The objective of this study was to evaluate the behavior in terms of the permanent deformation of four cold recycled asphalt mixtures stabilized with asphalt emulsion and foamed asphalt. The analysis was conducted considering three flow number test procedures adapted for cold recycled mixtures: (i) ABNT NBR 16505 (method A); (ii) adaptation of the FN test for CRAM according to Kim and Lee’s method (method B); (iii) 3D-Move analysis software simulation of pavement structures to address the stress magnitude for the FN test (method C). The influence of the curing process on the performance of the materials was also verified. The study used an extensive database of computed pavement responses from the four different asphalt pavement structures of the experimental section subjected to axial loading of a tandem axle using the 3D-Move pavement response analysis program. The FN results using the 3D-Move data (method C) demonstrated the good mechanical behaviour with respect to permanent deformation of the cold recycled mixtures subject to axial stress and temperature. The method proposed by Kim and Lee (method B) showed little efficacy for the analysis of the CRAMs tested in this work. The ABNT NBR 16505 method (method A), conventionally used for HMA, highlighted the influence of temperature (60°C) on the CRAM mixtures. For all FN test conditions, the curing was a preponderant factor for the performance of cold recycled asphalt mixtures and should be carefully evaluated to simulate the early stage of the mixtures in the field. It is also important to verify the influence of humidity and temperature on the permanent deformation mechanism of cold recycled asphalt mixtures.

1. Introduction

Cold recycling is an increasing trend in rehabilitation, maintenance, and intervention of distressed asphalt pavements. The main advantages of this technique are the economic and environmental benefits allowing faster interventions and shorter traffic disruption [1, 2]. In the recycling process, reclaimed asphalt pavement (RAP), usually generated from pavement milling [3], is incorporated to a new mixture through asphalt binder addition (stabilization). Virgin aggregates can also be incorporated to adjust the mixture’s aggregate gradation [4–6].

Cold recycled asphalt mixture (CRAM) is usually stabilized with foamed asphalt or asphalt emulsion. Active fillers may also be added (portland cement, hydrated lime, and others) to improve some mechanical properties, such as moisture resistance, and to increase early age resistance [5–8]. CRAM’s mechanical behaviour is dependent on various factors, such as the curing process, reclaimed asphalt pavement (RAP) source and gradation, moisture content, type and content of asphalt stabilization agent (foam or emulsion), presence of active fillers, and volumetric properties [2, 9, 10].

Considering the complex mechanical behaviour of CRAM, additional discussions are necessary on CRAM’s mechanical behaviour in the laboratory. An appropriate laboratory characterization of the CRAM may increase projects’ reliability, durability, and may reduce costs. Therefore, this work aims to assess the permanent deformation of four different CRAMs (these mixtures have been used as the base course in an experimental test section), stabilized with asphalt emulsion and foamed asphalt,
considering different flow number (FN) test procedures with respect to the loading condition and temperature, which were adapted for CRAM.

Rutting is considered by some researchers the main distress of asphalt pavements comprised by CRAM layers, including CRAM with the addition of portland cement or hydrated lime [5]. Rutting is affected by various factors: (i) asphalt content–higher stabilizing asphalt content leads to higher rutting probability [11, 12]; (ii) active filler addition (such as portland cement and/or hydrated lime) accounts for an increase in permanent deformation resistance [13–15]; (iii) higher temperatures lead to higher permanent deformation susceptibility [16–18]; (iv) higher RAP content may increase rutting resistance [19]; (v) longer curing periods reduce the rutting potential [20]. In general, stiffer CRAMs are less susceptible to rutting.

Different permanent deformation test methods can be used in the laboratory to assess the behaviour of the recycled asphalt mixtures. For CRAMs with mechanical behaviour similar to granular materials, repeated load triaxial tests are used to obtain permanent deformation prediction models, with a frequency generally around 1 Hz to 5 Hz, and the number of cycles ranging from 10,000 to 1,000,000 [21–23].

When CRAM behaves similar to a hot asphalt mixture (HMA), rutting tests are usually similar to those for HMA. One example is the flow number (FN) test, which is conducted without confinement, with load cycles limited to 10,000 cycles, and at 1 Hz [24, 25]. Some studies show that temperature, cure, and stress state directly influence the resistance to permanent deformation of CRAMs [24, 25].

The paper’s main objective is to evaluate the permanent deformation of different cold recycled asphalt mixtures under different flow number test conditions with respect to stress and the temperature.

2. Materials and Methods

2.1. Test Section. Four experimental sections, 100 m each, were built along the Fernão Dias Highway (BR-381), a heavy trafficked highway, located in the city of Extrema, Minas Gerais, in the southeast region of Brazil. The sections are comprised of CRAM (cold central plant recycling (CCPR)) and one well-graded crushed stone (GCS) base layer. Figure 1 illustrates the location of the test sections.

The pavement structures of the test sections are presented in Figure 2. HMA stands for hot mixture asphalt, GAP means gap-graded asphalt mixture, and remaining infrastructure refers to the old pavement system that remained after pavement milling. After the original pavement milling, the remaining infrastructure was tested by means of a light weight deflectometer (LWD) and the mean modulus value of 118 MPa was found. Explanations on the base layer materials are given in the next section.

2.2. Materials. Four different base layer materials were used to construct the test sections. The following nomenclature was adopted (Table 1): “AGG_xByF”, where “AGG” string represents the main aggregate of the mixture, and “xB” and “yF” strings represent, respectively, the content and type of the asphalt binder and the content and type of the active filler. “B” is the type of asphalt binder (code $E = \text{emulsion}$, $F = \text{foam}$) and “F” is the type of filler (code $C = \text{cement}$, $H = \text{hydrated lime}$).

Two different RAPs (with different aggregate gradation) were used in the CRAM preparation and were obtained from the pavement milling of different heavy traffic highways in Brazil. All mixtures’ gradations comply with Wirtgen’s specification for CRAMs [6]. The aggregate gradations of the base layer materials are presented in Figure 3, along with Wirtgen’s suggested limits for CRAM aggregate gradation. RAP_3E2C and RAP_3F2C mixtures have a nominal maximum aggregate size (NMAS) of 19 mm, and the RAP_2F1H has a NMAS of 25 mm. Base materials main characteristics are presented in Table 1.

From Table 1, significant total moisture content differences can be observed. This can be attributed to the presence of virgin aggregates, to the type of binder and to the aggregates’ gradation. Virgin aggregates absorb more moisture than RAP. Also, foamed mixtures normally need more moisture to assure a proper binder distribution when compared to emulsion stabilized mixtures. The total moisture content determination was based on the higher specimens’ dry density achieved after preliminary compaction and different moisture contents were assessed (5 different moisture content for each mixture).

Fine aggregate addition is important to ensure the best dispersion of the bitumen in CRAM. For the foamed asphalt mixtures, it occurs exclusively in the fine particles, thus increasing the cohesion of the compacted material. For this reason, some mixtures have also virgin aggregates in its composition.

To produce the foamed mixture RAP_3F2C, Wirtgen recycler model WL 10 S was used. Uncompacted samples from the test section’s base materials RAP_2F1H and GCS_2F1H were collected from the storage stockpiles during the test site construction and then compacted in the laboratory. RAP_3E2C was fully produced in the laboratory and was the only mixture that was also evaluated through the ignition test [26] to assess binder content. The average asphalt content found was 6.8% (1.8% emulsion residue + 5.0% RAP asphalt binder).

2.3. Compaction and Curing Process. The test section samples were prepared by means of the vibratory compaction method, using a 1500 W vibratory hammer with a 5 kg surcharge. Samples with a 100 mm diameter and a final height of 150 mm were produced (in two layers) using the same compaction procedure reported by Meneses et al. [27]. The curing process consisted of maintaining the compacted specimens in the forced draft oven at 40°C for different curing times (0 or 28 days). The samples tested without curing (time zero) were sealed after compaction and tested at the compaction moisture content.

2.4. Flow Number. The flow number (FN) test was used to evaluate CRAM’s permanent deformation characteristics
(primary, secondary, and tertiary zones) by subjecting the compacted specimens to a cyclic loading (1 Hz), without confinement. In the FN test, the total number of cycles and the duration of the test depend on the temperature and stress level [28]. The FN is then defined as the number of load cycles that takes the specimen to the beginning of the tertiary deformation zone, which corresponds to the minimum permanent axial deformation [29, 30]. The deformation data and the number of cycles are adjusted with the Francken model, which was determined by Biligiri et al. [31].

In this study, three different test methods were conducted for a more comprehensive characterization of CRAM’s permanent deformation: (i) ABNT NBR 16505 [32]; (ii) adaptation of the FN test for CRAM [24]; (iii) deviatoric stresses setup from 3D-Move analysis software simulation [33] of pavement structures.

The ABNT NBR 16505 [32] specifies a cyclic axial stress of 204 kPa at 60°C. This method aimed to evaluate the CRAMs in the same conditions that HMA mixtures applied in the wearing course are usually tested. Kim and Lee’s [24] method (developed for cold recycled asphalt mixtures) consisted of 140 kPa axial stress cyclic loading at 40°C (conditions considered closer to the asphalt pavement base layer). The objective of this method is reaching the tertiary zone in a reasonable number of cycles that do not exceed 10,000 load cycles. Simulations of the pavement structures of

| Stable agent | RAP_3E2C | RAP_3F2C | RAP_2F1H | GCS_2F1H |
|--------------|----------|----------|----------|----------|
| 3% slow setting polymer modified cationic emulsion | 3% 85/100 penetration grade foamed asphalt (2.6% foaming water) | 2.2% 50/70 penetration grade foamed asphalt (2.6% foaming water) | 2.0% 50/70 penetration grade foamed asphalt (2.6% foaming water) |
| Active filler | 2% portland cement | 2% portland cement | 1% hydrated lime | 1% hydrated lime |
| Aggregate mineral skeleton | 98% RAP | 68% RAP + 30% fine virgin aggregate | 89% RAP + 10% fine virgin aggregate | 99% virgin aggregate |
| Total moisture content | 5.5% | 6.5% | 7.5% | 7.5% |
the test sections were performed using the 3D-Move software, as an approach to define the magnitude of the deviatoric stresses.

3. Results and Discussion

3.1. 3D-Move Analysis Simulation. The 3D-Move software is a continuum-based finite layer approach to estimate pavement responses. The software analysis and considers important factors, such as moving dynamic loads, tire-pavement contact area, layer temperature, and viscoelastic properties of asphaltic materials [30, 34–38].

The four test sections (Figure 2) were simulated using the 3D-Move analysis program. Poisson’s ratio ($\nu$) of the HMA, GAP, and base layers were considered 0.35, while the remaining infrastructure was 0.45. A single semi-axle load (dual tire) configuration was selected, with a circular contact area (radius = 0.107 m). The circular contact area is one of the most adopted by researchers and transport agencies [38]. The contact pressure was 560 kPa, and loads of 8, 10, and 14 tonnes were evaluated. Load speeds of 40, 50, 75, 80, 100, and 120 km/h were simulated. The remaining infrastructure of the test sections was tested by means of a light weight deflectometer (LWD) and the mean modulus value of 118 MPa was found.

Different temperature conditions were used to simulate the effect of the temperature dependence of the recycled materials on the pavement structure response. For the HMA sections, 50°C and 40°C were adopted for the surface layer and base layer, respectively; for the gap-graded sections, 55°C for the surface layer and 50°C for the base layer [39]. In addition to the information required for the simulation with the 3D-Move analysis software, mixtures and binders’ viscoelastic properties were obtained through rheological tests.

For this work, only the vertical stress data from the simulations were considered, although displacements, strains, and horizontal stresses were also available from 3D-Move. The 3D-Move simulations were employed only to verify an approximate stress state condition that the materials would be submitted in the field. Results of vertical stress for the base layers (at the alignment of the outer tire middle—where higher vertical stresses were found) at 40 km/h are shown in Figure 4 (top, middle, and bottom layer).

For the RAP_3E2C, the maximum stress was 403.61 kPa at the top of the base layer. The stress level in the middle of the layer was approximately 60% lower than the maximum stress, and at the bottom, the stress level was 85% lower. Therefore, the top of the base layer was considered the critical point for vertical stress. The trend observed for the other pavement structures was similar.

The influence of the load speed on the base layer is shown in Figure 5. The load speed increase has caused a small stress value reduction. Considering the RAP_3E2C base layer, the stress level reduction was 5% when the load speed increases from 40 km/h to 120 km/h (from 403.61 kPa to 392.24 kPa). Again, the trend observed for the other pavement structures was similar.

The vertical stress response was then evaluated in different structures (Figure 2) to analyse the influence of the applied load and speed on the mechanical response of the base materials. Figure 6 shows the vertical stress at the top of the base layer for the different CRAMs.

From Figure 6, it is observed that the vertical stress values were significantly higher for the segments with thinner surface layer (30 mm GAP - RAP_2F1H and GCS_2G1H). For both segments, there is a small increase in stress after the load increase, due to the thin asphalt layer and the higher temperature used in the simulations. At the thicker surface layer pavements (125 mm HMA–RAP_3E2C and RAP_3F2C), the load increase from 8 tf to 14 tf, which was approximately 15% the vertical stress (at 40 km/h). The stress values were lower when compared to the thin surface segments.

After the 3D-Move analysis, the following stresses (considering the temperatures used in the simulations) were selected for the 3D-Move based FN tests: (i) RAP_3E2C—400 kPa axial stress at 50°C; (ii) RAP_3F2C—440 kPa axial stress at 50°C; (iii) RAP_2F1H—350 kPa axial stress at 50°C; (iv) GCS_2F1H—550 kPa axial stress at 50°C. ABNT NBR 16505 [32] and Kim and Lee’s [24] methods were used without changes.
3.2. Flow Number. The considered load configuration (for the flow number assessment) in 3D-Move was a dual wheel semi-axle, with 20 kN per tire. The contact pressure selected was 560 kPa, uniformly distributed on a 0.107 m radius circle. The loading speed was set to 40 km/h. The temperatures of 3D-Move simulations remained the same. The surface asphalt mixtures and the recycled bases were characterized by means of the dynamic modulus test ($|E'|$ and $\delta$), and the mixtures’ asphalt binder was rheologically characterized by means of a dynamic shear rheometer ($|G'|$ and $\delta$). This data is mandatory in the 3D-Move software. The mixtures’ $|E'|$ master curves are presented on Figure 7.

FN test results for the three different load/temperature conditions are presented in Figure 8 and Table 2. Two replicates were tested for each condition (some samples presented issues during the test, especially the samples without curing, and were discarded). In some cases, the sample did not reach the FN, especially when the test was performed with a 140 kPa axial stress at 40°C, according to the method suggested by Kim and Lee [24] for CRAM stabilized with asphalt emulsion. The FN result of the HMA used in the wearing course of the segments with RAP_3E2C and RAP_3F2C is also presented in Table 2 for reference.

The RAP_3E2C mixture behavior was the closest to the hot asphalt mixture behavior in terms of sensitivity to deformation. That behaviour may be related to the fact that this is the only mixture prepared with asphalt emulsion which did not include virgin aggregates (which has higher angularity and thus confers higher resistance to permanent deformation). However, the same did not happen for all CRAMs. Even for a high load cycle number (10,000 cycles), the foamed mixtures (RAP_3F2C, RAP_2F1H, and GCS_2F1H) did not reach the tertiary deformation zone for some procedures evaluated (especially after curing). It should be remarked that RAP_3E2C mixture.

The method proposed by Kim and Lee [24] showed little efficacy for the analysis of the CRAMs tested in this work. The specimens have well withstood the stress and temperature proposed by the method.

All mixtures (without curing) have reached the FN under the 3D-Move test conditions after 28 days of curing, except for the GCS_2F1H mixture. In this method (3D-
Move), the samples showed a greater influence of the deviatoric stress, and the specimens have reached the FN with a smaller load cycle number.

The ABNT NBR 16505 [32] method, conventionally used for HMA, highlighted the influence of the temperature increase (60°C). The samples reached the FN before the end of their load cycle.
Figure 7: Mixtures’ dynamic modulus (|E*|) master curve (source: Kuchiishi et al. [40]).

Figure 8: Continued.
of the test for most of the mixtures without curing, although the stress level values were almost half of the stresses adopted from 3D-Move simulations. This indicates that 60°C is critical for the loading conditions of the evaluated mixtures and it raises the question if this is the best option for base materials.

The mechanical response of the GCS_2F1H mixture was less influenced by the temperature variation, as most of its composition is virgin aggregates (lower binder content, if compared to the mixtures with RAP in its composition).

All methods highlighted the effect of curing on the permanent deformation behaviour of the tested materials.
The asphalt pavement design should address the curing process issue to avoid early material failure after opening to traffic [41].

3.3. Test Section Monitoring. The rutting of the experimental sections was monitored for 45 months (RAP_3E2C and RAP_3F2C) and 14 months (RAP_2F1H and GCS_2F1H). The field measurements were performed on the wheel path (inner and outer) and at every 20 meters of the sections. The mean results and their standard error are presented in Figures 9 and 10.

![Figure 9: Mean rutting (and standard error) vs. months after construction (RAP_3F2C and RAP_3E2C).](image)

![Figure 10: Mean rutting (and standard error) vs. months after construction (RAP_2F1H and GCS_2F1H).](image)

Besides the inherent high variability of some results (attributed to the manual measurement method), clear trends are observed. The rutting values of RAP_2F1H and GCS_2F1H sections were much higher than the RAP_3E2C and RAP_3F2C sections, mainly due to the pavement configuration (RAP_3E2C and RAP_3F2C structures have a thicker HMA layer), but may also be related to the construction process quality, as 2 mm rutting values were observed right after the sections’ construction. Therefore, it can be considered that RAP_3E2C and RAP_3F2C CRAMs have performed satisfactorily (only around 1 mm rut), even after almost four years of heavy traffic loads. RAP_2F1H and GCS_2F1H CRAMs have shown a worse performance, but once again, this may be related to the high stress that the CRAM layer was submitted due to the thin gap-graded asphalt mixture layer (30 mm). All test sections presented stabilized results after around 10 months of construction, attributed to the curing of the base materials. The field permanent deformation values are sufficient to validate the FN test results. The fact that some mixtures did not reach the flow number during FN tests can be related to a high permanent deformation resistance of the mixtures, since good rutting performance was observed in the field.

It is noted that RAP_3E2C and RAP_3F2C mixtures performed similarly in the field, from the rutting monitoring perspective. But these mixtures presented different behaviour under FN tests. This fact can be attributed to the differences in FN and field stress state and strain levels. It should also be remarked that in the field, the CRAM layers are under the surface course layer, which is responsible for absorbing traffic loads and better distributing them to the lower layers.

4. Conclusions

The present study evaluated the permanent deformation of CRAMs using three variations of the flow number method: (i) ABNT NBR 16505 [32]—204 kPa and 60°C (method A); (ii) the method proposed by Kim and Lee [24]—140 kPa and 40°C (method B); (iii) using the results of 3D-Move software (to define the deviatoric stresses), through the analysis of an extensive database obtained from the four asphalt pavement structures analyzed, submitted to dynamic loads of traffic at various speeds—400/440/550 kPa and 50°C (method C). Based on the results presented, the following conclusions can be made: [20, 42].

(i) 3D-Move software simulations proved to be a good analysis tool and aided the laboratory test’s stresses definition. The software efficiency was corroborated by the data obtained from the test sections survey

(ii) From the simulations, it was possible to observe the influence of the load speed and load magnitude, which was reflected on the FN test results

(iii) The curing was a preponderant factor for all studied mixtures, providing a greater resistance to permanent deformation at all conditions selected for the FN test. The FN test’s critical temperature needs to be better investigated to better correlate with the field data

(iv) The RAP_3E2C mixture was more influenced by the temperature and load magnitude in the laboratory tests. This may have happened due to the highest asphalt binder content among the mixtures tested and the form of binder dispersion (emulsion) in the mixture. In addition, the 98% RAP composition may have contributed to a greater susceptibility to permanent deformation at the laboratory

(v) The stress condition applied to the material plays a major role in the permanent deformation behaviour. The thicker wearing course layer on the top of
the CRAM layer will protect it from major rutting issues.

(vi) Field monitoring of the test sections has shown a trend that corroborates the FN test results: a good permanent deformation resistance performance was observed after months of monitoring and stabilization of the plastic deformation probably attributed to the curing process of the CRAM materials.

Data Availability

The data will be available from the corresponding author upon request by email (kamilla.vasconcelos@usp.br).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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