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Study of the influence of the mastic coating of untreated reclaimed asphalt pavement on the permanent and resilient behavior

Laura Gaillard¹, Cyrille Chazallon², Pierre Horny³, Juan Carlos Quezada⁴, and Jean-Luc Geffard⁵

ABSTRACT

Asphalt aggregates arise from the demolition of asphalt road layers. The ORRAP (Optimal Recycling of Reclaimed Asphalts in low-traffic Pavements) Project concerns the cold recycling of 100% Reclaimed Asphalt Pavement (RAP) without binder addition in base and subbase layers of low-traffic roads. In this context, a test program was performed with Rhine Region materials to evaluate the impact of the mastic coating of untreated RAP. A source of reclaimed asphalts with 4.4% of bitumen is tested before (RAP) and after binder extraction (RAP-BE), then is compared to an unbound granular material (UGM) with a similar particle size distribution. Repeated Load Triaxial (RLT) tests were conducted at several frequencies to study the permanent and resilient behaviors. The results show that the RAP before binder extraction and the UGM present similar permanent behaviors, while the aggregates without binder reveal low strains. Concerning the resilient phase, the RAP and the RAP-BE show similar levels of strains, but the resilient moduli

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3 of the UGM are significantly lower than those of the RAP. From the experimental results, the non-
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5 linear elastic Boyce model was fitted and brings out a highly anisotropic mechanical behavior of
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7 the RAP. Finally, the RAP shows a frequency sensitive viscous behavior due to the bitumen in the
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9 mastic, while the effect of frequency is negligible for the RAP-BE.

12 **Keywords**

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14 reclaimed asphalt pavement, mastic coating, repeated load triaxial test, mechanical behavior.
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19 **Introduction**

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22 Many studies on recycling of asphalt aggregates have been carried out, in particular on the
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24 incorporation of Reclaimed Asphalt Pavement (RAP) in hot asphalt mixtures¹⁻⁴, in warm processes
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26 by means of additives or foamed asphalts⁵⁻⁷, as well as in cold recycling with foamed or emulsion
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28 bitumen⁸⁻¹⁰. However, the use of RAP without any addition, developed in Sweden¹¹, is still not
29
30 widespread. In France, the cold recycling strategy allows to reuse RAP with high Polycyclic
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32 Aromatic Hydrocarbons (PAH) contents (from 50 mg/kg to 500 mg/kg). The ORRAP (Optimal
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34 Recycling of Reclaimed Asphalts in low-traffic Pavements) project concerns the cold recycling of
35
36 100% RAP without binder addition in base and subbase layers of low-traffic roads, instead of
37
38 Unbound Granular Materials (UGM). In this framework, the effect of the mastic coating is studied,
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40 to measure the benefit of this recycling. A series of Repeated Load Triaxial (RLT) Tests is carried
41
42 out at several frequencies to analyze the permanent strains and the resilient moduli of a source of
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44 untreated RAP with a PAH content of 298 mg/kg and to compare them with a conventional UGM.
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46 Then, the Boyce model is used to describe the resilient behavior of each material and to determine
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48 the resilient and characteristic moduli.
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Materials and Methods

Material characterization

The tested RAP (fig. 1) comes from demolition of wearing courses of the Rhine Region. This material is defined as 25 RAP 0/14, according to the French Standard NF EN 13108-8¹², where 25 is the maximum size of particles before binder extraction and 0/14 the grading of particles after binder extraction. The RAP contains 4.4% of grade 10/20 bitumen. This material is studied before (RAP) and after binder extraction (RAP-BE), and then compared to an unbound granular material (UGM) with a similar particle size distribution (fig. 3). The UGM comes from the Rhine alluvium with a silico-calcareous mineralogical nature. This material was obtained from a composition of different particle size fractions (fig 2). Table 1 gives the main characteristics of the RAP and UGM. Unbound granular materials and asphalt mixtures represent the limits of the RAP behavior. Figure 3 shows the 0/14 mm UGM and the 0/14 mm asphalt mix grading curves and the corresponding limits of the French Standards^{13,14}. The binder extraction produces fines, and consequently the fines content (passing through the 63 μm sieve) is multiplied by four after extraction.

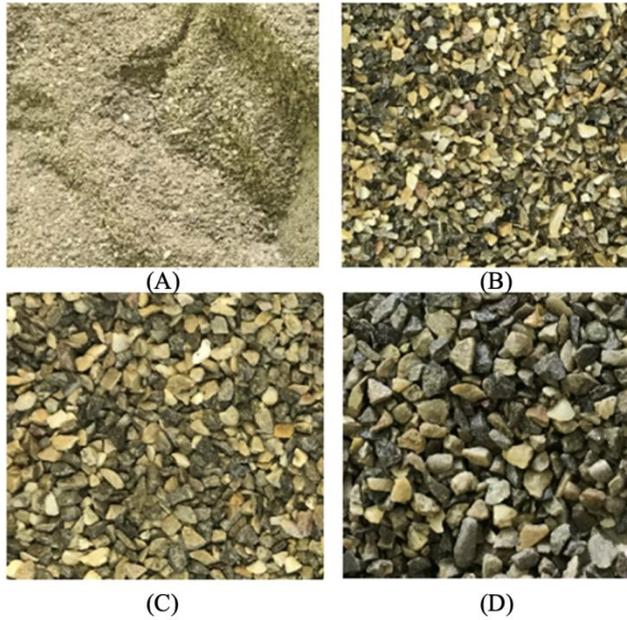
FIGURE 1

Reclaimed Asphalt Pavement from the Rhine Region

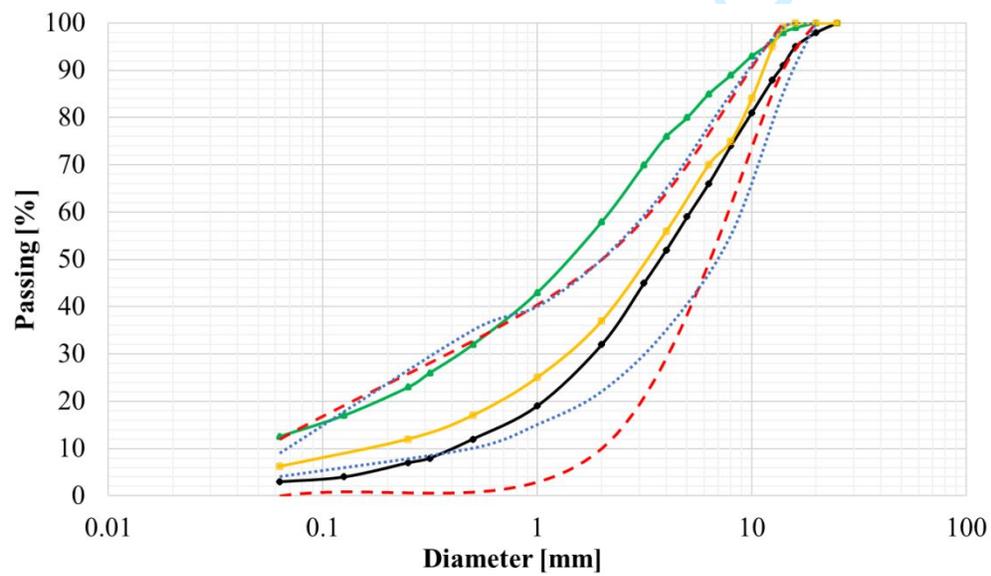


FIGURE 2

Size fractions for the composition of the UGM: (A) 0/4 mm (B) 4/6 mm (C) 6/10 mm (D) 10/14 mm

**FIGURE 3**

Particle size distributions of the studied materials



—●— RAP
 —●— UGM
 - - - Grading range of asphalt mixture 0/14
 - - - Grading range of UGM 0/14
 —●— RAP-BE

TABLE 1

Characteristics of the RAP and the UGM

	RAP	RAP-BE	UGM
Grading, mm	25 AE 0/14	0/14	0/14
Particle density, g/cm ³	2.48	2.65	2.64
Proctor maximum dry density, g/cm ³	2.02	2.21	2.16
Proctor optimum water content, %	5.86	5.31	7.60
Binder content, %	4,4	0	0
PAH content, mg/kg	298	0	0

Sampling

The specimens are compacted using a vibrocompression device in one layer, by applying simultaneously a vertical load and a horizontal vibration. This method guarantees a homogeneous density within the sample. The cylindrical sample has a diameter of 160 mm and a height of 320 mm. Table 2 presents the characteristics of different specimens.

TABLE 2

Characteristics of the specimens

	RAP	RAP-BE	UGM
Compaction density, g/cm ³	1.96	2.14	1.96
Void content	0.27	0.24	0.35
Porosity, %	21.1	19.29	25.85
Water content, %	3.9	3.3	3.9
Number of specimens	3	2	2

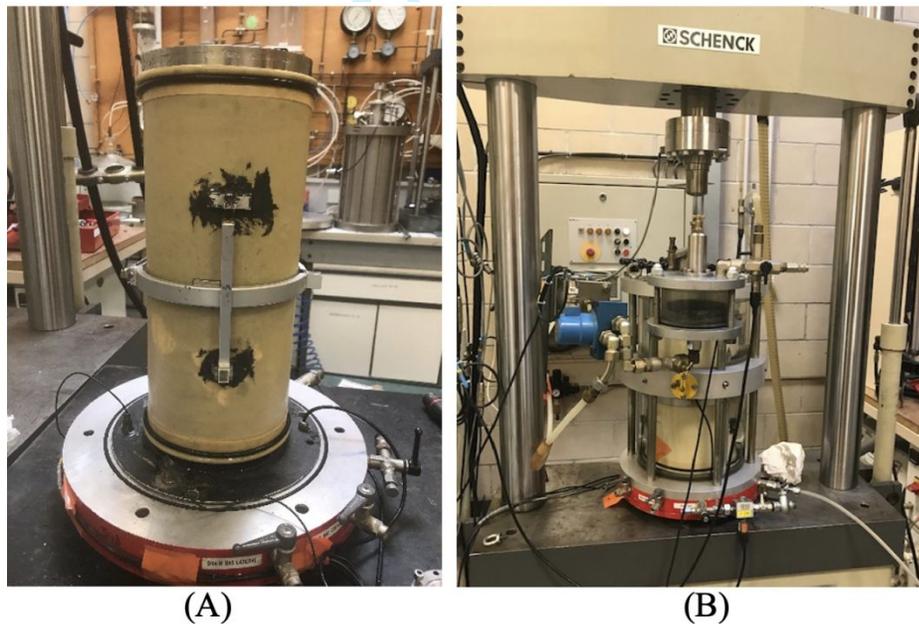
Triaxial apparatus

The sample is placed in a triaxial cell, and a constant or variable cell pressure is applied using water as confining fluid and a servo-pneumatic system. A hydraulic actuator is used to apply the cyclic axial load. The specimen is instrumented with three Hall effect displacement transducers:

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3 two axial and one radial. Figure 4 presents the experimental device. Our system can apply a
4 frequency of 10 Hz with constant cell pressure and 2 Hz with variable cell pressure. All the tests
5 are performed at laboratory temperature (20 °C) and using the same test procedures as for unbound
6 granular materials.
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15 **FIGURE 4**

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17 Experimental device: (A) instrumented specimen (B) triaxial cell on the hydraulic press
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44 **Repeated Load Triaxial (RLT) tests**

45 The sign conventions are:

- 46 - The stresses are positive in compression.
 - 47 - The axial and radial strains are positive in contraction.
 - 48 - A positive (negative) volumetric strain indicates a contractant (dilatant) behavior.
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54 The RLT test is one of the most reliable test methods to analyze the permanent and resilient
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behavior of unbound granular materials. The test method used in this work, defined by the French Standard EN 13286-7¹⁵, allows to simulate traffic loads. The test principle (fig. 5) consists in applying a cyclic axial stress σ_1 and a constant or variable confining pressure σ_3 . Equations (1) and (2) define the deviator stress q and the mean stress p . During the test, the axial strains ε_1 and the radial strains ε_3 are measured, then the deviatoric strains ε_q and the volumetric strains ε_v can be calculated (equations (3)-(4)).

$$q = \sigma_1 - \sigma_3 \quad \#(1)$$

$$p = \frac{\sigma_1 + 2 \sigma_3}{3} \quad \#(2)$$

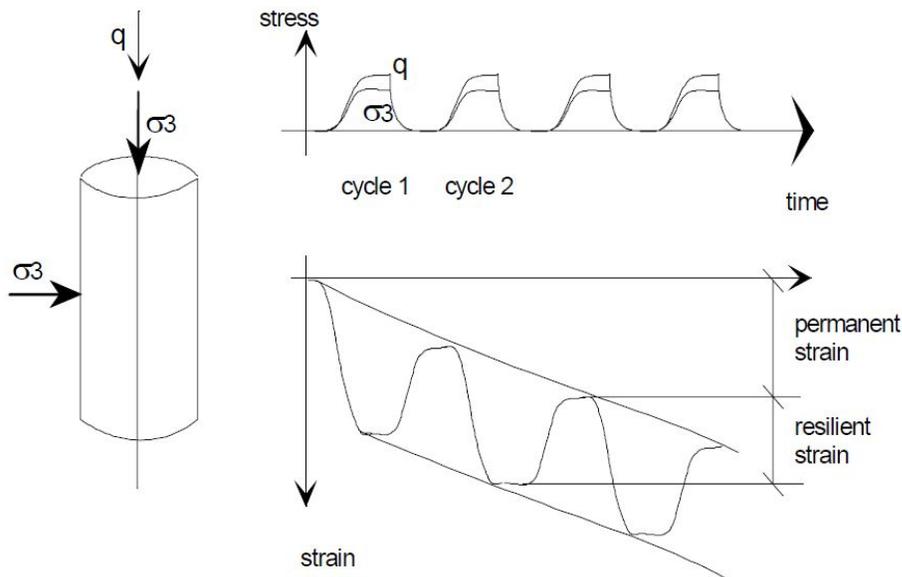
$$\varepsilon_q = 2 \frac{\varepsilon_1 - \varepsilon_3}{3} \quad \#(3)$$

$$\varepsilon_v = \varepsilon_1 + 2 \varepsilon_3 \quad \#(4)$$

The test presents two phases:

- The conditioning phase: application of a high stress level ($\Delta q=340$ kPa, $\Delta p=113$ kPa, $\sigma_3=70$ kPa) during 30,000 cycles at 2 Hz to stabilize the permanent strains.
- The resilient test: application of several stress paths, each during 100 cycles, to study the elastic strains at different frequencies (table 3). Figures 6 and 7 present the different stress paths with constant cell pressure ($\Delta q/\Delta p=3$) and variable cell pressure ($\Delta q/\Delta p \neq 3$).

The unbound granular material (UGM) is tested at a constant frequency of 2 Hz.

FIGURE 5Principle of the repeated load triaxial test¹⁶**TABLE 3**

Frequencies for the repeated load triaxial tests

Slope of stress path $\Delta q/\Delta p$	Frequency, Hz
0, 1, 1.5, 2	0.1, 0.5, 1, 2
3	0.1, 0.5, 1, 2, 5, 10

FIGURE 6

Stress paths with constant cell pressure

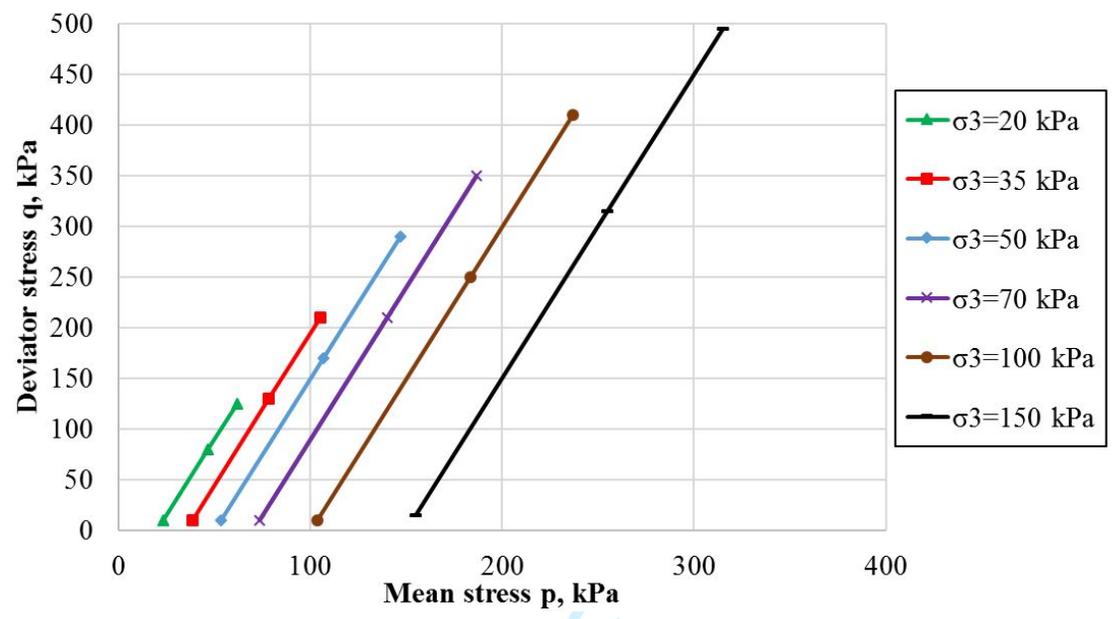
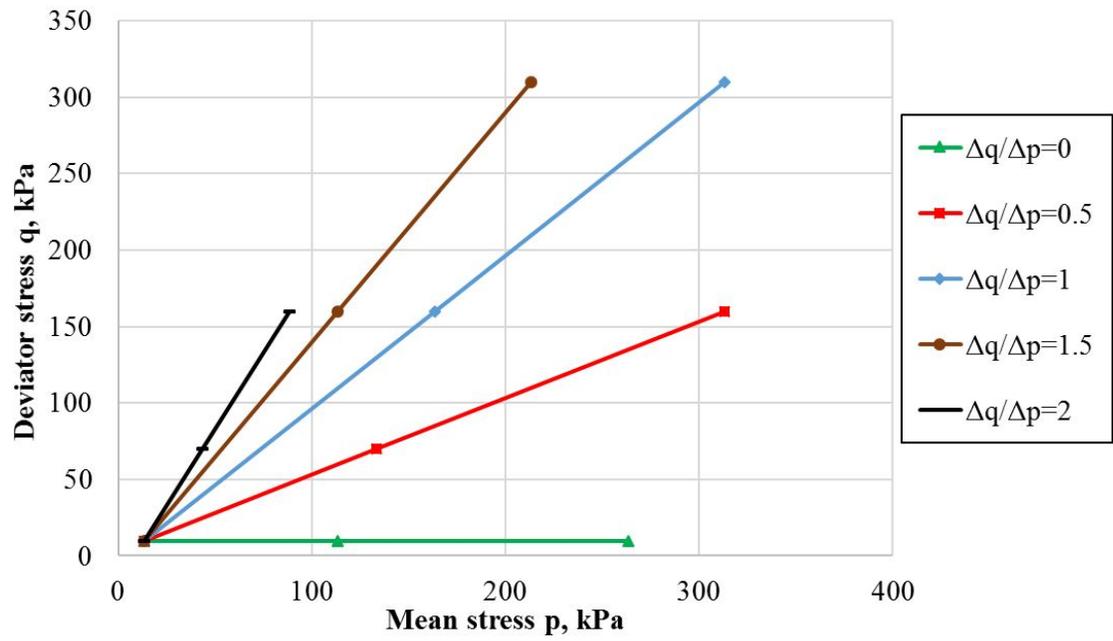


FIGURE 7

Stress paths with variable cell pressure



Results and discussion

Conditioning phase

Figures 8 and 9 show the evolution of the axial and radial permanent strains. The RAP before binder extraction and the UGM present similar permanent strains, particularly for the axial strains. However, the permanent strains of RAP-BE, after binder extraction, are much lower. These results can mainly be explained by the differences in fines content, in addition to the tested density and water content. The RAP before and after extraction present respectively 3.0% and 12.6% of fines. According to Jing, Nowamooz and Chazallon^{17,18}, the quantity of fines improves the rutting resistance, until a critical water content close to saturation. Indeed, before binder extraction, the fines are trapped in the mastic coating, while after the extraction the fines are released and lead to a reduction of the rutting.

According to the French Standard for Unbound Granular Materials (UGM) NF EN 13286-7¹⁵, the axial permanent strains of the RAP are high and outside the specifications for use in base and subbase layers of low traffic pavements. However, the RAP presents a rutting resistance similar to the tested UGM. In order to reduce the rutting, the *in situ* density can be increased.

FIGURE 8

Evolution of permanent axial strains

(with an indication of standard deviations at cycles 10,000 and 30,000)

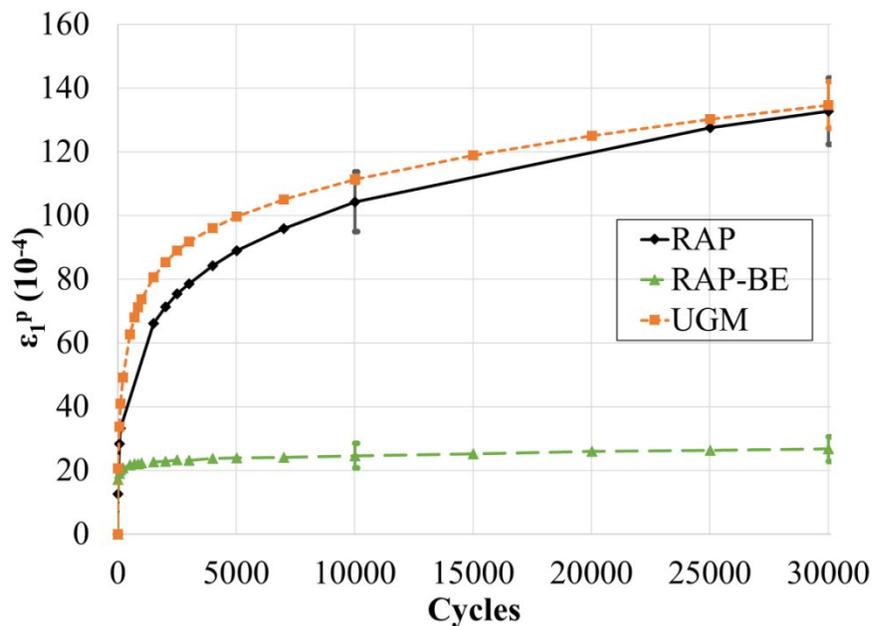
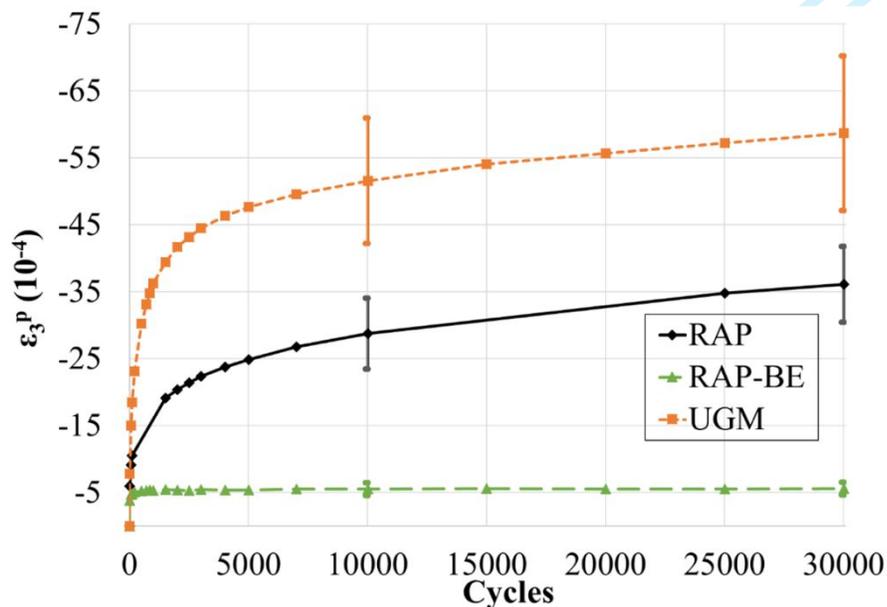


FIGURE 9

Evolution of permanent radial strains

(with an indication of standard deviations at cycles 10,000 and 30,000)



Resilient test

The resilient axial and radial strains are determined during the unloading phase of a cycle, using equations (5) and (6).

$$\varepsilon_1^r = \varepsilon_1^{max} - \varepsilon_1^{min} \quad \#(5)$$

$$\varepsilon_3^r = \varepsilon_3^{max} - \varepsilon_3^{min} \quad \#(6)$$

The resilient strains allow to calculate the resilient modulus, using equation (7) for constant confining pressure or equation (8) for variable confining pressure.

$$E_r = \frac{\sigma_1^r}{\varepsilon_1^r} \quad \#(7)$$

$$E_r = \frac{\sigma_1^{r2} + \sigma_1^r \sigma_3^r - 2 \sigma_3^{r2}}{\sigma_1^r \varepsilon_1^r + \sigma_3^r \varepsilon_1^r - 2 \sigma_3^r \varepsilon_3^r} \quad \#(8)$$

Boyce model

The non-linear elastic Boyce model¹⁹ effectively describes the resilient behavior of granular materials. Three parameters define this model: n , K_a related to the bulk modulus and G_a related to the shear modulus. Horny, Kazai and Piau²⁰ introduced the additional parameter γ to take into account anisotropy of modulus. Consequently, equations (9)-(12) specify the model stresses and strains.

$$q^* = \gamma \sigma_1 - \sigma_3, 0 < \gamma < 1 \quad \#(9)$$

$$p^* = \frac{\gamma \sigma_1 + 2 \sigma_3}{3} \quad \#(10)$$

$$\varepsilon_v = \frac{p^{*n}}{p_a^{n-1}} \left[\frac{\gamma + 2}{3K_a} + \frac{n-1}{18G_a} (\gamma + 2) \left(\frac{q^*}{p^*} \right)^2 + \frac{\gamma - 1}{3G_a} \frac{q^*}{p^*} \right] \#(11)$$

$$\varepsilon_q = \frac{2}{3} \frac{p^{*n}}{p_a^{n-1}} \left[\frac{\gamma - 1}{3K_a} + \frac{n-1}{18G_a} (\gamma - 1) \left(\frac{q^*}{p^*} \right)^2 + \frac{2\gamma + 1}{6G_a} \frac{q^*}{p^*} \right] \#(12)$$

Where:

p_a = atmospheric pressure, 100 kPa

The model parameters are calibrated using all experimental results and optimized using the least squares method.

Comparison with the UGM

Figures 10 and 11 present the results for the constant and variable cell pressure loadings respectively. Whatever the loading, the resilient behavior of the RAP and of the RAP-BE are similar, while the UGM presents higher strains and consequently lower resilient moduli.

At constant cell pressure, the behaviors of the RAP-BE and of the UGM are respectively contractant and dilatant, while the volumetric strains of the RAP are very small and depend on the confining pressure. For all three materials, the resilient modulus increases when the confining pressure increases. At variable confining pressure, the behavior of all three materials is purely contractant.

We notice that the UGM presents high strains, while the RAP specimens before and after binder extraction present similar levels of strains. Finally, if we consider RAP as an unbound

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3 granular material, the resilient moduli of RAP are high and indicate a good performance. These
4 values are significantly higher than those of the Rhine Region UGM.
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10 For the pavement design, the French Standard for UGM NF EN 13286-7¹⁵ defines the
11 characteristic elastic vertical modulus E_c corresponding to the stress path: $q_{\max} = 500$ kPa and p_{\max}
12 = 250 kPa. For the sake of precision, E_c is determined from the calibration of the Boyce model.
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14 For each material and frequency, the anisotropic Boyce model was fitted using all experimental
15 results. Table 4 summarizes the model parameters for the calibrations at 2 Hz. The last parameter
16 c is the correlation coefficient varying between 0 and 1.
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19 As expected, the UGM has a slightly higher correlation value. However, the model, developed for
20 granular materials, is also able to predict the behavior of the RAP before and after binder
21 extraction, with correlation values close to 0.9.
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24 Equation (13) details the relationship between γ , vertical modulus E_v and horizontal modulus E_h .
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26 The parameter γ reveals a highly anisotropic behavior for the RAP, with a ratio E_v/E_h equal to 4.5,
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28 whereas for the RAP-BE this value is close to 2.7.
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$$\frac{E_v}{E_h} = \frac{1}{\gamma^2} \#(13)$$

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33 Regarding the characteristic modulus E_c , the RAP has the highest value. According to the
34 French Standard for Unbound Granular Materials (UGM) NF EN 13286-7¹⁵, this value
35 corresponds to the performance of a good quality unbound granular material. After binder
36 extraction, the material maintains a high modulus. In comparison, the characteristic modulus of
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38 the UGM is significantly lower than that of the RAP.
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3 In terms of resilient behavior, the RAP before and after binder extraction present similar
4 levels of strains and modulus. Consequently, the mastic does not seem to have a significant impact
5 on the resilient behavior, at least for the tests at a frequency of 2 Hz. In order to understand the
6 role of the mastic, additional tests at different frequencies have been carried out and are presented
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FIGURE 10

Results for the constant cell pressure loadings at 2 Hz: (A) axial strains (B) radial strains (C) volumetric strains (D) deviatoric strains (E) resilient moduli

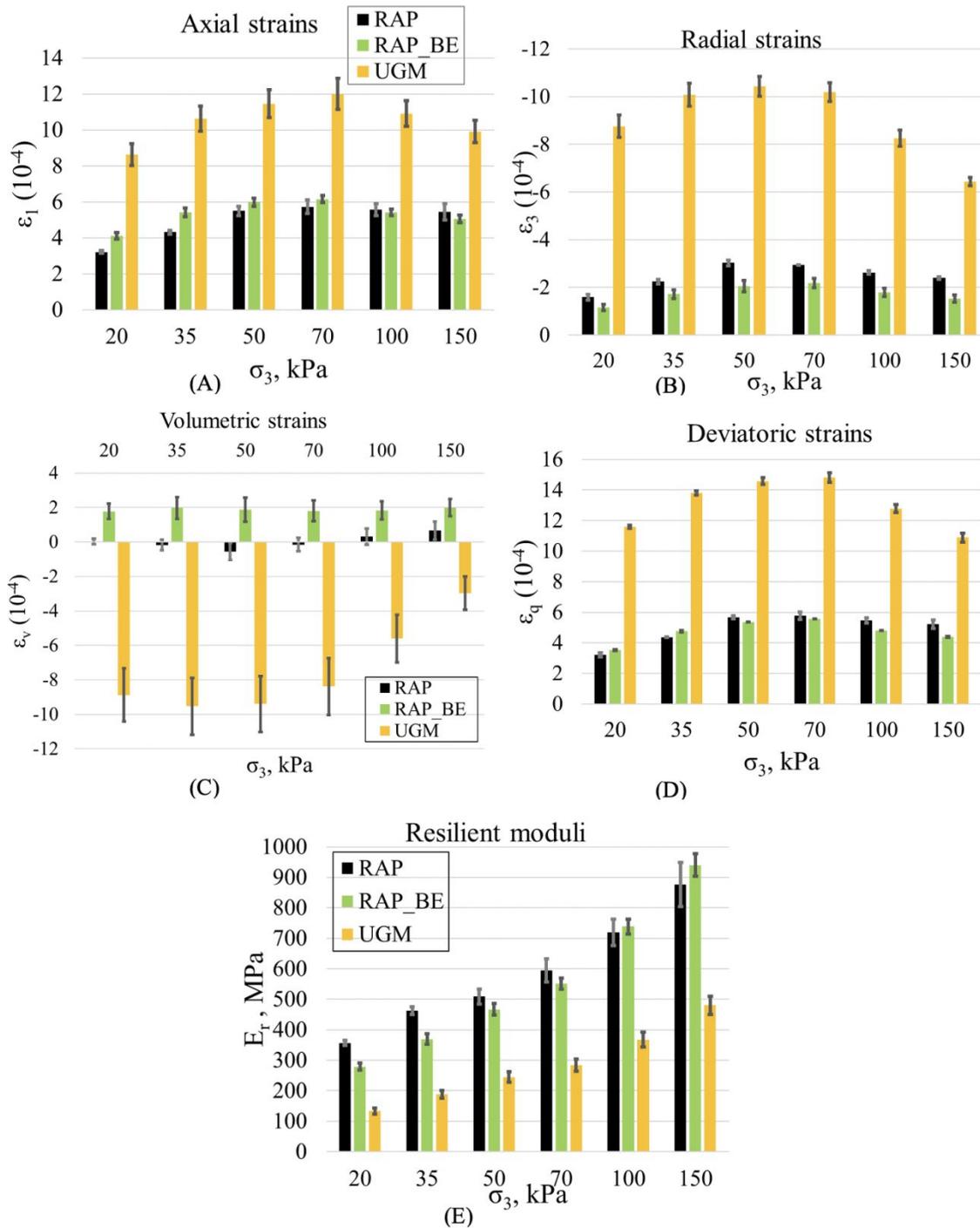


FIGURE 11

Results for the variable cell pressure loadings at 2 Hz: (A) axial strains (B) radial strains (C) volumetric strains (D) deviatoric strains (E) resilient moduli

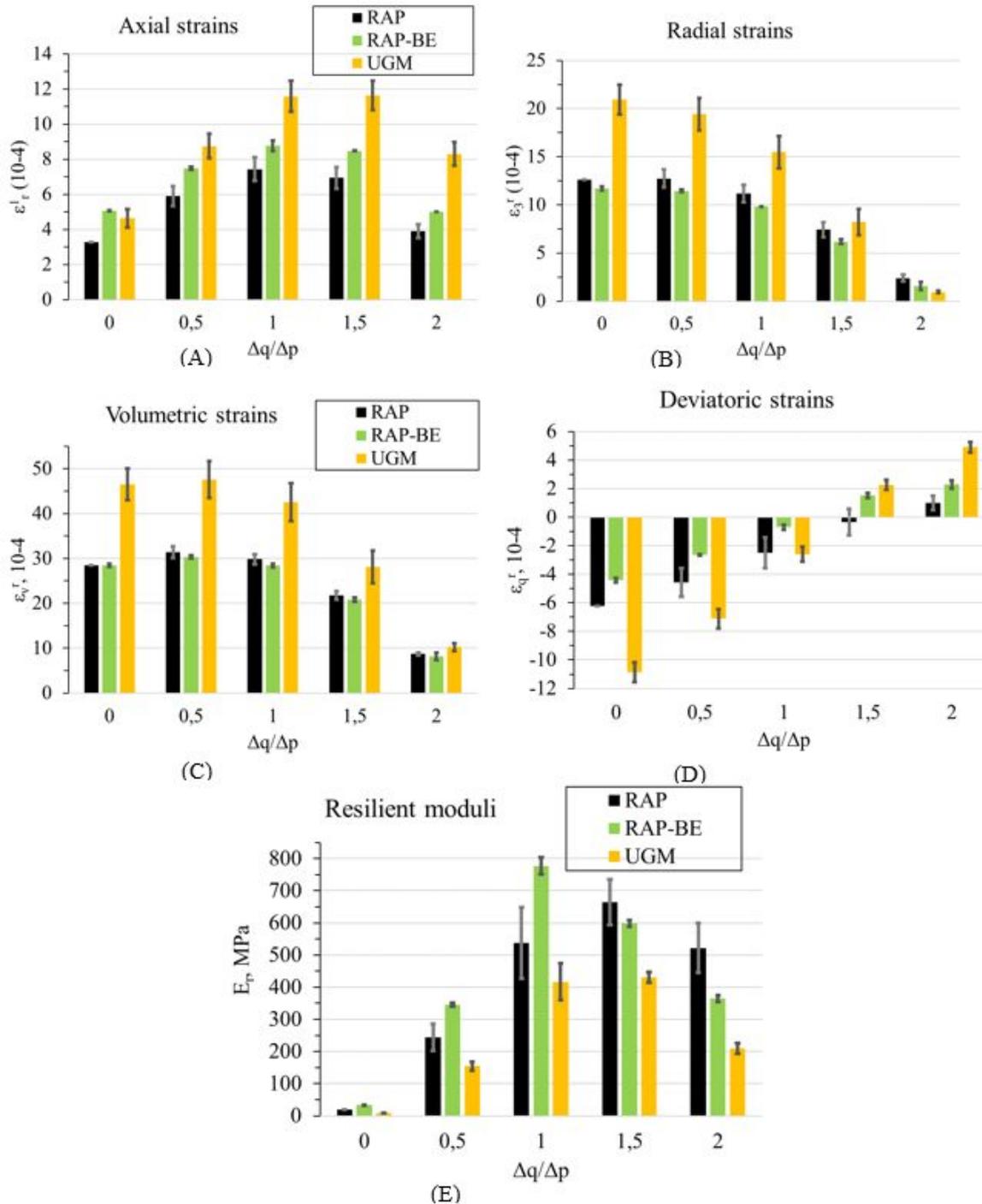


FIGURE 12

Boyce model calibration for the RAP at 2 Hz

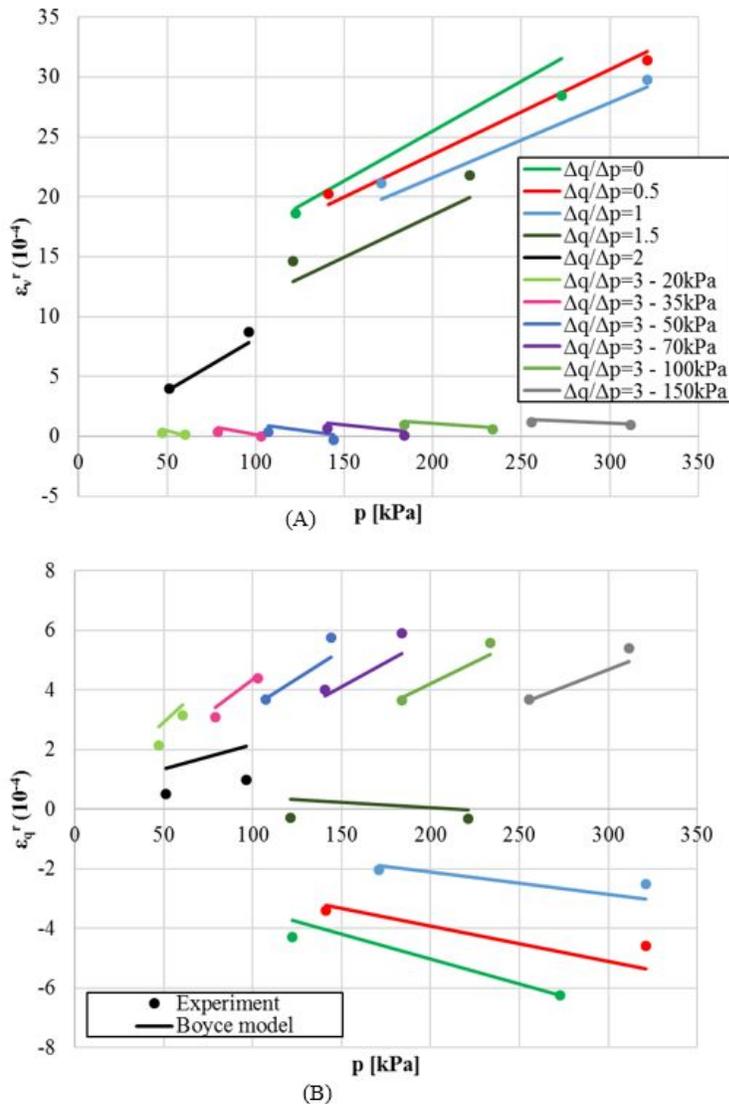


TABLE 4

Model parameters for calibrations at 2 Hz

Material	K_a , MPa	G_a , MPa	n	γ	c	E_c , MPa
RAP	20.73	52.18	0.34	0.47	0.88	519
RAP-BE	20.94	72.14	0.29	0.61	0.89	424
UGM	6.10	20.76	0.14	0.42	0.90	222

Influence of frequency

Figures 13 and 14 show the evolution of the radial and axial strains of the RAP and RAP-BE during a resilient cycle at several frequencies between 0.1 and 10 Hz.

First, the shape of cycles is similar for RAP before and after extraction. Both materials show a non-linear response typical of granular materials¹⁹. This phenomenon is characterized by a stress-strain curve with a hysteresis loop. The presence of bitumen does not change significantly the shape of the curves.

For the RAP, the test results indicate that the strains decrease when the frequency increases. Consequently, high frequency solicitations imply high modulus values. On the contrary, the influence of frequency is negligible for the RAP-BE. The maximum strains are almost the same for all frequencies, due to the absence of bitumen. In conclusion, the binder content of 4,4% in the RAP is sufficient to induce a viscous behavior, sensitive to frequency.

As shown on figure 15, the same effects can be observed for the volumetric and deviatoric strains, as well as for the characteristic modulus. Thus, the mastic coating has an influence on the behavior of the RAP and can allow a positive improvement of performance with time.

FIGURE 13

Evolution of (A) axial and (B) radial strains of the RAP during a resilient cycle at different frequencies for the stress path: $\Delta q/\Delta p=400/133 = 3$, $\sigma_3=100$ kPa

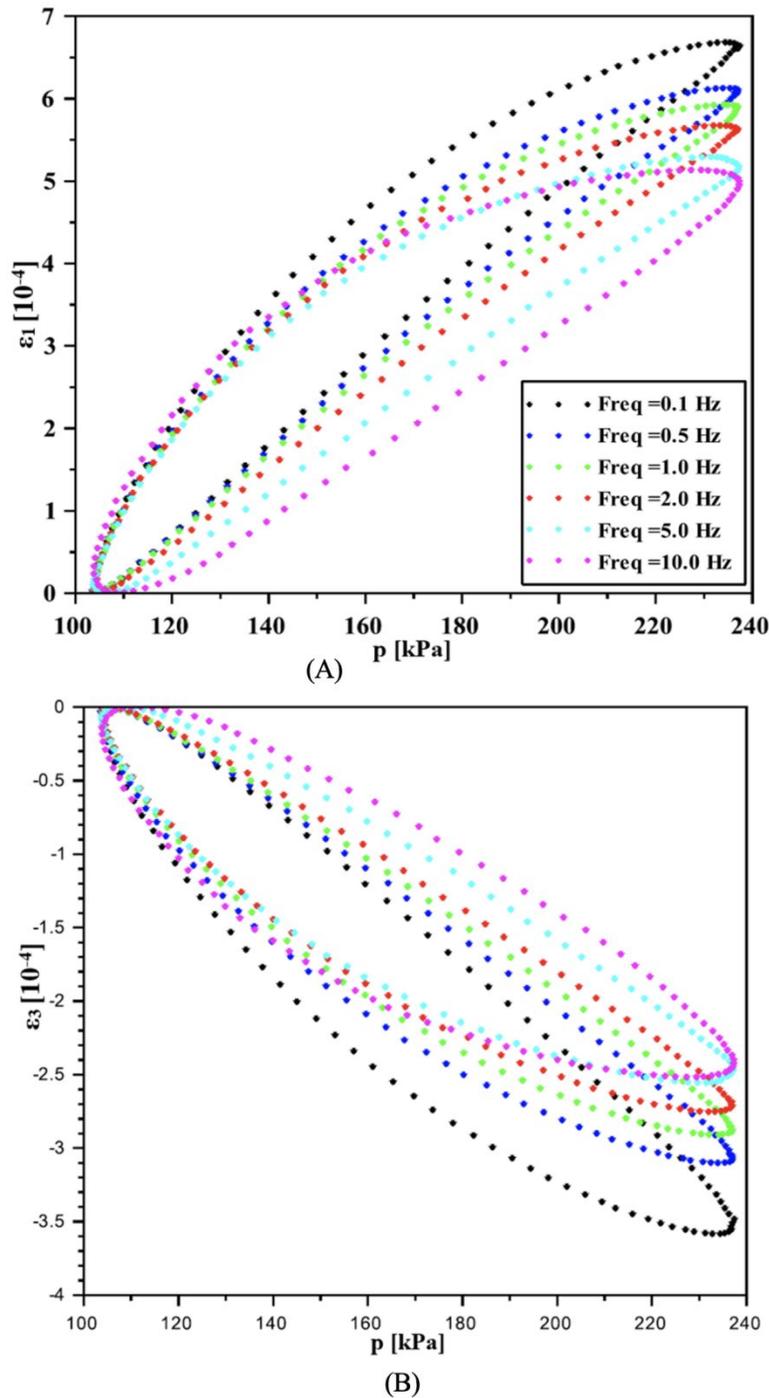


FIGURE 14

Evolution of (A) axial and (B) radial strains of the RAP-BE during a resilient cycle at different frequencies for the stress path: $\Delta q/\Delta p=400/133 = 3$, $\sigma_3=100$ kPa

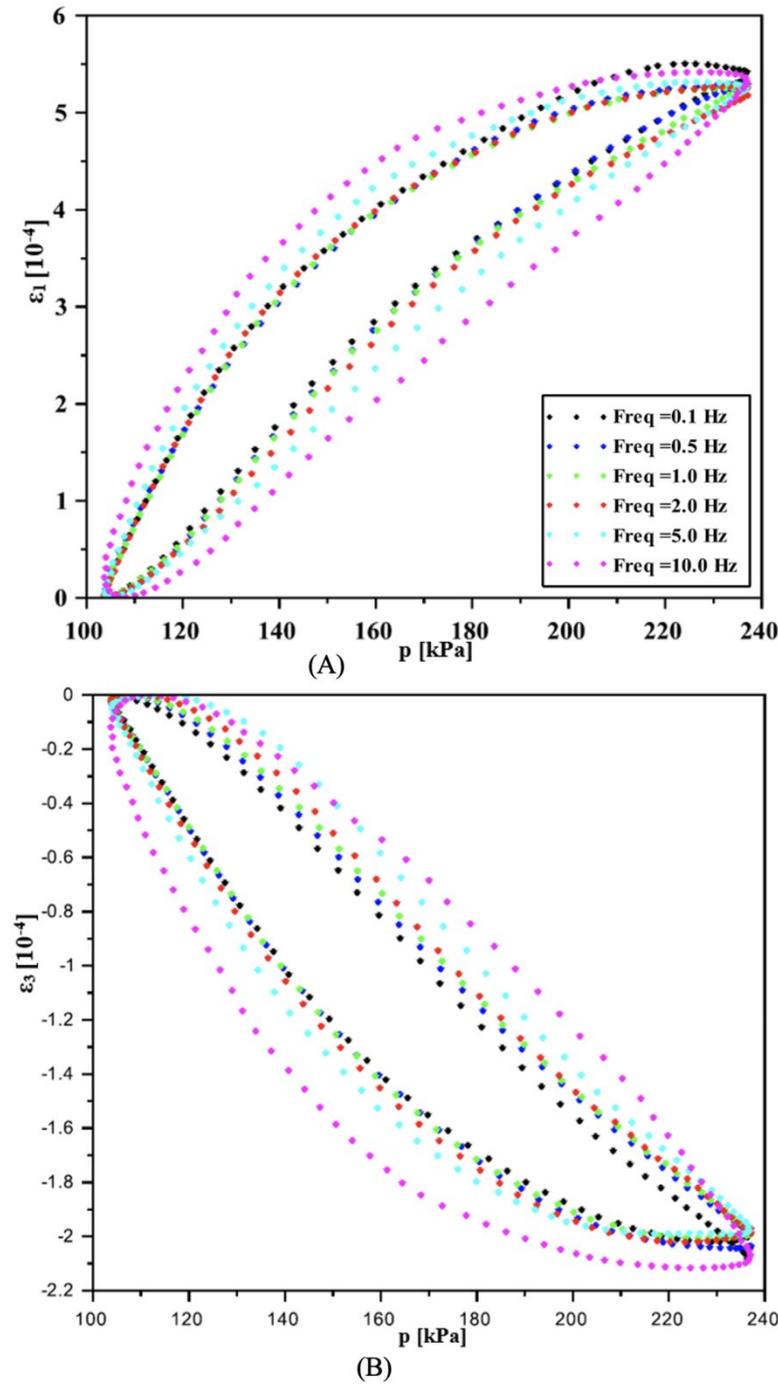
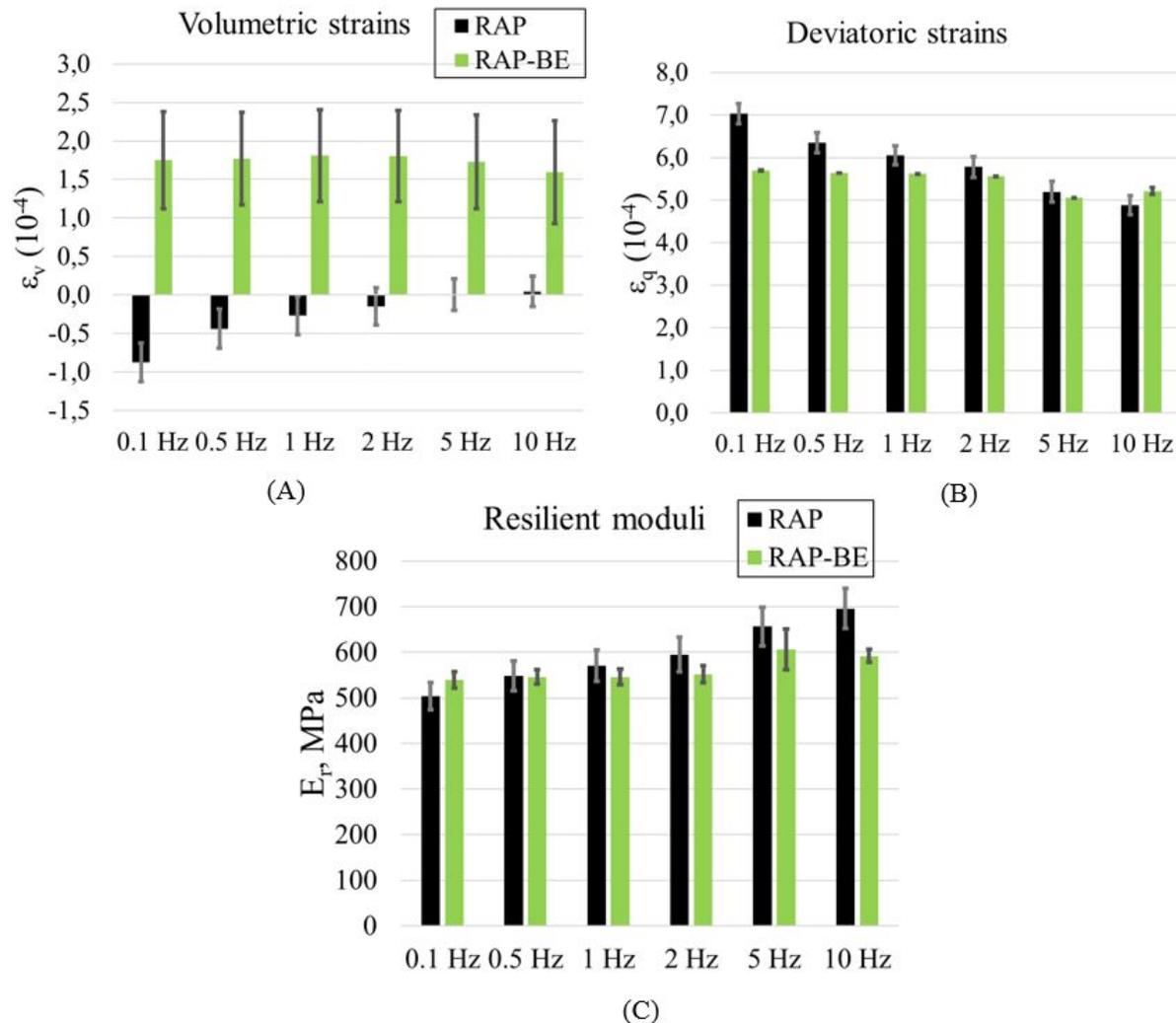


FIGURE 15

Results at several frequencies for the stress path $\Delta q/\Delta p=400/133 = 3$, $\sigma_3=100$ kPa: (A) volumetric strains (B) deviatoric strains (C) resilient moduli



Conclusions

This paper presents some results of the study of a source of Reclaimed Asphalt Pavement (RAP), with a high Polycyclic Aromatic Hydrocarbons (PAH) content (298 mg/kg). The difference between an unbound granular material and the RAP is the presence of the binder (or mastic), which ensures a smooth contact between the rigid particles. This contact has consequences on the permanent and resilient behavior.

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3 First, the conditioning phase reveals a clearly different permanent deformation behavior of
4 the RAP before and after binder extraction. One possible explanation is the important fines content
5 in the RAP-BE which has a beneficial effect on the rutting. The permanent strains of the RAP are
6 high and outside specifications, according to the French Standard for Unbound Granular Materials
7 (UGM) NF EN 13286-7¹⁵. Nevertheless, the reclaimed material and the tested UGM presents a
8 similar rutting resistance. In order to reduce the permanent strains, the *in situ* density can be
9 increased.
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19 Regarding the resilient behavior tests, the RAP specimens before and after binder
20 extraction present similar results, and their performances are significantly higher than those of the
21 UGM. The calibrations of the Boyce model, commonly used for granular materials, show that RAP
22 presents a very similar behavior, and can be considered and utilized as an unbound granular
23 material. However, the tests at different frequencies indicated some influence of the mastic on the
24 behavior of the RAP. The behavior of the RAP was found to be sensitive to frequency (with an
25 increase of stiffness when the frequency increases), whereas the impact of frequency on the RAP-
26 BE appeared negligible. Due to the mastic coating, bonding of the material could develop in the
27 field, with time, and under the effect of post-compaction and lead to an increase of the mechanical
28 properties with time.
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42 In comparison with the tested UGM, the mechanical performances of the RAP are higher
43 both regarding the rutting resistance and the characteristic elastic modulus, used for the pavement
44 design. Consequently, these results confirm that the untreated RAP can be used in place of UGM,
45 in base and subbase layers in low-traffic roads. This solution appears as an interesting alternative
46 to disposal for contaminated RAP.
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