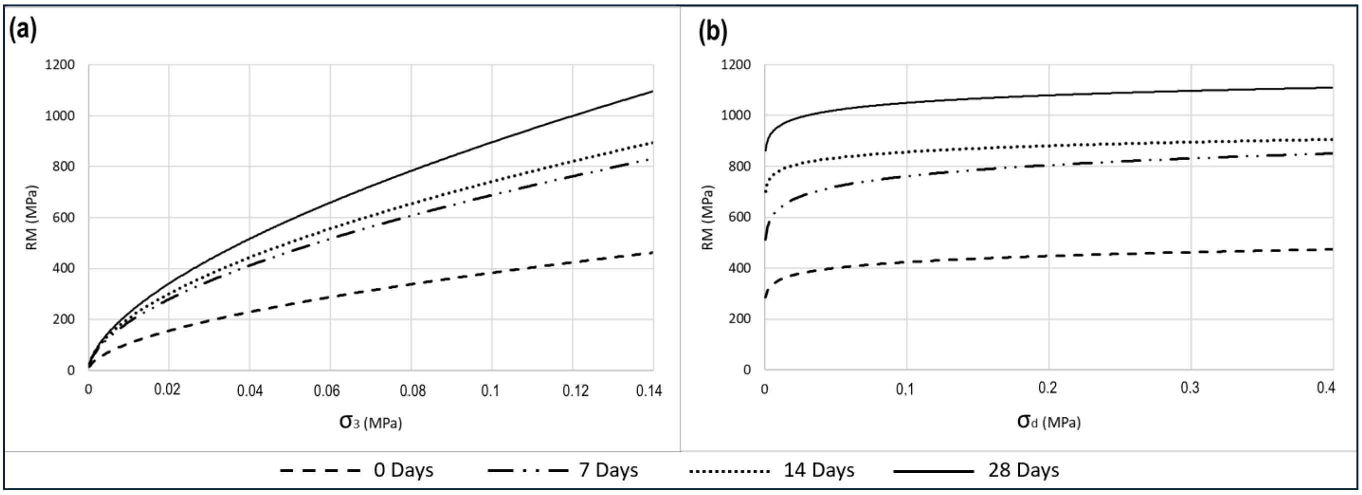

Figure 6. Resilient modulus vs. stress graph. (**a**) Constant σ_d stress and variable σ_3 stress; (**b**) Constant σ_3 stress and variable σ_d stress.

These findings suggest that a curing time of 7 days can provide satisfactory RM behavior for use in base layers, aligning well with practical design conditions. Despite the continued increase in resistance with longer curing periods, the modulus values determined in the present study are consistent with the typical range of values for granular materials reported by Bernucci et al. [78] (100 to 400 MPa) and the range proposed by Balbo [79] (200 to 350 MPa) and RM values similar to the lateritegravel from the state of Acre, Brazil (566 to 585 MPa) [80]. This further supports the adequacy of a 7-day curing period for achieving appropriate resilience characteristics in base layer applications.

Figure 7 presents the mixture's resilient behavior from a three-dimensional perspective. The material is more susceptible to variations due to confining stress, while the RM varies little due to deviatoric stress.

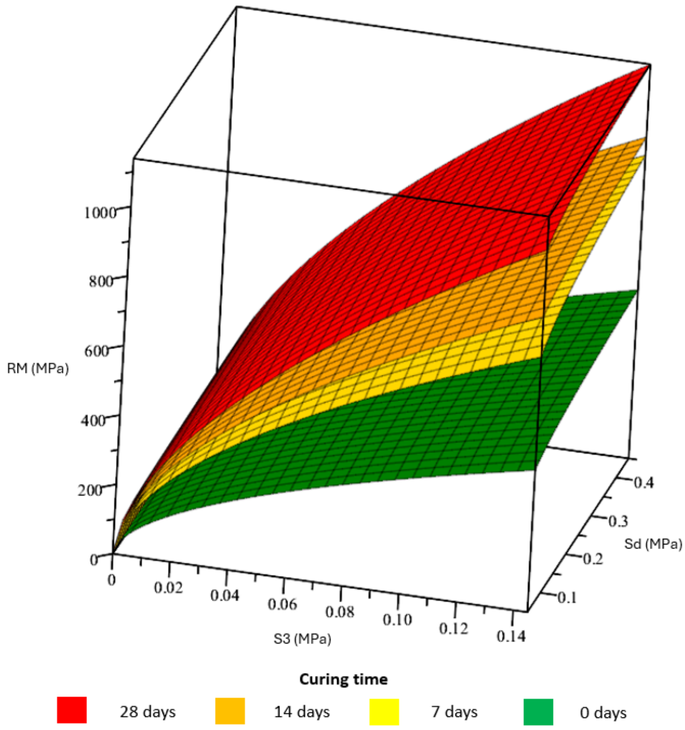

Figure 7. 3D graph of the resilient behavior of CRAM as a function of curing time conditions, deviator stress, and confining stress applied during the tests.

This behavior can be compared with the results presented in the study by Guatimosim et al. [31], who observed that a mixture composed of RAP treated with crushed cement, foam asphalt, and 1% hydrated lime resembled a granular material, as its stiffness depended on the stress state. Similarly, Kuchiishi et al. [42] found that mixtures without adding cement also showed dependence on confining stresses.

On the other hand, other researchers who concluded that the addition of 1% to 2% cement in CRAMs stabilized with asphalt emulsion produced a mixture independent of the stress state, as a single modulus value was obtained from triaxial resilient modulus tests at different confining pressures. The lesser dependence on the stress state in these mixtures is attributed to the hydration reaction of Portland cement [40,42,81].

4. Permanent Deformation (PD)

Figure 8 illustrates the behavior of the studied material concerning PD, comparing the results obtained in specimens with 0 and 28 days of curing.

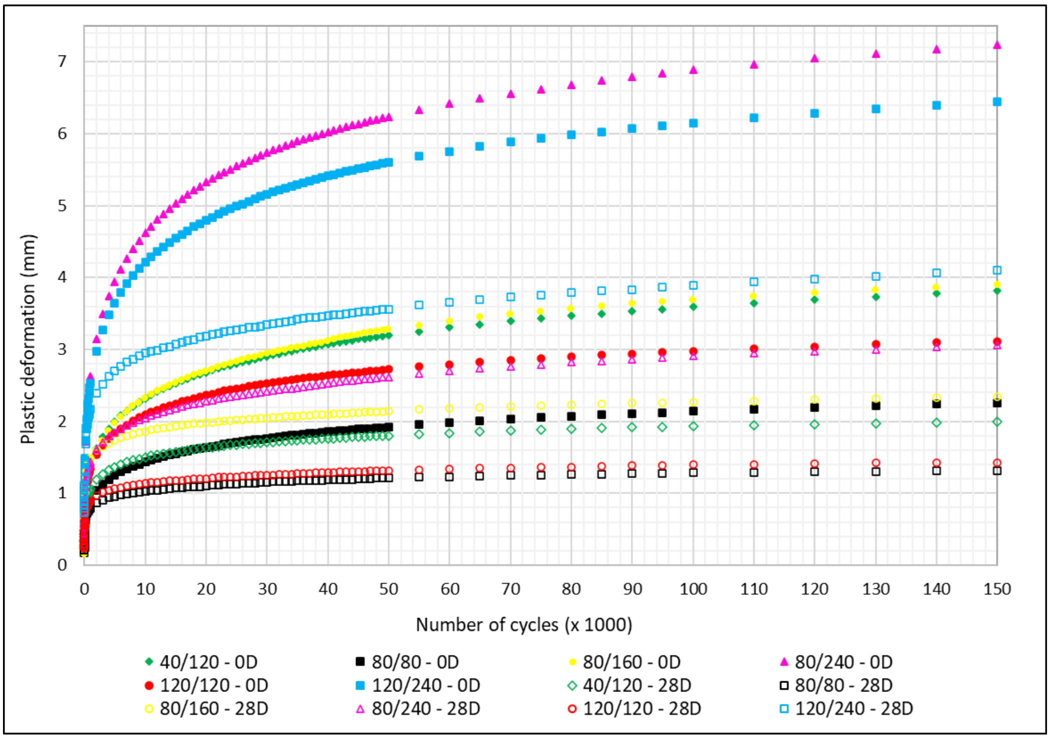

Figure 8. Accumulated permanent deformation at 0D and 28D of curing.

For mixtures with 0 days of curing the highest permanent deformationsrecorded were observed in tests whose stress pairs are 120/240 kPa and 80/240 kPa, confining versus deviator, respectively, reaching values close to 7 mm at the endof the tests.

The pair 80/160 kPa presented considerably smaller deformations than the pairs 120/240 kPa and 80/240 kPa. The smallest deformations were foundin the 80/80 kPa e 120/120 kPa tests.

The variations in PD increase with the rise in deviator stress and the growth of the $\sigma d/\sigma 3$ ratio (KPa/KPa). It is also evident that PD decreases with increasing confining stress and that the higher the $\sigma d/\sigma 3$ ratio, the greater the permanent deformation. This behavior indicatesthat the permanent deformations magnitude is related tothe ratio among $\sigma d/\sigma 3$ in a directly proportional relation.

The mixtures with 28 days of curing also the highest permanent deformationsrecorded were observed in tests whose stress pairs are 120/240 kPa and 80/240 ($\sigma d/\sigma 3$, KPa/KPa). however, reaching values close to 4 mm at the endof the tests, i.e., there was a reduction of up to 3 mm in the PD behavior after 28 days of curing.

Moreover, it can be observed that in some instances, mixtures with 0 days of curing accumulate deformations close to those at 28 days of curing, but for different $\sigma d/\sigma 3$ ratios, with a $\sigma d/\sigma 3$ ratio of 1 for 0 days and a $\sigma d/\sigma 3$ ratio of 2 for 28 days, in the stress pairs 120/120 ($\sigma d/\sigma 3$, KPa/KPa) and 80/240 ($\sigma d/\sigma 3$, KPa/KPa), respectively. However, none of the tests conducted with 0 days of curing showed a lower deformation rate than the samples with 28 days.

Observing the increase rate graph in PD by thecumulative vertical deformation it can be seenthat all of them tests to type B behavior accordingto the parameters of Dawson and Wellner [68] and Werkmeister [69]. The mixtures with 28 days of curing, the 80/80 kPa and 120/120 KPa pair reached the accommodation (behavior A), as it possible to see in Figure 9b, for the a $\sigma d/\sigma 3$ ratio of 1. The other pairs present behavior B.

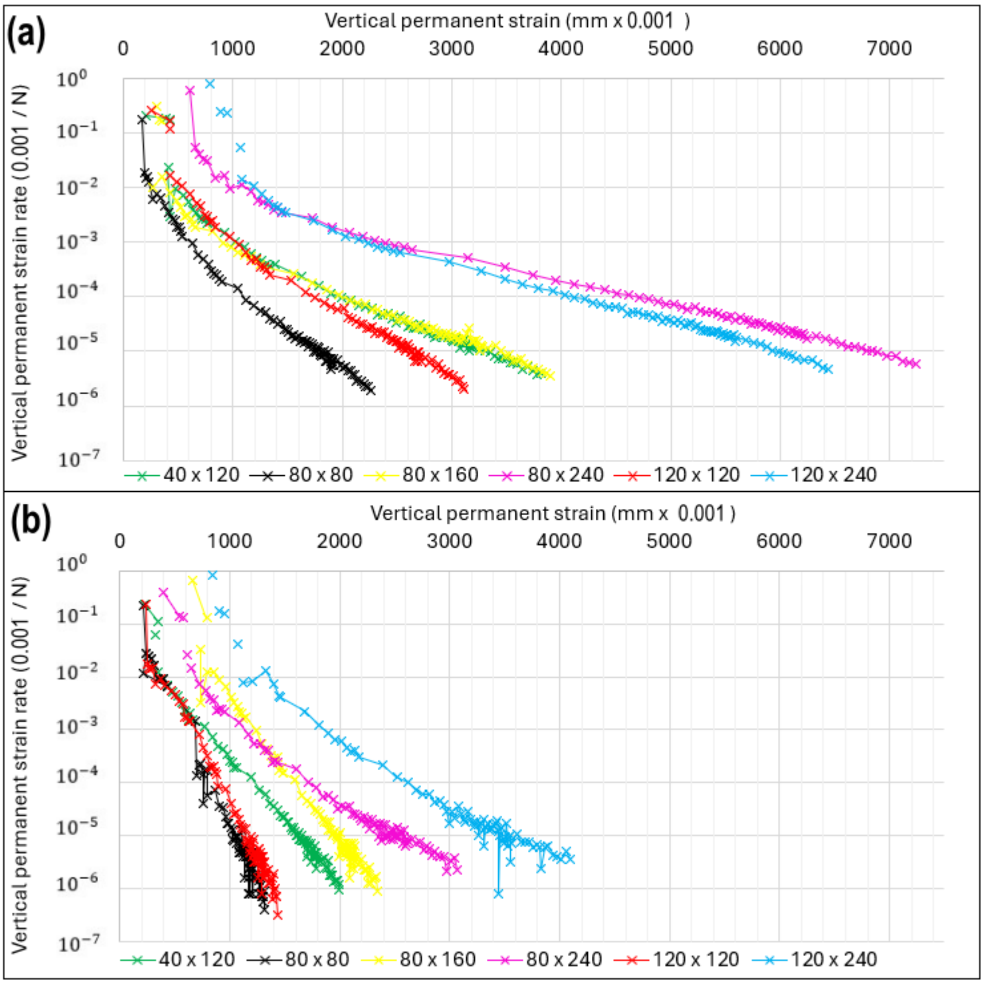

Figure 9. Permanent strain rate per accumulated strain. (**a**) Tests with 0-day curing time. (**b**) Tests with 28-day curing time.

However, some stress combinations show intermediate behavior, such as the stress pairs 40/120 ($\sigma d/\sigma 3$, KPa/KPa) and 80/160 ($\sigma d/\sigma 3$, KPa/KPa) at 28 days, with a gradual reduction in the deformation rate over the tests. On the other hand, samples with $\sigma d/\sigma 3$ ratios of 2 and 3, in the stress pairs 120/240 ($\sigma d/\sigma 3$, KPa/KPa) and 80/240 ($\sigma d/\sigma 3$, KPa/KPa), respectively, resulted in high permanent deformation rates at the end of the tests. This suggests that the material may not have reached stability, only a tendency towards accommodation [82], after 150,000 cycles, due to the rate of increase reaching values of 1×10^{-6} to 1×10^{-7} mm per cycle.

In practice, mixtures of RAP mixed with natural aggregates can be acceptable for use in the base of a pavement, provided that the accumulated deformation remains minimal (see the lower curves in Figure 8), as also corroborated by the studies of [41], who analyzed samples with 60% RAP and 40% VA). However, higher and non-stabilized deformation behaviors (such as the upper curves in Figure 8) suggest that the material may be subject to excessive stresses for this specific application, being more suitable for use in lower pavement layers where stresses are lower.

Furthermore, even though other studies consider curing times beyond 28 days [39,83], suggesting an analysis of the mixture behavior over curing periods longer than 28 days to determine if it will reach an increment rate of 10^{-7} mm or higher would not be trivial in terms of practical applicability in road infrastructure. Extending the curing time to improve the material's mechanical behavior may be impractical, as the execution process, the need for compaction of the upper layers, and rapid traffic release could be prohibitive for more extended periods.

In general, the behavior of RAP mixtures in unbound layers (base and sub-base layers) is an area that needs to be investigated, mainly through repeated load triaxial tests [23], as these mixtures remain susceptible to permanent deformation.

5. Conclusions

This study aimed to evaluate the influence of curing time on mixtures containing RAP, stabilized with emulsion and cement in the base layers of flexible pavements, yielding the following conclusions:

- A minimum curing time of 7 days was required to achieve typical RM values for granular materials used in base courses. With values between 500 and 600 MPa. Indicating good behavior in terms of resilience modulus. The RM increased 80% increase compared to the material tested immediately after compaction.
- The samples were more susceptible to permanent deformation when subjected to the repeated load triaxial test. Although the 28-day curing reduced the material's total PD by up to 58%, the material still showed high accumulated deformation at the end of the 150,000 cycles of the tests. None of the tests showed a plastic deformation rate below 10^{-7}, but they exhibited a tendency towards accommodation after 150,000 cycles. This indicates that even after 28 days of curing, the emulsion was unable to completely stabilize the mixture.
- The plastic deformation behavior observed in the triaxial tests must be taken into account when designing pavements containing RAP and asphalt emulsion. In addition, the analysis of this material in the repeated load triaxial test explains the premature deformations observed during the technical inspection mentioned in this study.

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References

1. Bonfim, V. *Sustainable Pavement*, 1st ed.; Exceção Editorial e Eventos: São Paulo, Brazil, 2020.
2. Andrews, J.; Radhakrishnan, V.; Koshy, R. Laboratory Evaluation of Emulsion-Treated Base Layer Mixes Incorporating Reclaimed Asphalt Pavement Materials. *J. Mater. Civ. Eng.* **2023**, *35*, 04023198. [CrossRef]
3. Renjith, R.; Robert, D.; Setunge, S.; Costa, S.; Mohajerani, A. Optimization of fly ash based soil stabilization using secondary admixtures for sustainable road construction. *J. Clean. Prod.* **2021**, *294*, 126264. [CrossRef]
4. Silveira, V.; Guimarães, A.; Castro, C. Study of the application of coke boiler ash in base and sub-base layers of pavements. *Transportes* **2019**, *27*, 194–208. [CrossRef]
5. Apaza, F.R.; Guimarães, A.C.R.; Sousa, M.A.d.S.; Castro, C.D. Study on the use of Iron Ore Residue in microsurfacing. *Transportes* **2018**, *26*, 118–138. [CrossRef]
6. Silveira, V.; Guimarães, A.; Coelho, L.; dos Santos, W.; da Silveira, P.; Monteiro, S. Recycling Iron Ore Waste through Low-Cost Paving Techniques. *Sustainability* **2024**, *16*, 5570. [CrossRef]
7. Yu, H.; Zhu, X.; Qian, G.; Gong, X.; Nie, X. Evaluation of phosphorus slag (PS) content and particle size on the performance modification effect of asphalt. *Constr. Build. Mater.* **2020**, *256*, 119334. [CrossRef]
8. Bona, A.; Silveira, V.; Guimarães, A.; Silva, C. Study on recycling of steel slag in pavement layers. *Rev. Ibero Am. Ciências Ambient.* **2020**, *11*, 167–183. [CrossRef]
9. Loures, R.; Guimarães, A.; Silva, B.H.; Castro, C. Cold mix containing steel slag: A viable alternative for pavement construction. *Transportes* **2018**, *26*, 54–67. [CrossRef]
10. Pinto Netto, Q.; Guimarães, A. Laboratory characterization of mining residues as alternative aggregates for asphalt mixtures. *Rev. Ibero Am. Ciências Ambient.* **2018**, *9*, 88–98. [CrossRef]
11. Guimarães, A.C.R.; Costa, K.Á.; Reis, M.d.M.; Santana, C.S.A.; Castro, C.D. Study of controlled leaching process of steel slag in soxhlet extractor aiming employment in pavements. *Transp. Geotech.* **2021**, *27*, 100485. [CrossRef]
12. Friber, M.; Guimarães, A.; Martins, C.; Soares, J. Study of the Mining Waste in the Production of Calcined Aggregate for Use in Pavement. *Minerals* **2023**, *13*, 1543. [CrossRef]
13. Barbosa, V.; Guimarães, A.; Marques, M.; Castro, C. Study of Acre soils for the production of calcined clay aggregates and mixtures for pavement bases—A strategic alternative for the state of Acre. *Rev. Mil. Ciência Tecnol.* **2020**, *37*, 5–18.
14. Feng, W.; Liu, F.; Yang, F.; Jing, L.; Li, L.; Li, H.; Chen, L. Compressive behaviour and fragment size distribution model for failure mode prediction of rubber concrete under impact loads. *Constr. Build. Mater.* **2021**, *273*, 121767. [CrossRef]
15. Jian, S.M.; Wu, B. Compressive behavior of compound concrete containing demolished concrete lumps and recycled aggregate concrete. *Constr. Build. Mater.* **2021**, *272*, 121624. [CrossRef]
16. Specht, L. Evaluation of Asphalt Mixtures Incorporating Recycled Tire Rubber. Ph.D. Thesis, Programa de Pós-Graduação em Engenharia Civil, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brazil, 2004.
17. Chiu, C.T.; Lu, L.C. A laboratory study on stone matrix asphalt using ground tire rubber. *Constr. Build. Mater.* **2007**, *21*, 1027–1033. [CrossRef]
18. Silva, J.d.; Pereira, I.; Pinheiro, É.C. Analysis of the technical feasibility of using waste tire rubber in asphalt pavements. *Braz. J. Dev.* **2021**, *7*, 108529–108544. [CrossRef]
19. Flores, G.; Gallego, J.; Miranda, L.; Marcobal, J.R. Design methodology for in situ cold recycled mixtures with emulsion and 100% rap. *Constr. Build. Mater.* **2019**, *216*, 496–505. [CrossRef]
20. Thakur, J.; Han, J. Recent development of recycled asphalt pavement (RAP) bases treated for roadway applications. *Transp. Infrastruct. Geotechnol.* **2015**, *2*, 68–86. [CrossRef]
21. Naser, M.; Abdel-Jaber, M.; Al-Shamayleh, R.; Ibrahim, R.; Louzi, N.; AlKhrissat, T. Improving the Mechanical Properties of Recycled Asphalt Pavement Mixtures Using Steel Slag and Silica Fume as a Filler. *Buildings* **2023**, *13*, 132. [CrossRef]
22. Gallo, P.; Belhaj, M.; Valentin, J. Laboratory Study of Asphalt Concrete for Base Course with Reclaimed Asphalt, Recycling Agents, and Jute Fibres. *Appl. Sci.* **2024**, *14*, 239. [CrossRef]
23. Coelho, L.; Guimarães, A.; de Azevedo, A.; Monteiro, S. Sustainable Reclaimed Asphalt Emulsified Granular Mixture for Pavement Base Stabilization: Prediction of Mechanical Behavior Based on Repeated Load Triaxial Tests. *Sustainability* **2024**, *16*, 5335. [CrossRef]
24. Hu, Y.; Allanson, M.; Sreeram, A.; Ryan, J.; Wang, H.; Zhou, L.; Airey, G.D. Characterisation of bitumen through multiple ageing-rejuvenation cycles. *Int. J. Pavement Eng.* **2024**, *25*, 2365350. [CrossRef]
25. Hu, Y.; Ryan, J.; Sreeram, A.; Allanson, M.; Pasandín, A.R.; Zhou, L.; Singh, B.; Wang, H.; Airey, G.D. Optimising the dosage of bio-rejuvenators in asphalt recycling: A rejuvenation index based approach. *Constr. Build. Mater.* **2024**, *433*, 136761. [CrossRef]
26. Hu, Y.; Omairey, E.; Hughes, D.; Bailey, H.; Watkins, M.; Twitchen, J.; Airey, G.D.; Sreeram, A. Recovering the properties of aged bitumen using bio-rejuvenators derived from municipal wastes. *Constr. Build. Mater.* **2024**, *438*, 137268. [CrossRef]
27. Adwani, D.; Pipintakos, G.; Mirwald, J.; Wang, Y.; Hajj, R.; Guo, M.; Bhasin, A. Examining the efficacy of promising antioxidants to mitigate asphalt binder oxidation: Insights from a worldwide interlaboratory investigation. *Int. J. Pavement Eng.* **2024**, *25*, 2332363. [CrossRef]
28. Guimarães, A.; Motta, L.d. A Study on Permanent Deformation of Lateritic Soils Including the Shakedown Concept. In *Advances in Transportation Geotechnics*, 1st ed.; CRC Press: London, UK, 2008; p. 8, ISBN 9780429207280. [CrossRef]

29. Modarres, A.; Rahimzadeh, M.; Zarrabi, M. Field investigation of in-place cold recycling pavement rehabilitation. *Resour. Conserv. Recycl.* **2014**, *83*, 112–120. [CrossRef]
30. Fu, P.; Harvey, J. Temperature sensitivity of foamed asphalt mix stiffness: Field and lab study. *Int. J. Pavement Eng.* **2007**, *8*, 137–145. [CrossRef]
31. Guatimosim, F.V.; Vasconcelos, K.L.; Bernucci, L.L.B.; Jenkins, K.J. Laboratory and field evaluation of cold recycling mixture with foamed asphalt. *Road Mater. Pavement Des.* **2016**, *19*, 385–399. [CrossRef]
32. Kim, Y.; Lee, H.; Heitzman, M. Validation of new mix design procedure for cold in-place recycling with foamed asphalt. *J. Mater. Civ. Eng.* **2007**, *19*, 1000–1010. [CrossRef]
33. Diefenderfer, B.K.; Bowers, B.F.; Schwartz, C.W.; Farzaneh, A.; Zhang, Z. Dynamic modulus of recycled pavement mixtures. *Transp. Res. Rec. J. Transp. Res. Board* **2016**, *2575*, 19–26. [CrossRef]
34. Smith, S.; Braham, A. Comparing layer types for the use of pavement ME for asphalt emulsion full depth reclamation design. *Constr. Build. Mater.* **2018**, *158*, 481–489. [CrossRef]
35. Meocci, M.; Grilli, A.; Torre, F.L.; Bocci, M. Evaluation of mechanical performance of cement–bitumen-treated materials through laboratory and in-situ testing. *Road Mater. Pavement Des.* **2017**, *18*, 376–389. [CrossRef]
36. DNIT. *Asphalt Paving–Preparation of Specimens for for Mechanical Testing Using the Superpave or Marshall Gyratory Compactor–Procedure*; Technical Report; National Department of Transportation Infrastructure: Rio de Janeiro, Brazil, 2018.
37. Comite Europeen de Normalisation, European. *Bituminous Mixtures—Test Methods—Part 23: Determination of the Indirect Tensile Strength of Bituminous Specimens*; Technical Report; Comite Europeen de Normalisation, European: Brussels, Belgium, 2017.
38. Comite Europeen de Normalisation, European. *Bituminous Mixtures—Test Methods for Hot Mix Asphalt—Part 26: Stiffness*; Technical Report; Comite Europeen de Normalisation, European: Brussels, Belgium, 2012.
39. Unger Filho, W.; Klinsky, L.; Motta, R.; Bernucci, L.L. Cold Recycled Asphalt Mixture using 100% RAP with Emulsified Asphalt-Recycling Agent as a New Pavement Base Course. *Adv. Mater. Sci. Eng.* **2020**, *2020*, 5863458. [CrossRef]
40. Bessa, I.S.; Almeida, L.R.; Vasconcelos, K.L.; Bernucci, L.L. Design of cold recycled mixes with asphalt emulsion and portland cement. *Can. J. Civ. Eng.* **2016**, *43*, 627–635. [CrossRef]
41. Allah, S.; Tanyu, B.; Dawson, A. Reclaimed Asphalt Pavement (RAP) as an Unbound Base Course Material: A Mechanistic Design Approach Based on Multi-stage Repeated Load Triaxial Tests. *Transp. Geotech.* **2022**, *33*, 100729. [CrossRef]
42. Kuchiishi, A.K.; Vasconcelos, K.; Bariani Bernucci, L.L. Effect of mixture composition on the mechanical behaviour of cold recycled asphalt mixtures. *Int. J. Pavement Eng.* **2019**, *22*, 984–994. [CrossRef]
43. Ullah, S.; Tanyu, B. Methodology to develop design guidelines to construct unbound base course withreclaimed asphalt pavement (RAP). *Constr. Build. Mater.* **2019**, *223*, 463–476. [CrossRef]
44. Guthrie, W.S.; Cooley, D.; Eggett, D.L. Effects of Reclaimed Asphalt Pavement on Mechanical Properties of Base Materials. *Transp. Res. Rec.* **2007**, *2005*, 44–52. [CrossRef]
45. Guduru, G.; Tavva, T.; Kuna, K. Estimation of Reclaimed Asphalt Pavement (RAP) characteristics using simple indicative tests. *Road Mater. Pavement Des.* **2022**, *23*, 822–848. [CrossRef]
46. Chakravarthi, S.; Kumar, G.; Shankar, S.; Vishnu, R. Effect of Emulsified Asphalt Content on Creep Behavior and Mechanical Properties of Cold Recycled Emulsified Asphalt Bases. *J. Rehabil. Civ. Eng.* **2021**, *9*, 133–147. [CrossRef]
47. Pinilla, J.; Miller, G.; Cerato, A.; Snethen, D. Influence of curing time on the resilient modulus of chemically stabilized soils. *Geotech. Test. J.* **2011**, *34*, 364–372. [CrossRef]
48. Mousa, E.; El-Badawy, S.; Azam, A. Evaluation of reclaimed asphalt pavement as base/subbase material in Egypt. *Transp. Geotech.* **2021**, *26*, 100414. [CrossRef]
49. de Medeiros, A.S.; Sant'Anna Cardoso, M.H.; Vieira da Silva, M.A. Evaluation of the Mechanical Behavior of Soil Stabilized with Asphalt Emulsion Using Multi-Stage Loading. *Civ. Eng. J.* **2024**, *10*, 20–40. [CrossRef]
50. Asphalt Institute. *A Basic Asphalt Emulsion Manual. The Asphalt Institute Manual Series No. 19*; Asphalt Institute: Lexington, KY, USA, 1997.
51. Pi, Y.; Huang, Z.; Pi, Y.; Li, G.; Li, Y. Composition design and performance evaluation of emulsified asphalt cold recycled mixtures. *Materials* **2019**, *12*, 2682. [CrossRef] [PubMed]
52. Asphalt Academy. *Bitumen Stabilized Materials, a Guideline for Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilized Materials*; TG2 Technical Guideline; Asphalt Academy: Pretoria, South Africa, 2009.
53. Sabita. *Technical Guideline: Bitumen Stabilised Materials*, 3rd ed.; Southern African Bitumen Association (Sabita): Cape Town, South Africa, 2020.
54. *ABNT NBR 10235*; Methylene Blue Solution—Determination of Factor by Titration with a Solution of Titanium Trichloride—(TiCl3)—Standardization. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2015.
55. *ABNT NBR 12052*; Soils and Fine Aggregate–Determination of Sand Equivalent Value—Method of Test. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 1992.
56. *ABNT NBR MN 30*; Fine Aggregate—Test Method for Water Absorption. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2021.
57. *ABNT NBR MN 52*; Fine Aggregate—Determinação of the Bulk Specific Gravity and Apparent Specific Gravity. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2021.

58. *ABNT NBR 14491*; Asphalt Emulsions—Determination of Saybolt Furol Viscosity. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2007.
59. *ABNT NBR 6570*; Asphalt Binders—Determination of Sedimentation and Stability to Storage of Asphalt Emulsions. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2016.
60. *ABNT NBR 14393*; Asphalt Emulsions—Determination of Sifting. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2012.
61. *ABNT NBR 6567*; Asphalt Binders—Asphalt Emulsions—Determination of Particle Charge. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2015.
62. *ABNT NBR 14376*; Asphaltic Emulsions—Determination of the Solids Content of Conventional or Modified Asphalt Emulsions—Expeditious Methods. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2019.
63. *ABNT NBR 6299*; Asphalt Emulsions—Determination of pH. Brazilian Association of Technical Standards: Rio de Janeiro, Brazil, 2012.
64. National Department of Transportation Infrastructure—DNIT. *Pavement—Soils—Compaction Test Using Tripartite Molds*; National Department of Transportation Infrastructure: Rio de Janeiro, Brazil, 2023.
65. DNIT. *Pavement-Soils-Determination of Resilience Modulus*; Technical Report; National Department of Transportation Infrastructure: Rio de Janeiro, Brazil, 2018.
66. National Department of Transportation Infrastructure—DNIT. *Pavement—Soils—Determination of Permanent Deformation*; National Department of Transportation Infrastructure: Rio de Janeiro, Brazil, 2018.
67. Lima, C.; Motta, L.; Aragão, F. Permanent deformation tests: Effect of the number of loading cycles on the interpretation of the behavior of soils and gravels. *Rev. Matéria* **2020**, *26*, e13044. [CrossRef]
68. Dawson, A.; Wellner, F. *Plastic Behavior of Granular Materials*; Report ARC Project 933 Reference PRG99014; University of Nottingham: Nottingham, UK, 1999.
69. Werkmeister, S. Permanent Deformation Behavior of Unbound Granular Materials in Pavement Constructions. Doctoral Thesis, Universidade Técnica de Dresden, Dresden, Germany, 2003.
70. Cerni, S.; Cardone, F.; Virgili, A.; Camilli, S. Characterisation of Permanent Deformation Behaviour of Unbound Granular Materials Under Repeated Triaxial Loading. *Constr. Build. Mater.* **2012**, *28*, 79–87. [CrossRef]
71. Brown, S.; Needham, D. A study of cement modified bitumen emulsion mixtures. In Proceedings of the Association of Asphalt Paving Technologists, Saint Paul, MN, USA, 2000; pp. 92–121.
72. Betti, G.; Airey, G.; Jenkins, K.; Marradi, A.; Tebaldi, G. Active fillers' effect on in situ performances of foam bitumen recycled mixtures. *Road Mater. Pavement Des.* **2016**, *18*, 281–296. [CrossRef]
73. Ebels, L. Characterisation of Material Properties and Behaviour of Cold Bituminous Mixtures for Road Pavement. Ph.D. Thesis, Stellenbosch University, Stellenbosch, South Africa, 2008.
74. Guimarães, A.; Motta, L. Mechanical Behavior of Basaltic Rocks from Serra Geral Formation Used as Road Material in Santa Catarina State, Brazil. *Soils Rocks* **2016**, *39*, 203–210. [CrossRef]
75. Zago, J.; Pinheiro, R.; Baroni, M.; Specht, L.; Delongui, L.; Sagrilo, A. Study of the Permanent Deformation of Three Soils Employed in Highway Subgrades in the Municipality of Santa Maria-RS, Brazil. *Int. J. Pavement Res. Technol.* **2021**, *14*, 729–739. [CrossRef]
76. Pascoal, P.; Sagrilo, A.; Baroni, M.; Specht, L.; Pereira, D. Lateritic Soil Deformability Regarding the Variation of Compaction Energy in the Construction of Pavement Subgrade. *Soils Rocks* **2023**, *46*, e2023009922. [CrossRef]
77. Sagrilo, A.V.; Pascoal, P.T.; Baroni, M.; Back, A.H.; Pinheiro, R.J.B.; Specht, L.P.; Guimarães, A.C.R. Contribution to Resilient and Permanent Deformation Investigation of Unbound Granular Materials with Different Geological Origins from Rio Grande do Sul, Brazil. *Soils Rocks* **2023**, *46*, e2023009822. [CrossRef]
78. Bernucci, L.B.; Ceratti, J.A.P.; Soares, J.B.; da Motta, L.M.G. *Asphalt Pavement, Basic Training for Engineers*, 2nd ed.; PETROBRAS, ABEDA: Rio de Janeiro, Brazil, 2006; p. 504.
79. Balbo, J.T. *Pavimentação Asfáltica: Materiais, Projeto e Restauração*, 1st ed.; Oficina de Textos: São Paulo, Brazil, 2007; p. 560.
80. Guimarães, A.C.R.; de Lima, C.D.A.; Aragão, F.T.S.; da Motta, L.M.G.; dos Santos, J.T.A. Mechanical Characterization of an Alternative Laterite Gravel Used as Pavement Material. *Soils Rocks* **2024**, *47*, e2024010622. [CrossRef]
81. Kuchiishi, A.K.; Andrade, L.R.d.; Bessa, I.S.; Esteves, S.F.; Vasconcelos, K.L.; Bernucci, L.L.B. Influência da granulometria nas propriedades mecânicas de misturas recicladas a frio estabilizadas com emulsão asfáltica e cimento Portland. In Proceedings of the Congreso Ibero-Latinoamericano del Asfalto, Medellin, Colombia, 27–30 November 2017.

82. Lima, C.; Motta, L. Study of Permanent Deformation and Granulometric Distribution of Graded Crushed Stone Pavement Material. *Procedia Eng.* **2016**, *143*, 854–861. [CrossRef]
83. Jallu, M.; Saride, S.; Arulrajah, A.; Challapalli, S.; Evans, R. Effect of Curing Time on the Performance of Fly Ash Geopolymer-Stabilized RAP Bases. *J. Mater. Civ. Eng.* **2021**, *33*, 04021001. [CrossRef]