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Investigation on the effect of high amount of Re-recycled RAP with Warm mix asphalt (WMA) technology

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ABSTRACT
In this paper, the effect of the combined use of re-recycled Reclaimed Asphalt Pavement (RAP) on the performance properties of Warm Mix Asphalt (WMA) was experimentally investigated at both binder and mixture scales. First, a virgin 50/70 Pen grade binder and fresh Gabbro aggregates were used to prepare a conventional Hot Mix Asphalt (HMA) for surface layers as a reference mixture. Then, the same reference mix type was used to produce a mixture designed with 40% of RAP, 160/220 Pen grade binder, and Sasobit to prepare the first generation of Warm Mix Asphalt (WMA-1) mixture. Next, WMA-1 was artificially aged to simulate the re-recycled RAP, and the same mix design was adopted to prepare the second generation of WMA with re-recycled RAP identified as WMA-2. Finally, fatigue and low temperature performance of the mixture was evaluated for the three recycling level (reference, first and second recycling). In addition, rheological tests were conducted on the entire set of six asphalt binders used for the mix design, including virgin 50/70, 160/220 Pen grade binders, extracted binders from RAP, WMA-1, artificial aged WMA-1, and WMA-2. Results of asphalt mixtures indicate that WMA-2 shows better low temperature properties compared to the other two mixtures associated with limited reduction in the fatigue response. Concerning asphalt binders, similar rheological properties were observed within virgin 50/70, and two WMA extracted binders in a wide range of temperatures. The present study supports the idea of using re-recycled RAP up to 40% together with WMA technology in the mix design.

1. Introduction
In the attempt to globally achieve the climate-neutral goal, different technologies, materials, and methods have been proposed and evaluated in the pavement construction sector. In this sense, circular economy and resource efficiency have been seen as a roadmap to be adopted to improve the resilience of infrastructures while maximizing their associated climate and economic benefits. Various types of waste materials such as Reclaimed Asphalt Pavement (RAP), Construction and Demolition Waste (CDW), steel slags, plastics, crumb rubber, and glass have been successfully recycled in pavement construction [1–3]. Among these end-of-life materials, RAP has become the most commonly recycled material in asphalt pavements [4–6]. Nevertheless, as the pavement infrastructures continue to age, the need for an established routine-based and repeated recycling process emerges as a fundamental practice to be developed and adopted in the road construction industry.

In the past and more recently, re-recycling of asphalt pavement was investigated in different studies in Japan, U.K., Switzerland, and South Korea [3,7–10]. The experimentation conducted in this series of research efforts has shown that RAP has the potential of being used for a second round of recycling up to a content of 40% in conventional Hot Mix Asphalt (HMA). In addition, comparable performance could be achieved with or without incorporating Asphalt Recycling Agents (ARAs) [11] in the mix design.

Over the years, several studies have indicated that the aged RAP may lead to brittle mixtures with reduced relaxation behavior and hence more prone to cracking at lower temperatures and under repeated loading [12,13]. On the other hand, the increased stiffness of the recycled material may be beneficial at high temperatures resulting in pavements having a better performance against rutting [14,15]. Although several research efforts were devoted to investigating the possibility of using re-recycled RAP, most of these studies focused on the...
application in HMA. Limited attempts are available in the literature on incorporating other materials, such as ARAs and different production techniques, including Warm Mix Asphalt (WMA).

WMA technology was proposed in the 1990s to reduce the emission of greenhouse gas and ultimately develop environmentally friendly and sustainable transportation infrastructures [16,17]. Currently, this technology can achieve performance comparable to the conventional HMA mixture with a reduction of production temperature of 20°C to 40°C [17]. In a previous study [18], it was found that the decrease in production temperature can be ultimately beneficial to the overall aging of the asphalt mixture for both short- and long-term aging conditions. In a recent state-of-art review work by Guo et al. [19], several previous research efforts indicated that WMA designed with RAP shows promising performance over the entire spectrum of service temperatures. However, no previous work was conducted on the combined use of re-recycled RAP and WMA technologies to the knowledge of the authors. Hence, in this paper, the potential of using these two technologies for pavement construction is experimentally studied.

2. Objective and research approach

In this paper, the possibility of using 40% of re-recycled RAP combined with Warm Mix Asphalt (WMA) technology is experimentally investigated at the asphalt binder and mixtures levels. First, a mix-design commonly used for a dense-graded surface layer material in Germany [20], AC 11 D N, was selected, and a reference RAP source was identified. The AC 11 D N mix formula was then used for manufacturing three different asphalt mixtures: one conventional Hot Mix Asphalt (HMA) and two WMA mixtures containing 40% of original RAP and re-recycled RAP, corresponding to the first and second generation of recycled mixtures. Next, the fatigue and thermal properties of asphalt mixtures were evaluated with the Uniaxial Tension Compression Test (UTCT) [21] and Thermal Stress Restrained Specimen Test (TSRST) [22], respectively. Meanwhile, the rheological properties of the six different asphalt binders used for the mixture preparation were investigated. The proposed research methodology is summarized in Fig. 1.

![Fig. 1. Research approach.](image)

![Fig. 2. Grading curve of HMA.](image)
3. Materials

3.1. Asphalt mixtures

Based on the active German standard [20], a conventional mix design for dense-graded surface layer mixtures, AC 11 D N, was selected to produce all three different asphalt mixtures. In particular, a Hot Mix Asphalt (HMA) consisting of an unmodified virgin 50/70 binder [26, 27] and fresh Gabbro aggregate was prepared as reference material. In addition, two Warm Mix Asphalt (WMA) composed by mixing a 160/220 pen-graded binder and Sasobit with 40% recycled materials and 60% fresh Gabbro aggregates were manufactured to address the combination of double recycling and WMA technology. The design and actual grading curves of HMA are shown in Fig. 2.

A single target binder content of 6.2% together with an air voids volume of 1.6% was set for all the mixtures. The actual binder content and air voids are reported in Table 1. The Recycled Asphalt Pavement (RAP) material (obtained from a local asphalt plant) that was used for the first generation of recycled mixtures (WMA-1) has a Nominal Maximum Aggregate Size (NMAS) of 11.2 mm [28]. According to EN 12697–3 [29] and EN 933–1 [28], the RAP gradations before (black curve) and after (white curve) binder extraction were determined, and the results are displayed in Fig. 3; the binder content in the RAP material is 4.25%.

In the preparation of the mixtures, the dosage of warm mix asphalt additive (Sasobit) and the amount of the 160/220 asphalt binder, which is performing as an ARA [11], were adjusted based on the binder content of the RAP and the properties in the recycled materials (Table 1). In addition, a refined dosage of ARA and additive was selected to account for the actual aging level of the artificially aged WMA-1.

In the case of WMA-1, the RAP provided by a local producer was directly incorporated in the mix design. Next, the WMA-1 mixture was artificially long-term aged in the laboratory to prepare the second generation of RAP (re-recycled RAP). For this purpose, a laboratory aging process on loose mixtures proposed in the past was adopted. This relies on the use of the Pressure Ageing Vessel (PAV) [30] with a duration of 20 h at a temperature of 90 \(^\circ\)C under the pressure of 2.1 MPa [31]. To obtain aging level and associated rheological properties comparable to the original RAP material, several aging durations (20 h, 25 h, 30 h, 35 h, and 40 h) were used to artificially age the WMA-1 mixture after reducing it to a loose condition (Fig. 4). At each aging level, the artificial aged WMA-1 extracted binder was compared with the RAP binder. The parameters of the Performance Grade (PG) [32] and penetration grading [26] systems were used for this purpose. When the duration of 35 h was used, similar PG and penetration grading were obtained for artificial aged WMA-1 and RAP extracted binders. Details on the different aging levels and grading parameters are reported in the next section (Table 2).

Finally, the corresponding WMA-2 mixture was prepared with re-recycled RAP (artificially aged WMA-1 mixture after 35 h of PAV). In the last fabrication step, the German roller sector compactor [33] was used to prepare mixtures slabs (320 mm \(\times\) 260 mm \(\times\) 100 mm) from which prismatic specimens were cut for fatigue [34] and low

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**Table 1**

Basic properties and mix design of the entire set of asphalt mixtures.

|            | HMA   | WMA-1 | WMA-2 |
|------------|-------|-------|-------|
| Recycled level | virgin | RAP   | re-recycled RAP |
| Aggregates  | 100%  | 60% Gabbro + 40% | 60% Gabbro +40% |
| Binder type | 50/70 | 4.2% 160/220 | 3.6% 160/220 |
| Binder content [%] | 6.3 | 6.2 | 6.2 |
| Additives | – | 0.3% Sasobit | 0.2% Sasobit |
| Density [g/cm\(^3\)] | 2.56 | 2.54 | 2.56 |
| Air void [%] | 1.7 | 1.5 | 1.6 |
| Mixing Temperature [\(\degree\)C] | 160 | 135 | 135 |

**Table 2**

Conventional testing results and PG for the entire set of asphalt binders.

| Binder type | 25 \(^\circ\)C Penetration (0.1 mm) | Softening Point (\(^\circ\)C) | PG |
|------------|----------------------------------|-----------------------------|----|
| 50/70      | 53                               | 49.7                        | 70-22 |
| 160/220    | 187                              | 37.0                        | 52-34 |
| RAP binder | 10                               | 78.8                        | 82-10 |
| WMA-1 binder | 44                           | 53.2                        | 70-22 |
| 35 h PAV aged WMA-1 binder | 11 | 77.6 | 82-10 |
| WMA-2 binder | 46                           | 51.8                        | 70-22 |
| 20 h PAV aged WMA-1 binder | 26 | 64.3 | 76-16 |
| 25 h PAV aged WMA-1 binder | 20 | 68.2 | 76-10 |
| 30 h PAV aged WMA-1 binder | 15 | 71.2 | 82-10 |
| 40 h PAV aged WMA-1 binder | 10 | 81.1 | 88-10 |

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![Image of materials](image1.jpg)

Fig. 3. Black and white curves of the RAP material.

![Image of PAV method](image2.jpg)

Fig. 4. PAV aging method for asphalt mixtures: (a) loose materials; (b) configuration.

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12697–3 [29] and EN 933–1 [28], the RAP gradations before (black curve) and after (white curve) binder extraction were determined, and the results are displayed in Fig. 3; the binder content in the RAP material is 4.25%.
4.1.1. Uniaxial Tension Compression test (UTCT)

In this study, the Uniaxial Tension Compression Test (UTCT) method [21] under a sinusoidal cyclic stress loading mode was used to evaluate the fatigue behavior of the asphalt mixtures. A constant frequency of 10 Hz and a testing temperature of 20 °C were selected. An amplitude sweep test, with a strain level, $\varepsilon$, smaller than $25 \times 10^{-6}/m$, was initially performed to decide the suitable stress level within the LVE range. An initial amplitude stress level of 0.3 MPa was determined and used for the first 2000 cycles. Then, an additional 0.15 MPa was added to every 2000 cycles until the specimen experience macro cracking phenomena. This method is intended to simulate the accumulated deteriorating effects of the repeated traffic loading and has been validated in a previous study by the authors [21]. Such an experimental procedure was developed in the recent past in Germany [21] as an alternative to the conventional standardized fatigue test described in EN 12697–24 [34]. The testing configuration is shown in Fig. 5. A prismatic specimen was used for this purpose, and the real-time deformation was captured by using two Linear Variable Differential Transformers (LVDTs), attached to both sides of the test sample. The dimensions of the specimen were set to $40 \text{mm} \times 40 \text{mm} \times 160 \text{mm}$ based on the recommendation of the current European standard [22] on the mixture aggregate size.

Two parameters, $N_{f50}$ and $N_{macro}$, were used to evaluate the fatigue resistance of asphalt mixtures (see schematic in Fig. 6) [36]. $N_{f50}$ identifies the loading cycle numbers associated with a 50% decrease in the initial stiffness modulus $E_0$ (average value of the initial 500 cycles stiffness modulus). $N_{macro}$ can be obtained from the peak of energy ratio, $ER$, curve as this is associated with the beginning of the macro-crack (Fig. 6). $ER$ is calculated with Equation (1):

$$ER(N) \sim N \cdot |E|_N$$

where $|E|_N$ is the stiffness modulus, and $N$ is the corresponding loading cycle numbers.

Both allowable load cycle numbers, $N_{f50}$ and $N_{macro}$, provide an estimation of the fatigue life.

4.1.2. Thermal stress Restrained specimen test (TSRST)

The low temperature resistance of asphalt mixtures was addressed with the TSRST tests [22]. Two parameters, Fracture temperature, $T_F$ [°C], and corresponding thermal strength, $\sigma_{CR}$ [MPa], were recorded for comparison purposes. The tests were applied conducted on the entire set of three mixtures, and three replicates were prepared. Further details on the testing protocol can be found in the European standard EN 12697–46 [22].

4.2. Asphalt binders

The behavior of the asphalt binder was evaluated based on three experimental methods. Temperature-frequency sweep (T-f-sweep) tests, Linear Amplitude Sweep (LAS) [24], and Binder-Fast-Characterization-Test (BTSV) [30,25], were performed with a Dynamic Shear Rheometer (DSR) [23] (Fig. 7a) to rheologically characterize the entire set of six asphalt binders displayed in the top part of Table 2 (light gray).
temperature range from $-30$ °C to $+80$ °C with an interval of $10$ °C, and covering a frequency between 0.1 and 10 Hz. For each material and testing condition, an amplitude sweep (A-sweep) test was first performed to identify the Linear Viscoelastic (LVE) range and determine the suitable stress/strain value. For the T-f-sweep test, at least two replicates were prepared for each binder and geometry. To cover the entire spectrum of temperatures, three different testing geometries, 25, 8, and 4 mm (Fig. 7 b, c, and d), were selected. Based on the available DSR devices' capability [37], a mixed-mode approach using strain-control at high temperatures while stress-control for intermediate and low temperatures, was adopted to obtain more reliable results. It should be noticed that for low temperature DSR tests with the 4 mm geometry, a novel experimental and data preprocessing method, previously developed by the authors [38], was applied. More information about the 4 mm DSR method can be found elsewhere [39,40].

4.2.2. Linear amplitude sweep (LAS)

Linear Amplitude Sweep (LAS) test was used to evaluate the binders fatigue performance by using the 8 mm DSR geometry at 20 °C (Fig. 7c), detailed testing protocol is presented in the AASHTO standard TP101 [24]. A minimum of three replicates was performed for each material. The principle of this test relies on an oscillatory strain sweep test that generates damage to the asphalt binder by applying linear continuously increasing strain amplitudes. In Equation 2 [24], the number of cycles to failure was calculated with the failure definition of a 35% reduction compared to the initial modulus.

$$N_f = A (\gamma_{max})^B$$

(2)

where A and B are Visco-Elastic Continuum Damage (VECD) model coefficients. Parameter A is related to the storage capability of the

![Fig. 7. (a) available DSR device, (b) 25 mm, (c) 8 mm and (d) 4 mm plate-plate geometries.](image)

![Fig. 8. BTSV plane and example of binders blending in the context of recycling.](image)
material; it represents the ability to keep its integrity during the loading cycles and damage accumulation. Therefore, when the storage modulus decreases at higher loading cycles (a reduction for A), the material presents reduced fatigue resistance due to the accumulated damage. Parameter B describes the sensitivity of the asphalt binder to strain level change. Higher absolute values of parameter B indicate that the fatigue life decreases at a higher rate when strain level amplitude increases. Therefore, a higher A combined with a lower absolute B implies relatively better fatigue resistance.

In this study, the entire set of six asphalt binders in the upper part of Table 2 were attempted to be tested. However, due to the high stiffness of the RAP binder [5,41] and the 35 h PAV aged WMA-1 binder, these two materials failed at much lower strain (2%) levels compared to the maximum 30% strain of the LAS procedure. Therefore, LAS results were obtained only on the remaining four asphalt binders.

4.2.3. Binder-Fast-Characterization-Test (BTSV)

In Europe, the penetration grading system [26] is commonly adopted to characterize and grading the asphalt binder. However, it was observed that this system is unable to provide sufficiently reliable results, especially for modified and recycled binders. For this reason, an alternative testing method named Bitumen Typisierungs Schnell Verfahren - BTSV (Binder-Fast-Characterization-Test) [25] was proposed in the recent past.

The experimental procedure relies on the application of the DSR at high temperatures (25 mm geometry). During the test, a steady increase in temperature (from 20 \(^\circ\)C to 90 \(^\circ\)C and \(\Delta T = 1.2 \, \text{C/min}\)) is imposed on the binder sample, which is subjected to a constant shear stress of 500 Pa at a frequency of 10 rad/s (1.59 Hz). Based on a large binder dataset, an average critical value of \(|G^*|\) equal to 15 kPa was associated with the corresponding softening point temperature [25]. As a result, two key parameters are recorded, the softening temperature \(T_{\text{BTSV}}\), and the corresponding phase angle \(\delta_{\text{BTSV}}\), to generate the BTSV plane \((T_{\text{BTSV}} - \delta_{\text{BTSV}})\) (Fig. 8). Besides replacing the softening point, it was shown that this method can be further used to design asphalt mixtures containing recycled materials and ARAs [2,11].

5. Results and analysis

5.1. Asphalt mixtures

5.1.1. Uniaxial Tension Compression test (UTCT)

Four samples were tested for each material to achieve good repeatability. A simple visual comparison of the stiffness modulus \(|E|\) vs. the number of loading cycles is shown in Fig. 9. It can be observed that HMA and WMA-1 mixtures have very similar fatigue behavior, while a slight decrease in fatigue response is experienced for WMA-2. To better understand the effect of recycled materials on fatigue behavior, numerical results are listed in Table 3 with the summary of \(E_0\), \(N_{f0}\), \(N_{macro}\), and \(ER_{max}\). Also, since this test was performed in a stress-controlled mode, the initial vertical deformation in the first 1000 cycles was calculated and displayed.

In Table 3, similar parameters are found within these three mixtures. WMA-1, containing the original RAP material, exhibits the best fatigue performance, while HMA and WMA-2 show a comparable fatigue response. In the case of WMA-2, a limited reduction was found in \(ER_{max}\) and \(N_{f0}\) compared to the other two materials, while HMA has the lowest

| Table 3 |
| Summary of the fatigue testing results for the entire set of asphalt mixtures |

|          | HMA   | SD*  | WMA-1 | SD*  | WMA-2 | SD*  |
|----------|-------|------|-------|------|-------|------|
| \(E_0\) MPa | 5813.925 | 321.025 | 6321.815 | 456.552 | 6145.089 | 654.653 |
| \(N_{f0}\) [-] | 12.397 | 561 | 12.684 | 876 | 10.420 | 549 |
| \(N_{macro}\) [-] | 5732 | 321 | 6404 | 264 | 5810 | 354 |
| \(ER_{max}\) [MPa] | 4.04E + 10 | 4.03E + 08 | 4.31E + 10 | 9.85E + 07 | 3.74E + 10 | 2.22E + 08 |
| initial deformation [mm] | 0.0093 | 0.0001 | 0.0093 | 0.0006 | 0.0102 | 0.0006 |

SD*: standard deviation

5.1.2. Thermal Stress Rutting Test (TSRST)

In Table 4 with the summary of \(E_0\), \(N_{f0}\), and \(ER_{max}\), numerical results are listed for the entire set of asphalt mixtures. It can be observed that HMA and WMA-1 mixtures have very similar fatigue behavior, while a slight decrease in fatigue response is experienced for WMA-2. To better understand the effect of recycled materials on fatigue behavior, numerical results are listed in Table 4 with the summary of \(E_0\), \(N_{f0}\), and \(ER_{max}\). Also, since this test was performed in a stress-controlled mode, the initial vertical deformation in the first 1000 cycles was calculated and displayed.

| Table 4 |
| TSRST results for the entire set of asphalt mixtures |

|          | HMA   | SD*  | WMA-1 | SD*  | WMA-2 | SD*  |
|----------|-------|------|-------|------|-------|------|
| fracture temperature \(T_f\) \([{^\circ}\text{C}]\) | -23.3 | 0.81 | -25.0 | 0.65 | -27.3 | 0.52 |
| thermal strength \(\sigma_{cry}\) [MPa] | 4.764 | 0.43 | 4.775 | 0.54 | 4.632 | 0.43 |

SD*: standard deviation

Fig. 9. Changing of stiffness modulus and \(N_{f0}\) for the entire set of asphalt mixtures.
Therefore, overall similar fatigue behavior can be observed for the WMA-2 mixture compared with the other two materials; this is especially true for HMA. In this study, due to the limited amount of re-recycled RAP materials, only a single stress level and one temperature were used to easily compare fatigue behavior.

5.1.2. Thermal stress Restrained specimen test (TSRST)

In the present section, the fracture temperature and the related thermal strength are reported to address the effect of recycled materials on the low temperature response in Table 4.

Lower failure temperatures are observed in the WMA mixture prepared with recycled materials. WMA-2 mixture containing re-recycled RAP exhibits the best thermal cracking behavior. In the case of thermal strength, all the mixtures present a similar response, with a moderate reduction for WMA-2. As for fatigue, the potentially less aged recycled material incorporated in WMA-2 may be the reason why lower thermal cracking temperature is observed as a consequence of better relaxation properties.

5.2. Asphalt binders

5.2.1. Temperature-frequency sweep tests

Master curves of complex modulus, $|G^*|$, and phase angle, $\delta$, were generated based on the Christensen-Anderson-Marasteanu (CAM) model [42,43] and the Williams–Landel–Ferry (WLF) equation [44]. The equations are shown below:

$$G^*(f, T) = \frac{G_{\infty}}{1 + (f_c/\alpha(T)f)^{k}} \sinh \frac{90 m}{1 + (f_c/f)^{k}} \sinh \frac{90 m}{1 + (f_c/f)^{k}}$$

$$\log_{10}(T) = \frac{c_1(T - T_0)}{c_2 + (T - T_0)}$$

where,

- $f$ is the frequency (Hz); $f_c$ is the location parameter (frequency at which $G' = G''$); $\alpha(T)$ is the horizontal shift factor at temperature $T$ [44]; $G_{\infty}$ is the glassy shear modulus when frequency $f \to \infty$; $k$ and $m$ are dimensionless shape parameters; $T_0$ is the reference temperature; $c_1$ and $c_2$ are constants. A reference temperature of 20 °C was selected in this study. In Fig. 10, the master curves of the complex shear modulus, $|G^*|$, and phase angle, $\delta$, are illustrated for the entire set of six asphalt binders.
It can be seen that, except for the RAP and 35 h PAV aged WMA-1 binder, all the other binders have a similar trend for both shear modulus and phase angle. It is not surprising that the RAP and 35 h PAV aged WMA-1 binders locate in the region of high complex modulus and low phase angle, while the 160/220 binder presents an opposite behavior while. A trend similar to that of the virgin 50/70 binder can be observed for the two binders extracted from the WMA mixtures; this suggests that the combination of soft 160/220 binder, RAP binder, and WMA additives was capable of achieving similar target design properties to the virgin material.

Besides the simple visual comparison, accurate evaluation of the asphalt binders’ rheological properties can be obtained from the parameters of the CAM model and the WLF equation, Table 5 lists all fitting parameters of the CAM model and WLF equation for the entire set of asphalt binders. The coefficient of determination $R^2$ is listed in the last column. The parameters in Table 5 provide a clear understanding of the rheological behavior of asphalt binders and confirm the finding in the visual comparison of the master curves. Asphalt binders in both WMA mixtures present similar rheological properties to the target virgin 50/70 binder.

Additional parameters can be used to characterize the rheological behavior of asphalt binders further and indirectly evaluate the effect of aging, such as the Glover-Rowe parameter [45], the rheological index $R$ [46], and the crossover temperature $T_{crossover}$ [47]. Detailed definitions and explanations about these parameters can be found in previous publications [47–49]. In this study, crossover temperature (where the phase equals to 45° at 1.59 Hz) and the Glover-Rowe parameter are derived from the master curves to analyze the impact of aging on the binder response. The equation of Glover-Rowe parameter is given below:

$$G - R = \frac{G^* \times (\cos\delta)^2}{\sin\delta}$$  \hspace{1cm} (3)

where, $G^*$ and $\delta$ are the complex modulus and phase angle at 15°C and 0.005 rad/s. The results of these two parameters of the entire set of six asphalt binders are listed in Table 6.

It can be seen that the RAP together with 35 h PAV aged WMA-1, and 160/220 binders present the stiffest and softest characteristics, respectively. The reference virgin 50/70 binder has similar values with the two binders extracted from WMA mixtures. A similar trend is observed for the crossover temperature of the 50/70 binder and the binder extracted from the WMA-2 mixture. Both the G-R parameter and the crossover temperature support the results of the rheological analysis performed on the master curves.

### 5.2.2. Linear amplitude sweep (LAS)

The output of the LAS tests is presented in Table 7. As previously remarked, the RAP and 35 h PAV aged WMA-1 binders failed immediately, and it was not possible to record enough data to calculate the fatigue parameters; therefore, the LAS results for this material are not included.

Except for the soft 160/220 binder, similar values of parameter $A$ are observed for the 50/70 and the WMA-2 binder, parameter $B$, a closer value is observed for WMA-1 and WMA-2 than the original binder 50/70. Hence, the asphalt binder from the reference mixture and WMA-1 have a similar fatigue response, while the WMA-2 binder presents a slightly poorer fatigue life. This trend is consistent with what was observed at the mixture scale. The fitted value of $N_{50}$, which represents the fatigue life of asphalt binder, under two different strain levels, 2.5%, and 5%, supports this finding.

### 5.2.3. Binder-Fast-Characterisation-Test (BTSV)

The two parameters of the BTSV tests, softening temperature ($T_{BTSV}$), and the corresponding phase angle ($\delta_{BTSV}$) are listed in Table 8 for the entire set of six asphalt, the corresponding BTSV plane is illustrated in Fig. 11. This consists of a series of boxes associated with the conventional penetration grading system [25]. Such a graphical representation facilitates the identification of the domain within which binders commonly used in Europe can be located based on the BTSV parameters. According to the BTSV results, a similar asphalt binders’ ranking can be observed also in the case of the high temperature properties. Virgin 50/70 binder and two binders extracted from WMA mixtures have relatively similar results while a maximum difference of 1.5°C and 3.1° are found within $T_{BTSV}$ and $\delta_{BTSV}$, respectively. It should be noticed that

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### Table 5

| Asphalt Binders | $G_0$ (MPa) | $G_\infty$ (MPa) | $f_t$ | $k$ | $m_\nu$ | $c_1$ | $c_2$ | $R^2$ |
|-----------------|-------------|-----------------|-------|-----|---------|-------|-------|-------|
| 50/70           | 0           | 1100            | 0.206 | 1.05| 15.46   | 135.76| 1.000 |
| 160/220         | 0           | 1100            | 1921.06| 0.227| 1.00   | 14.71 | 154.90| 1.000 |
| RAP binder      | 0           | 1100            | 0.02  | 1.18| 28.57   | 222.67| 0.999 |
| WMA-1 binder    | 0           | 1100            | 50.12 | 0.135| 1.16   | 25.38 | 230.53| 1.000 |
| 35 h PAV aged WMA-1 binder | 0     | 1100            | 1.33  | 0.213| 1.02   | 15.09 | 129.65| 1.000 |
| WMA-2 binder    | 0           | 1100            | 106.47| 1.25 | 1.05   | 14.43 | 282.62| 0.999 |

### Table 6

| Asphalt Binders | G-R parameter | Crossover temperature parameter $T_{crossover}$ | $G^*$ (MPa) |
|-----------------|---------------|---------------------------------------------|-------------|
| 50/70           | 488.00        | 6.6                                         | 34.334      |
| 160/220         | 1.43          | −6.0                                        | 44.829      |
| RAP binder      | 691543.16     | 25.7                                        | 22.435      |
| WMA-1 binder    | 501.32        | 7.2                                         | 32.972      |
| 35 h PAV aged WMA-1 binder | 621451.65 | 23.8                                        | 31.525      |
| WMA-2 binder    | 382.43        | 5.8                                         | 30.865      |

### Table 7

| Asphalt Binders | $A$ | $B$ | $N_{50}$ |
|-----------------|-----|-----|----------|
| 50/70           | 1.36E + 05 | −2.846 | 10,107 [2.5% strain level] |
| 160/220         | 0.86E + 05  | −2.286 | 10,445 [2.5% strain level] |
| Extracted WMA-1 binder | 1.35E + 05  | −3.181 | 7317 [2.5% strain level] |
| Extracted WMA-2 binder | 1.39E + 05  | −3.428 | 8234 [2.5% strain level] |

### Table 8

| Asphalt binders | $T_{BTSV}$ [°C] | $\delta_{BTSV}$ [°] |
|-----------------|-----------------|---------------------|
| 50/70           | 51.8            | 81.5                |
| 160/220         | 39.8            | 82.5                |
| Extracted RAP binder | 80.1         | 76.2                |
| 35 h PAV aged WMA-1 binder | 76.3        | 74.7                |
| Extracted WMA-1 binder | 53.1         | 79.0                |
| Extracted WMA-2 binder | 52.1         | 82.1                |
all of these three binders locate in the 50/70 box (Fig. 11). This suggests that asphalt binders in both WMA mixtures present BTSV parameters that are consistent with those of the reference binder at high temperatures.

6. Summary and conclusion

In this paper, the possibility of using a re-recycled Recycled Asphalt Pavement (RAP), up to 40%, in combination with the Warm Mix Asphalt (WMA) technology for designing surface layer mixture was experimentally investigated. A set of three asphalt mixtures, including one conventional Hot Mix Asphalt (HMA) and two WMA containing recycled RAP and re-recycled RAP, were tested to evaluate their mechanical properties. Different rheological tests were also conducted on the corresponding six different asphalt binders. The performance of asphalt mixture and binder in terms of fatigue and thermal properties, and rheological behavior was addressed. Based on the experimental work and data analysis, the following conclusions can be drawn:

- The softening action of the fresh 160/220 binder can substantially restore the rheological behavior of the aged asphalt binder to achieve the target performance property of a virgin unmodified 50/70 binder. This is supported by the response of the WMA mixtures containing different generations of recycled materials in comparison to the reference HMA mixture.
- Similar fatigue and low temperature behavior were observed for reference HMA and two WMA mixtures prepared with different generations of RAP. Better low temperature fracture performances were found for WMA mixtures prepared with recycled materials.
- Similar rheological characteristics, including fatigue and high temperature properties, can be achieved for the extracted binder in both WMA mixtures when compared with the reference virgin binder; this is especially true for the WMA-2 mixture extracted binder.
- Careful attention needs to be devoted to the aging protocol of RAP used in the laboratory as this may affect the actual degree of aging and hence the final mix design formula ultimately resulting in undesired material performance. In the present study, aging time was selected as a target parameter to achieve similar properties between the original RAP and the second generation of RAP experimentally obtained.

This experimental study provides evidence on the possible application of re-recycled RAP combined with WMA technology. Nevertheless, it should be remarked that only limited asphalt mixtures with re-recycled RAP were prepared and tested in the laboratory environment. Additional materials and expanded experimentation work need to be evaluated and performed respectively to further support the current findings with the ultimate goal of leading the research toward the achievement of green and sustainable infrastructure.

Author Contributions The authors confirm contribution to the paper as follows: Di Wang and Augusto Cannone Falchetto conceived and designed the experiments; Di Wang, Chiara Riccardi, and Augusto Cannone Falchetto wrote the paper; Babak Jafari performed the experimental work; Di Wang and Chiara Riccardi contributed to data analysis; Chiara Riccardi and Augusto Cannone Falchetto provided additional recommendations; Michael P. Wistuba revised the paper. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 11. BTSV plane of the entire set of binders.
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