

## Research Article

# Cold Recycled Asphalt Mixture using 100% RAP with Emulsified Asphalt-Recycling Agent as a New Pavement Base Course

**Wilson Unger Filho** <sup>1,2</sup>, **Luis Miguel Gutiérrez Klinsky**,<sup>2</sup> **Rosângela Motta**,<sup>1</sup>  
and **Liedi Légi Bariani Bernucci**<sup>1</sup>

<sup>1</sup>Transportation Engineering Department, Escola Politécnica, University of São Paulo, São Paulo, Brazil

<sup>2</sup>CCR Highway Research Center, Grupo CCR, São Paulo, Brazil

Correspondence should be addressed to Wilson Unger Filho; [wunger87@gmail.com](mailto:wunger87@gmail.com)

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The rehabilitation process of asphalt pavements using the technique of milling and filling can cause several environmental problems due to either the disposal of the milled asphalt mix or the exploration of natural resources. One alternative to mitigate these impacts is to reuse this milled material, known as reclaimed asphalt pavement (RAP), in the construction of new pavement layers. Within the several available techniques to reuse the RAP, cold recycling using an emulsified asphalt-recycling agent has shown great potential. The aim of this study is to evaluate the application of a cold recycled asphalt mix using 100% RAP with an emulsified asphalt-recycling agent as a new pavement base course. A trial section was built employing this material as a pavement base course in a heavy traffic highway in Brazil, and its structural behavior was monitored for 12 months using a Falling Weight Deflectometer (FWD) to assess its performance over time. Furthermore, a laboratory-testing program was performed to evaluate the recycled mixture stiffness and strength through resilient modulus and indirect tensile strength tests. These tests were used to investigate the influence of the storage interval (7, 14, and 28 days) considering the time between mixing and compaction of the mixture. The effect of the curing time after compaction (1, 3, 7, 26, and 56 days) was also assessed. It was verified in laboratory and in the trial section that the stiffness increases with curing time. Furthermore, the backcalculated elastic resilient moduli indicated values in the same order of magnitude to those obtained in the laboratory tests. In addition to the laboratory test findings, it was also observed that the longer the period of storage, the higher the values of stiffness and tensile strength for short periods of curing. This behavior was not verified when longer curing periods were used. In general, the use of cold recycled asphalt mixtures as base course of new pavements proved to be a promising alternative to reuse RAP.

## 1. Introduction

Reclaimed asphalt pavement (RAP) is produced from milled deteriorated asphalt pavement and has been used in new hot or cold asphalt mixtures. The advantages of using RAP include reducing the exploration of virgin material, saving cost and decreasing the use of natural resources, and providing less environmental damage [1].

During the 1990s, the technique of pavement base in-place recycling with RAP became a common solution in Brazil. However, the rate of recycling Brazilian asphalt layers for application in new pavements is still low, and it may be

explained by the belief that conventional hot asphalt mixtures have better performance than the recycled ones.

Recycling techniques may be classified in several manners. For example, the Asphalt Recycling and Reclaiming Association (ARRA) defines five categories: cold planning, hot recycling, hot in-place recycling, cold recycling (in-place or in central plant), and full depth reclamation. The selection of which recycling technique is the most appropriate for each rehabilitation project, balancing advantages and disadvantages of each one, depends on several factors, such as level of pavement degradation and equipment and materials availability.

Cold recycling should be the preferred recycling method due to the economic benefits to be achieved by reducing the consumption of production energy and natural resources [2]. When performed at the right time, that is, prior to full degradation of the pavement structure, maintenance costs can be reduced by 30% to 50% over conventional milling and filling solutions [3]. In addition, it is possible to reuse the full asphalt layer, minimizing virgin materials acquisition, transportation, construction periods, and landfilling.

This research has the objective of evaluating the application of a cold recycled asphalt mix using 100% RAP produced with an emulsified asphalt-recycling agent for a new pavement base course. For assessing the mixture's performance in the field, 2 km of a new pavement lane was built as a trial section of a heavy traffic highway in São Paulo, Brazil. The structural behavior was monitored through FWD in the field for 12 months after construction. Additionally, samples of the cold recycled mixture were collected during the construction of the trial section and were used in a laboratory program to investigate the effects of material storage and curing time. The storage period here refers to the time between mixing and compaction and the curing time refers to the time elapsed after compaction until tests are performed.

## 2. Cold Recycled Asphalt Mixtures with Emulsified Asphalt-Recycling Agents

Cold asphalt recycling can be produced with different additives and materials, mixed in place or in specific recycling plants. Thus, the recycling methodology is usually classified as granulometric stabilization, chemical stabilization (with lime, Portland cement, or fly ash), and asphaltic stabilization (emulsified or foamed).

Emulsified asphalt (or asphalt emulsion) is a suspension of small asphalt binder droplets in water with the help of an emulsifying agent by mechanical action [4]. Emulsified asphalt-recycling agents, as designated by ARRA [5] and FHWA [3], are products specifically developed for cold asphalt recycling and can contain mineral or vegetal additives to partially rejuvenate the RAP residual asphalt. An emulsified asphalt-recycling agent is formulated to enhance some characteristics of the final recycled asphalt mix for both mechanical and workability purposes.

Cold recycled mixtures are usually classified as stabilized or asphalt mixtures, depending on their mechanical properties. For example, the stabilized mixture has low amounts of nonactive asphalt binder residue in the RAP, which may have low influence in the mechanical behavior of the mix. In that case, the stabilized mixtures show a hybrid behavior between a granular material and a cemented material or hot mix asphalt [6].

On the other hand, when the asphalt binder residue in the RAP is active, it is considered as an asphalt recycled mixture, so traditional methodologies may be used for the mixture design. In this case, the emulsified asphalt-recycling agent is specifically selected for RAP with active residual asphalt binder [5].

Another aspect that should be recognized is the manner in which the recycling materials coat the RAP. For example, the foamed asphalt is distributed in small spots of asphalt binder in the RAP surface after the asphalt bubbles explode. This procedure creates many bonding points, generating a mix with a behavior between a granular material and an asphalt mixture. Still, in the case of the emulsified asphalt-recycling agent, after the emulsions rupture, the spots of the asphalt binder flow to the RAP surface. Therefore, a thin and continuous asphalt film, such as an asphalt mixture, covers the RAP surface. However, the bonding is weaker than in the latter because of the thickness of the asphalt film [6].

It is important to consider that cold asphalt mixtures, recycled or not, lose moisture over time, which is usually recognized as the curing period. During this period, the cold asphalt mixtures tend to increase the mechanical resistance regarding tensile strength and stiffness. Also, in this period the interaction between the recycling agent and the RAP residual aged asphalt is developed [5], at least with its most external layer. This mechanism could be explained by the molecular mass exchange between the aromatics molecules and the residual asphalt binder [7].

Studies have investigated the influence of different recycling agents, contents, compaction method and energy, granulometry correction, and curing period [8, 9], such as those by Andrade [10]. However, the storage period has not been studied systematically. The influence of the storage period in the mechanical behavior of the final recycled asphalt mix is very important for the logistics when recycling asphalt plants are far away from the construction site. For an overall view, the mechanical properties of cold recycled asphalt mixtures from different studies are summarized in Table 1. It is noted that the curing time, curing temperature, and compaction do not follow a standardized protocol; thus, it is difficult to perform further comparative analysis. The use of cement in cold recycled asphalt mixtures allows the improvement of the strength by promoting demulsification of emulsified asphalt and producing cement hydrates [12].

Additionally, Meocci et al. [2] noted that the commonly used accelerated curing process (72 h at 40°C) did not allow the definitive mixture strength and stiffness to be reached, obtaining higher values after 10 days, a behavior that should also be evaluated in this research with a variation in the curing time. The same authors also observed an evolution of stiffness in deflection measurements with 29 and 90 days in the field.

Finally, another characteristic that affects the curing of recycled mixtures is the influence of temperature. During curing, higher temperatures resulted in higher modulus increase and maximum values, while at low temperatures the curing process is slower, which does not penalize the potential performance of the mixture [14].

## 3. Materials

*3.1. RAP and Emulsified Asphalt-Recycling Agent Characterization.* Ten thousand tons of RAP from maintenance activities of the highway were available for the current study. Three samples were collected at different

TABLE 1: Mechanical properties of cold recycled asphalt mixtures with emulsified asphalt-recycling agent.

Authors	Indirect tensile strength (ITS) <sup>(1)</sup>	Resilient modulus <sup>(1)</sup>	Curing period	Storage period	Compaction	Portland cement?	Observations
David [8]	—	3,000 MPa to 3,500 MPa	24 h at 60°C	Not specified	Marshall	Yes	Resilient modulus at ITS configuration
Silva [9]	0.35 MPa	1,000 MPa to 1,200 MPa	7 and 28 days	Not specified	Modified Proctor	Yes	Resilient modulus at triaxial configuration, almost not influenced by confining stress
Andrade [10]	-	1,000 MPa to 1,200 MPa	28 days at 60°C +	Not specified	Modified Proctor	Yes	Resilient modulus at triaxial configuration, almost not influenced by confining stress
Mollenhauer et al. [11]	0.4 MPa (7 days) 0.6 MPa (14 days) 0.1 MPa (2 days) 0.2 MPa (3 days)	—	7 and 14 days	Not specified	Marshall and gyratory compactor	Yes	Resilient modulus at ITS configuration
Ma et al. [12]	0.3 MPa (4 days) 0.4 MPa (7 days) 0.4 MPa (3 days)	—	2, 3, 4, and 7 days at room temperature and 48 h at 60°C	Not specified	Marshall	Yes	Average ITS from 3 different recycling agents
Meocci et al. [2]	0.7 MPa (13 days)	4,000 MPa 5,000 MPa	72 h at 40°C and additional 10 days at 20°C, resp.	Immediately	Gyratory compactor	Yes	Use of cement increased the values of ITS and RM
Raschia et al. [13]	0.4 MPa (28 days) <sup>(2)</sup> 0.6 MPa (28 days) <sup>(3)</sup>	3,000 MPa <sup>(3)</sup>	14 days at room temperature and 14 days at 40°C	Not specified	Gyratory compactor	No	Values from samples mixed and compacted at 25°C <sup>(2)</sup> soft asphalt <sup>(3)</sup> Hard asphalt
Raschia et al. [13]	0.4 to 0.5 MPa (28 days) <sup>(3)</sup>	2,000 MPa <sup>(3)</sup>	14 days at room temperature and 14 days at 40°C	Not specified	Gyratory compactor	No	Values from samples mixed and compacted at 5°C <sup>(3)</sup> hard asphalt

<sup>(1)</sup>Resilient modulus and indirect tensile strength were measured after the curing time. <sup>(2)</sup>soft asphalt. <sup>(3)</sup>hard asphalt.

points of the pile, and then the RILEM (*Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions*) guidelines were followed to analyze gradation, binder content, and binder consistency [15] in laboratory. As shown in Figure 1, the three RAP samples were in accordance with the medium gradation suggested by ARRA [16]. The average grading curve after the asphalt binder extraction (white curve) is also shown.

The Soxhlet extraction method was used to determine the asphalt binder content of the RAP samples. The results showed a slight variability among their contents (5.3%, 4.7%, and 4.9% of residual asphalt binder). Also, the Abson method [17] was used to obtain the residual asphalt binder and its penetration, and softening points were analyzed. The results showed penetration between 10 and 11 ( $\times 10^{-1}$  mm) and a softening point between 92°C and 95°C, showing lower

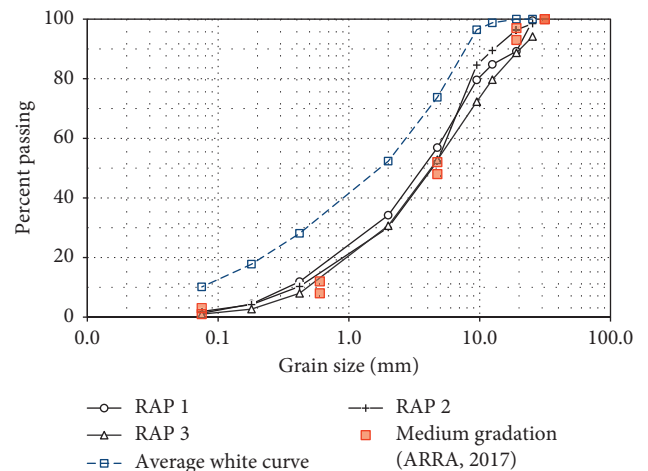


FIGURE 1: Grain-size distribution of the RAP samples.

penetration and a higher softening point than virgin asphalt binder values, even after the Rolling Thin Film Oven Test [18]. The asphalt binder, simulated by the RTFOT test after hot mixing, should have presented a maximum softening point of 60°C and penetration between 15 and 22 ( $\times 10^{-1}$  mm). Therefore, the values obtained demonstrate the aging of the residual asphalt binder.

The emulsified asphalt-recycling agent used in this study contained SBS (Styrene-Butadiene-Styrene), a cationic slow set emulsion with a mineral rejuvenating agent, developed specifically for the RAP under study. It considered the degree of oxidation of the RAP residual binder, the surface energy, and the specific surface area (SSA) characteristics of the RAP [19].

**3.2. Cold Asphalt Recycled Mixture Design.** Marshall Compaction was used to prepare specimens containing 2.0%, 2.5%, and 3.0% of the emulsified asphalt-recycling agent. After compaction with 75 blows per face, specimens were cured for 72 h at 60°C and later maintained at room temperature for 24 h. The results of the Marshall Stability test showed that specimens with 2.5% of the emulsified asphalt-recycling agent had the higher values. This amount was then defined as the design content to be used in the recycling project, following the mix design of ARRA [5].

It is known that the addition of cementitious materials, such as lime or Portland cement, can increase tensile strength and stiffness. However, in this study it was added only the emulsified asphalt-recycling agent.

**3.3. Cold Asphalt Recycled Mixture Production.** The production of the cold asphalt recycled mixtures was performed using a stationary recycling plant, RT-500, shown in Figure 2. This plant has specific parts to crush and sieve the RAP, and a 31 mm sieve was used to limit RAP particles at this maximum size.

During the cold asphalt recycled mixture production, 500 kg of this material was collected for characterization in a laboratory program. This material was stocked loose in the laboratory at room temperature until the respective tests were performed. It is important to mention that the same materials used in the cold recycling plant in this project were provided to the laboratory tests.

As the RAP moisture content was found at 2.5% and the addition of emulsion included 1.0% of water, the final moisture content of the recycled mixture was around 3.5%. In order to prevent the variation of moisture content by either rain or evaporation, the recycled mixture remained covered in the field with plastic, while in laboratory the material remained stored in a closed plastic barrel.

## 4. Laboratory Study

**4.1. Influence of the Method and Energy Compaction.** The first part of this study sought determining which method and energy of compaction would be used in the laboratory program. To evaluate how each compaction method would affect the bulk density of the compacted mix and

consequently the air voids, three methods and six energies were analyzed: (i) modified Proctor (MPT), (ii) Marshall with 50 and 75 blows (M50 and M75) on each side, and (iii) gyratory compactor with 50, 75, and 100 gyrations (G50, G75, and G100). Three specimens were molded per condition. The average results are shown in Figure 3.

As seen in Figure 4, indeed, the specimens molded using a modified Proctor test showed the lowest bulk density and consequently the highest air voids content, while the ones compacted using the gyratory compactor presented higher bulk density and lower air voids. That difference of apparent bulk depending on the type of compaction and the energy applied presents itself as a reasonable explanation of the different results found in this paper when compared to other researches, as shown above.

Although the specimens compacted in the gyratory compactor present higher values of indirect strength and resilient modulus, in Brazil such compaction would hardly be achievable on the field because of the available compaction equipment. For this field research, a tandem roller was first used for the compaction of the cold recycled mix. A 9-wheel roller weighting approximately 25,5t rolled 16 times, and then a tandem roller was again used for finishing. The use of a sheep foot roller was also tested; however, due to the irregularity caused in the layer without a compaction gain, it was decided to use only tandem and tire rollers. Regardless of the number of rollings, it was not possible to achieve a higher compaction density than the one found by the Marshall method with 75 blows per side.

**4.2. Storage and Curing Times Influence.** The storage period and curing time effects on ITS and resilient modulus were evaluated in laboratory. Three storage periods 7, 14, and 28 days were selected in this study to assess the influence of the time between the mixing and the compaction of the cold recycled asphalt mixture with the asphalt emulsified asphalt-recycling agent.

After compaction, the cylindrical specimens were cured for 1, 3, 7, 14, and 28 days, until ITS [20]; and resilient modulus [21] were performed. Three specimens were compacted at each condition of storage periods and curing time using a Marshall compactor with 75 blows per face, as recommended by ARRA [5].

After compaction, each specimen was cured for 72 h at 60°C in a forced air oven to accelerate the initial curing period. Only 1-day specimens were kept at this condition for 24 h. After that, specimens were then cured at room temperature at 25°C. ITS and resilient modulus tests were performed at 25°C. Figures 3 and 5 show the results of both tests, respectively, indirect tensile strength and resilient modulus.

The results show that three days of curing increased significantly the stiffness and strength of the cold recycled mixes. It is observed that storing the loose mixes for 28 days did not spoil their mechanical behavior; on the contrary, the resilient modulus and the tensile strength were increased, proving that these types of mixtures can be stored. After 1-day curing, specimens that were compacted after the storage periods of 7 and 14 days did not have enough cohesion to be



FIGURE 2: Cold in-place recycling train set up as a stationary cold central plant recycling.

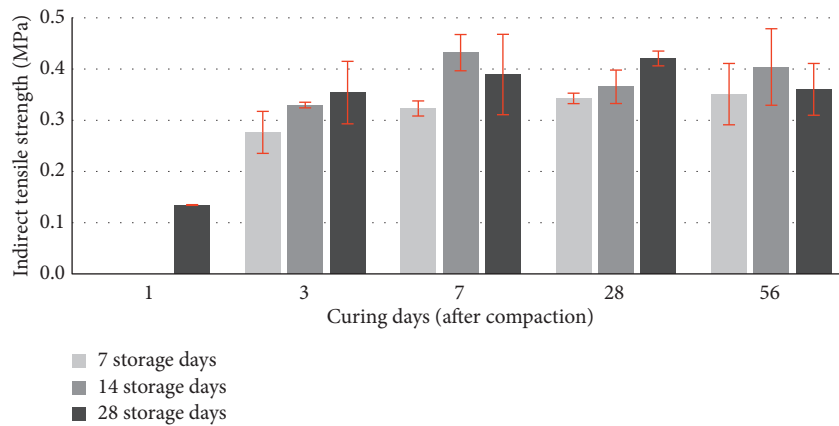


FIGURE 3: Tensile strength after a storage period of loose mix during 7, 14, and 28 days and curing time and compaction of 1, 3, 7, 28, and 56 days.

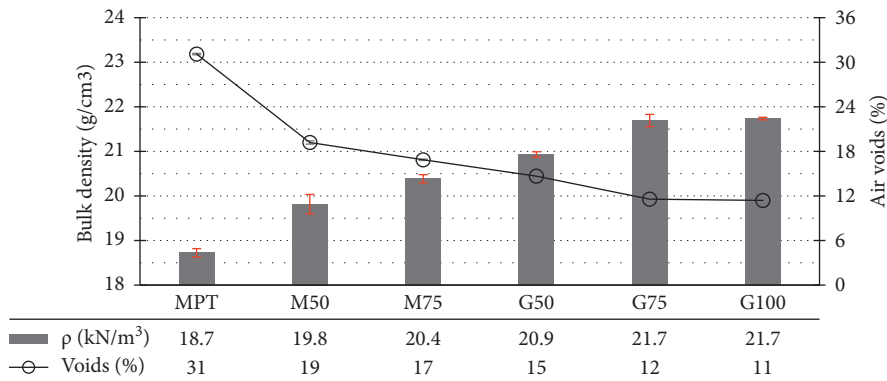


FIGURE 4: Bulk density and air voids depending on the type of compaction and compaction energy.

tested at the tensile strength. This behavior may denote that the moisture reduction is not the only reason for the stiffness and strength increases, but also the time of interaction between the aged asphalt and the emulsified asphalt-recycling agent influences the mechanical behavior of these recycled mixtures.

The mixtures stored for 7 days produced specimens that, after 7 days of curing, had average tensile strength below 0.3 MPa, that is, the minimum recommended value by

ARRA [16]. However, when the same mixtures were stored for 14 and 28 days, the values attended this recommendation, showing again that there was an interaction between the aged asphalt and the emulsified asphalt-recycling agent during the storing period.

The ITS results found in this research were similar to some previously presented studies, with a particularity, with the exception of the mixture evaluated in the study of Raschia et al. [12]; the others had some cement Portland

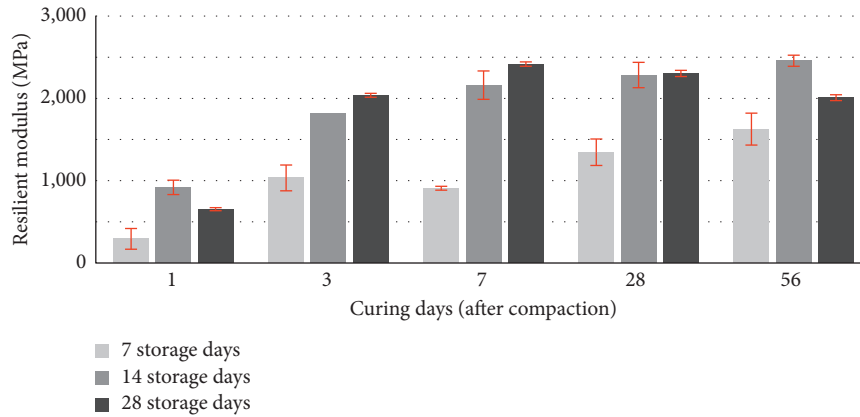


FIGURE 5: Resilient modulus after a storage period of loose mix during 7, 14, and 28 days and curing time and compaction of 1, 3, 7, 28, and 56 days.

content, which may explain similar tensile strength values even for specimens compacted in smaller energies, such as the modified Proctor [9].

When compared to results obtained by Mollenhauer et al. [11] and Raschia et al. [12], ITS values of the current research were lower. In this case, besides the Portland cement content in the study of Mollenhauer et al. [11], the compaction method used by them was the gyratory compaction, which may have provided a better compaction and, consequently, lower air voids. However, when compared to the research of Ma et al. [10], which used the Marshall compactor, the ITS values of the current research were similar, although the curing time was shorter. It is important to point out that Ma et al. [10] used cement Portland in the mixture, which not only enhances the strength, but also quickens the curing process because the cement consumes the water from the mix due to its hydration. Regarding the resilient modulus, results obtained in this study are quite similar to those of other researches previously shown in Table 1, ranging from 1,500 to 2,000 MPa.

When compared, for example, to the values obtained by Silva [9] and Andrade [13], the results of resilient modulus obtained were higher. However, the test configuration and compaction methods were different. Those authors molded the specimens with modified Proctor (resulting in lower specimen compaction) and tested them using a triaxial configuration. In comparison with the research by Raschia et al. [12], when analyzing mixing and compaction at 25°C, lower stiffness values were found. That difference can be correlated with compaction, but in this case the gyratory compactor resulted in better compaction, yielding higher stiffness values.

## 5. Test Section Construction and Monitoring

The designed pavement structure for the trial section was constructed in a heavy traffic highway in Brazil, and it is presented in Figure 6. As seen, 150 mm of the cold recycled mixture was designed as a base course. In addition, keeping the sustainability view of this research, the subgrade

Micro surfacing	12 mm
Hot mix asphalt	50 mm
Base: RAP cold recycled mix	150 mm
Subbase: Well-graded crushed stone	200 mm
Subgrade reinforcement: Recycled construction and demolition	400 mm
Subgrade	-

FIGURE 6: Designed pavement structure for the trial section.

reinforcement was also designed with recycled aggregates from construction and demolition waste.

The average daily number of commercial vehicles in one year is around 9,000. Similar to the trial section in the fast lane (leftmost lane), the heavy traffic vehicles in the project lane correspond to 3% of the total (270 heavy vehicles) and AASHTO Equivalent Single Axle Load (ESAL), in this lane, is  $1.7 \text{ E} + 06$  for a 10-year project, which is 3% of the total in the runway of  $5.7 \text{ E} + 07$  ESALs. As the test section has lighter traffic than the other lanes, it is expected to perform better in the long term regarding permanent deformation and fatigue life.

In terms of the construction process, the cold recycled mixture was produced in the stationary recycling plant and stored for 30 days. The construction of the cold recycled mixture layer was done in two layers, aiming at 150 mm of thickness after compaction. The second layer execution only began when the bottom layer achieved a moisture content under 3%. The tack coat between both cold recycled mix layers was made using the Rapid Set Emulsion at the rate of  $0.4 \text{ l/m}^2$ . Figure 7 shows the cold recycled mixture after the first use of the steel wheel roller.

The compaction control indicated at least  $21.03 \text{ kN/m}^3$ , aiming at achieving a degree of compaction of 95% or higher. After finishing the recycled layers, 50 mm of hot mix asphalt was used as a wearing course. The time between the execution of the second layer of cold asphalt recycled mix and the hot asphalt mix asphalt was between 5 and 15 days, depending on the construction progress and the cold asphalt recycled mix moisture content (3%).



FIGURE 7: Construction of the first layer of the cold recycled mixture.

Subsequently, in an effort to redress the horizontal signing of the road, a 12 mm layer of micro surfacing was placed. The completed additional lane is presented in Figure 8.

Construction activities at the trial section proved that the cold recycled mixtures have good workability and the equipment needed is the same used regularly in the construction of new asphalt pavements.

After the construction of the trial section, the structural monitoring activities began. As a result, the deflection basins were measured using a FWD, with a standard load of 20.1 kN. The analysis of the deflection condition aimed to assess the recycled mixture stiffness increase of regular traffic along the curing process in the field over time. As shown in laboratory evaluation, stiffness of the recycled mixture should increase after the curing process.

The FWD deflection measurements were made after 7, 90, 180, and 360 days of the trial section construction. “ $D_x$ ” corresponds to the deflection value measured at “ $x$ ” mm of the load application point. Thus, the  $D_0$  values (vertical displacement under the point of the load) obtained were corrected to a reference temperature of 25°C and can be seen in Figure 9.

It was noted that the deflection values were reduced during the curing period of the pavement structure. Also, field results show an improvement of the structural behavior in terms of pavement stiffness, probably due to the curing process. As the other pavement layers do not have characteristics that could justify this deflection reduction, curing of the recycled mix may provide a significant stiffness increase over time. However, it is important to point out that the first FWD measurement survey was made right after construction in March, which is the end of the rainy season in the state of São Paulo. In contrast, other measurement surveys occurred in August, October, and again March, 360 days later. Climatic conditions of a city nearby the area of the trial section are presented in Figure 10.

In order to mitigate this doubt, the  $D_{1200}$  (vertical displacement measured at 1200 mm from the load) points from

the deflection basins were also analyzed, aiming at identifying if the moisture content of the subgrade could have influenced the  $D_0$  values. Results showed that the  $D_{1200}$  values have remained in the same baseline as seen in Figure 11. This analysis confirmed that the moisture content of the subgrade might not have influenced the results of  $D_0$  from the first to later field surveys.

Another parameter that can be used to evaluate the base stiffness is the Base Damage Index (BDI). The BDI is the difference between the displacements measured at 300 mm ( $D_{300}$ ) and at 600 mm ( $D_{600}$ ) in the FWD loading plate. It is considered as the best indicator of the pavement base layer condition, being inversely proportional to its stiffness [22]. BDI values greater than 400  $\mu\text{m}$  result in a deficient pavement [23]. The results obtained in this analysis are presented in Figure 12. For the BDI trial section analysis, 100  $\mu\text{m}$  was adopted as a limit for a “great base condition.” It is important to highlight that as this parameter is determined using  $D_{30}$  and  $D_{60}$ , any data distortion due to temperature correction on  $D_0$  would not affect the BDI value.

The BDI assessment showed an expressive stiffness increase of the cold recycled mixture along the curing time. From Figure 12, it is noted that the higher values were about 90  $\mu\text{m}$ , while the lower BDI values are 40  $\mu\text{m}$ . This behavior agrees to the tendency observed previously in this paper regarding the laboratory tests results.

In addition to stiffness, the resistance to permanent deformation was also measured by measuring rutting. A possible deformation could have occurred by any of the granular layers, by deformation of the hot mix asphalt or cold recycled mixture, or by an integration of all deformations. To measure the rutting, a Dynatest pavement scanner equipped with two high-performance 3D lasers was used, which is capable of generating a sectional road surface with a resolution of one millimeter. The measurement was performed one and a half years after the test section construction.

The local transport agency (*Agência de Transporte do Estado de São Paulo* (ARTESP)) requires a maximum



FIGURE 8: Additional lane to the left opened to traffic.

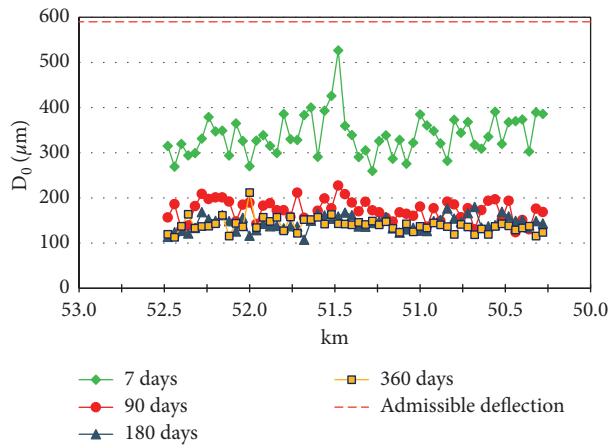


FIGURE 9: Maximum deflection  $D_0$  measured with FWD after 7, 90, 180, and 360 days of the trial section construction.

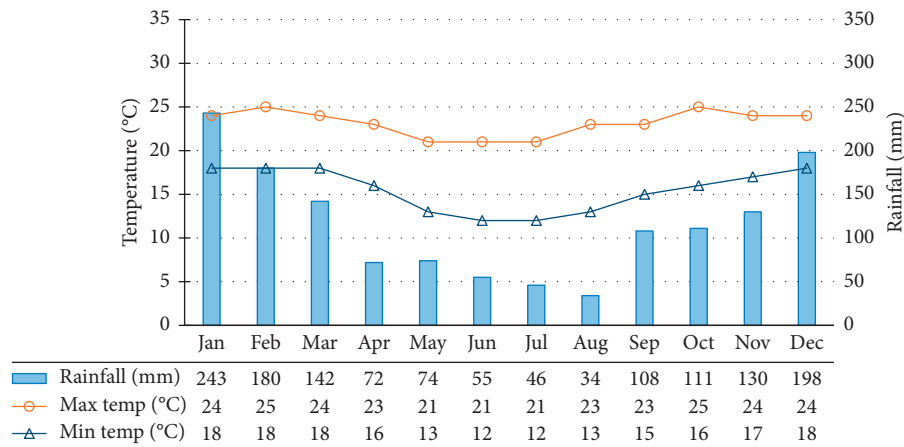


FIGURE 10: Annual temperature and precipitation in the trial section area: Araçariçuama (source: <https://www.climatempo.com.br/climatologia/2206/aracariguama-sp>).



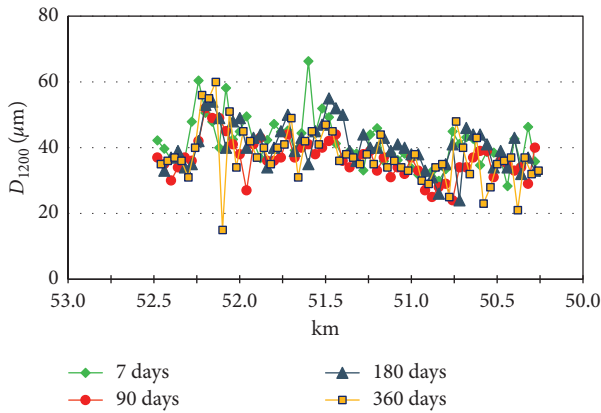


FIGURE 11: Deflections  $D_{1200}$  measured with FWD after 7, 90, 180, and 360 days of the construction.

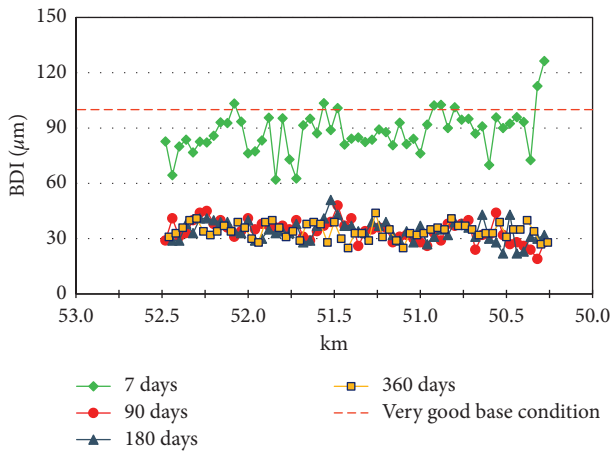


FIGURE 12: Base Damage Index (BDI).

average rutting of 7 mm per kilometer. The rutting was calculated every 40 m, and the average between the left rutting and right rutting was obtained. Figure 13 shows the average rutting values at every 40 m, as well as the average per kilometer.

Although it was not possible to measure the evolution of rutting from construction to the current measurement (545 days), it is possible to verify that one year and six months after construction the average rutting is low, at about 4 mm in the most critical segment, with isolated points measuring a maximum of 6 mm. In addition, as mentioned earlier, the 4 mm corresponds to the sum of the permanent deformations in each of the layers; that is, the deformation of the recycled cold asphalt layer was even less, indicating that it can have a good resistance to permanent deformation.

Another parameter measured was an evolution of longitudinal road profile, by measuring of the International Roughness Index (IRI). Measurements were performed with a laser profilometer 180 and 545 days after the construction of the test section. For a better understanding of the results, the IRI values were integrated every 200 m and are shown in Figure 14.

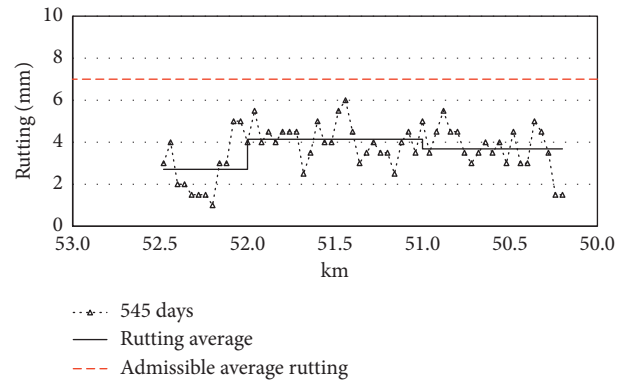


FIGURE 13: Rutting measured with a 3D laser pavement scanner after 545 days of the construction.

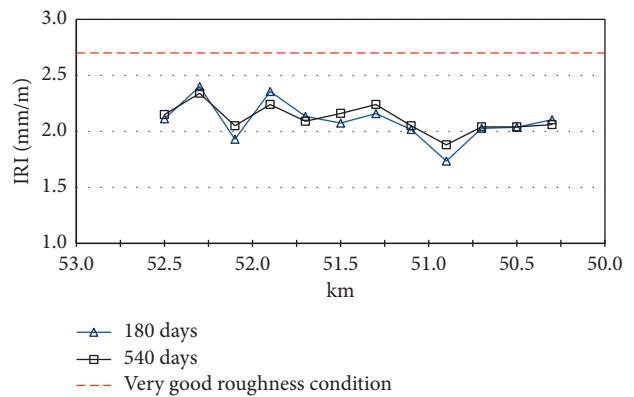


FIGURE 14: International Roughness Index (IRI) after 180 and 545 days of the construction.

The IRI variation was negligible over 1 year. The average IRI in the test section remained at 2.1 mm/m, with small variations in size. Thus, it is possible to affirm that the longitudinal irregularity did not evolve in that first year of evaluation. The evolution of the irregularity may be indicative of the evolution of pavement defects, which was not shown in the analyzed period.

**5.1. Backcalculation.** The last analysis regarding the evolution of the cold recycled mixtures stiffness was the backcalculation in terms of elastic moduli. The software EVERCALC was used, resulting in several simulations of multiple linear elastic layers. Each basin was backcalculated individually, obtaining an elastic modulus for each tested layer.

The first measurement, 7 days after the construction was finished, indicated that the cold recycled mixture layer had an average elastic modulus of 358 MPa and a coefficient of variation (CV) of 43%. When performing the second measurement, despite the wide range of values, the average modulus increased to 1,725 MPa, and CV was 37%. By the third measurement, 180 days later, the elastic modulus remained the same as the previous one, at an average value of

TABLE 2: Main environmental gains with the recycled pavement in section test.

Material	Amount
RAP	2,800 t
Construction and demolition waste	7,900 t
Hot mix asphalt	-610 t
Crushed stone	-14,800 t
Soil excavation and disposal	-4,000 t
Fuel consumption in hot mixing asphalt plants	-45 t

1,840 MPa and a 36% CV. By the last measurement, 360 days later, the average modulus was 1,835 MPa with a CV of 27%.

The values obtained in the trial section were quite similar to those performed using laboratory tests (around 1,800 MPa). This behavior may demonstrate that the evaluation of stiffness in laboratory could properly estimate the stiffness of the cold recycled mixture from the field.

**5.2. Environmental Aspects and Costs.** The execution of the test segment provided several environmental and financial gains when compared to a conventional solution. The traditional pavement had been designed with 80 mm hot mix asphalt, 150 mm well-graded crushed stone, 400 mm dry macadam, and 400 mm ungraded crushed stone. Table 2 shows the main environmental gains with the recycled pavement.

In addition, it is possible to mention the reduction of energy for mixing the hot mix asphalt and reduction of smoke emissions from the hot mix asphalt in the environment.

At this point, a more complete financial analysis seems hasty, as a correct analysis should be made throughout the entire life cycle of the pavement. However, when comparing the structure adopted with the conventional one previously dimensioned for the same 10-year project period, it was possible to obtain a cost reduction of the pavement of about 14% and 8% of the total cost of construction.

## 6. Conclusions

The objective of this study was to evaluate the application of a cold recycled asphalt mix using 100% RAP produced with an emulsified asphalt-recycling agent, without cement, as a new pavement base course.

- (1) Laboratory analyses first assessed the influence of the storage period and the curing time of the cold recycled mixture. It was observed that the storing time enhanced, at first, the mechanical properties of the cold recycled mixtures, probably because of the interaction between the aged asphalt and the emulsified asphalt-recycling agent in the loose condition of the mixtures. Over the curing time, this initial increase became indifferent, with all samples reaching the same levels.
- (2) A minimum 7-day curing time was required to achieve the minimum ITS recommended by ARRA. The final value of the MR after 56 days of curing was

between 1,500 and 2,500 MPa, which was consistent with other researches and the arbitrated values for the design.

- (3) The final deflection and the final BDI indicated a good structural capacity of the base in terms of stiffness. During the trial section monitoring, after one year and half, there was no sign of distress in the surface, and the pavement stiffness increased during the curing time, reproducing the behavior observed in the laboratory. The rutting and the IRI remained within the maximum values established by the road authority, showing no early increase.
- (4) The variation in rainfall and temperature did not affect the deflection measures. The values in opposite climatic conditions 180 and 360 days after construction were similar.
- (5) Also, it is important to mention that this technique can reuse 100% of the RAP, reducing the cost and the environmental impact of this material. In addition, when the RAP cannot be reused locally in the pavement, it is possible to utilize it for different purposes. The testing results showed that cold recycled asphalt mixtures using an emulsified asphalt-recycling agent prompted improved mechanical characteristics that can be used as an alternative to new asphalt pavement courses.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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