100% recycled high-modulus asphalt concrete mixture design and validation using vehicle simulator

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HIGHLIGHTS

- RAP properties are well matched for use in high-modulus asphalt mixtures.
- Laboratory performance of 100% RAP HMAC is close to reference mix.
- Traffic load simulator reveals insufficient cracking resistance of 100% RAP mixes.
- Crack propagation testing is recommended for design of high content RAP mixtures.
- Higher binder content is required in 100% RAP mixes compared to reference.

ABSTRACT

High modulus asphalt concrete (HMAC) mixtures are designed for high rutting resistance, high modulus and excellent fatigue performance. This is achieved through the use of high content of hard bitumen, low air void content, and use of performance-based testing for mixture design. Such approach is presumably well-matched for application of Reclaimed Asphalt Pavement (RAP): the RAP binder is hard because of aging, RAP mixes inherently have low air voids and performance-based mix design is recommended to increase the degree of reliability when using high RAP mixes. Here we present a study focused on designing and validating performance of HMAC from 100% RAP. Through multiple design iterations we found that it was not possible to fully fulfill the fatigue, modulus and rutting requirements for either of the recycled HMAC mixture types (C1 or C2) although the performance of one of the 100% RAP mixtures came close to the HMAC design requirements. Nevertheless, validating of the best-performing 100% RAP HMAC slabs using vehicle load simulator demonstrated that the recycled HMAC is significantly less resistant towards crack propagation compared to a conventional HMAC. This highlights the importance of testing cracking resistance for high RAP mixes.

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1. Introduction

A significant amount of research is focused on increasing the use of reclaimed asphalt pavement (RAP) in production of hot mix asphalt. As a result, RAP recycling rates have been steadily growing [1,2]. Nevertheless, in many locations RAP is still abundant and stockpiles keep accumulating. In Switzerland, for example, around 2.5 million tons of asphalt are milled annually. Around 30% (750,000 t) are unused and of the 70% that are recycled, a part is down-cycled for use in lower value applications [3]. The situation is similar elsewhere: as a result of the excess
RAP and distrust in high RAP hot asphalt mixtures, RAP is often used in construction of unbound base layers, for road shoulders and low traffic intensity roads thus diminishing its value [4,5]. This is a waste of resources. RAP is the most valuable when used in hot mix asphalt due to the ability to replace bitumen, which is the most expensive part of the mixture [6,7]. At the same time it is a sustainable approach because use of RAP reduces the need for non-renewable resources [8,9]. For these reasons, every effort should be made to increase the proportion of reclaimed asphalt that is re-used for production of new asphalt mixtures.

Further advancements in design of hot-mix asphalt are necessary to increase the mean RAP content in asphalt pavements. This concerns all aspects of the road construction industry: milling technologies, RAP management, production technologies, paving, mixture design, and quality control methods. The focus of this article is on the potential of using RAP in an innovative way – for production of High Modulus Asphalt Concrete (HMAC) entirely from RAP.

HMAC, also known by the French abbreviation EME (Enrobés à Module Élevé), was developed in France with the objective to improve the mechanical properties of asphalt concrete providing high modulus, good fatigue behavior and excellent rutting resistance. HMAC mixtures are primarily used for base and binder courses and allow reducing pavement layer thickness or increasing pavement life span. Two types of HMAC are often distinguished: C1 – with primary focus towards resistance to permanent deformation and C2 – with high resistance to both permanent deformation and fatigue. These properties are achieved through use of high content of hard (and often polymer-modified) binder, low air void content and application of performance-based testing requirements for fatigue, modulus and rutting resistance.

Such approach seems well matched with the use principles of RAP because:

1) RAP binder is aged thus naturally provide the required hard-grade binder for HMAC [10–13];

2) high RAP mixtures chronically demonstrate low air voids [14–17];

3) performance-based mixture design is recommended for high-RAP mixtures because of unknown binder blending, relatively little field performance experience and potential for cracking [4,13,18–20].

For these reasons, it is worth exploring if RAP could be used in HMAC.

RAP has already been used in HMAC mixtures with a performance similar to virgin mixtures. Miro et al. [14] concluded that up to 30% RAP addition to HMAC did not deteriorate its properties both for lab-produced and plant-produced mixtures. Addition of 50% RAP, however, reduced fatigue performance. Similarly, studies by Ma et al. [21,22] noted that up to 30% RAP can be incorporated in HMAC. The authors did not encourage higher RAP contents because of the deteriorating low temperature and fatigue cracking resistance. In a separate study Ma et al. [23] noted that addition of synthetic low-molecular weight polylefin polymers can help improve the performance of HMAC mixtures with up to 60% RAP. Such conclusions are also supported by studies of conventional asphalt concrete mixtures [24–26]. In fact, the increased risk of cracking is the main reason for the reluctance of road agencies to allow higher RAP contents. Unfortunately, performance-based cracking resistance tests are still not well developed [18]. For that reason, a Mobile Model Load Simulator (MMLS3) was used in this research to verify the cracking resistance of the designed mixtures. The vehicle load simulator applies a downscaled load to a pavement slab and multiple researchers have demonstrated the usefulness of the simulator to evaluate fatigue resistance of asphalt pavement [27–29].

At the same time, it has to be recognized that high RAP content does not automatically lead to reduced cracking resistance. Adequate counter measures have to be taken – such as use of rejuvenators, softer binder grades, performance-based mixture design methods, etc. Success of such measures is supported by multiple studies where low temperature cracking for high RAP mixtures has demonstrated similar performance to conventional designs [5,10,30,31]. Likewise, improved fatigue performance of high RAP mixtures has been often reported [26,32–34]. One explanation is that this performance depends on the test method and mode of load application. At low strains (or low stress) which is relevant for thick pavements a stiff mixture is likely to have a longer fatigue life, while at high strains (or high stress) which simulates thinner pavements a more flexible HMA will have a longer fatigue life. This highlights the importance of considering the pavement structure in conjunction with mix design. RAP may be beneficial to increasing pavement life if it is used in the right layer of a purposefully designed pavement structure.

1.1. Objective

The objective of the study is to investigate the potential to design HMAC mixtures from 100% reclaimed asphalt pavement and validate the results using a vehicle load simulator.

2. Materials and methods

2.1. Materials

RAP milled from an undefined location in Switzerland was used for the research. It was screened in a RAP processing facility to fractions of 0/11 mm and 11/22 mm. The binder penetration of the 0/11 mm fraction was 22 × 0.1 mm while the 11/22 mm fraction had a binder penetration of 28 × 0.1 mm. The RAP binder content and RAP aggregate grading curved (white curves) are summarized in Table 1.

The 100% RAP mixtures were composed of reclaimed asphalt with maximum grain size of 22 mm (black curve), but as it can be seen in Table 1, 90% of the 11/22 fraction particles pass through 16 mm sieve. Thus, if only RAP aggregates were to be used, the only option was to design a mixture with maximum aggregate size of 16 mm. HMAC 16 mixtures are not specified in Switzerland so there was no mixture available to use as reference. Instead, an HMAC 22 mixture designed according to the Swiss specifications was supplied by an asphalt plant and used as a reference. In other countries HMAC 16 mixtures are routinely used and have the same performance-based requirements as coarser mixtures [35]. It was therefore decided to apply the Swiss performance-based requirements of HMAC 22 for the 100% RAP HMAC 16 mixtures designed in this study.

The reference HMAC 22 mixture was used in a parallel project [36] to determine the thresholds for fatigue and modulus for inclusion in HMAC specifications in Switzerland. The required values used in the study are based on the recommendations from that project.

Virgin bitumen was used in the mixtures with the goal of ensuring the required performance-based properties of the HMAC mixtures. Two types of virgin bitumen were used:

- Penetration grade 10/20 bitumen having penetration of 18 × 0.1 mm.
- Natural bitumen from Croatia having penetration below 1 × 0.1 mm and softening point of 115 °C. This bitumen has a high asphaltene content of >50% and was used to increase the stiffness of the mixture when necessary.
2.2. Methods

The experimental program is outlined in Fig. 1. HMAC C1 and C2 were prepared for both reference and 100% RAP mixtures. The different materials and their proportion that were used to prepare the 100% RAP mixtures will be presented in detail along with the discussion. Conventional tests were performed on all the mixtures but the emphasis of the study was on ensuring correspondence to performance-based design criteria. Finally, validation of the optimum design using Model Mobile Load Simulator was intended to compare 100% RAP and the reference mixture.

2.2.1. Constituent material tests

Binder was extracted from RAP according to EN 12697-1 using toluene and recovered by rotary evaporator according to procedure described in EN 12697-3. Gradation of the mixtures was determined according to EN 12697-2 after extracting the binder (white curve).

Flow coefficient of fine portion (0.063–2 mm) of the aggregates was tested according to EN 933-6. The test is performed by measuring the time that is necessary for a specified volume of the material to flow through a standardized funnel. The less angular the aggregates, the faster they flow.

Penetration of bitumen was determined at 25 °C according to EN 1246. The penetration of the blend between RAP and virgin binders within the HMAC mixtures was estimated using Eq. (1). The penetration of the blend of RAP and virgin binders with the natural bitumen was estimated using an equation provided by the producers of the natural bitumen (Eq. (2)).

\[
\log P_{\text{blend}} = \frac{A \log P_{\text{RAP}} + B \log P_{\text{virg}}}{100} \tag{1}
\]

\[
P = P_{\text{blend}} \cdot \exp(-0.0433 \cdot C) \tag{2}
\]

2.2.2. Mixture production

Laboratory mixtures were prepared using a heated batch mixer at 175 °C. The constituent materials were heated at this temperature in an oven for 3 h before mixing. This temperature was selected according to the recommendations from Swiss specifications for target binder grade (10/20). During mixing, the different fractions of RAP were first mixed together for 1 min, followed by addition of the virgin bitumen and additional 4 min of mixing. Because of RAP agglomerations and the relatively wide fractions that are normally used, high-RAP mixtures are prone to inhomogeneous particle size distribution. To improve uniformity, the RAP obtained from the asphalt plant was split into subsamples of approximately 10 kg using a riffle box. These subsamples were then used for laboratory mixing.

2.2.3. Sample preparation

Marshall samples were prepared at 175 °C and compacted with 50 blows to each side according to EN 12697-34 after re-heating of the asphalt mixtures. To minimize aging, the samples were heated in a microwave oven for 10 min, followed by a conventional oven for 50 min. The prepared Marshall samples were used to determine the void characteristics for each mixture according to EN 12697-8. The determined bulk density from Marshall samples was then used to calculate the necessary mixture mass for slab samples. The slabs with dimensions of 18 cm × 50 cm × 10 cm were prepared using a French roller compactor. To prepare the stiffness and fatigue test samples, four 100 mm samples were cut from each slab. They were subsequently cut and polished to 40 mm height. To avoid edge effect and maximize homogeneity, all faces of the samples were cut.

2.2.4. Stiffness and fatigue

Stiffness (according to EN 12697-26) followed by fatigue test (EN 12697-24) on the same specimens was performed using cyclic indirect tensile test on cylindrical shaped specimens (IT-CY) of
150 mm in diameter and 60 mm in height. Stiffness tests were performed by applying a sinusoidal load at frequency of 10 Hz and 10 °C, as defined for type testing by EN 13108-20. The load level was chosen to induce horizontal strains in the specimen in the range between 0.05 and 0.10‰. Although the European standard requires four replicates for stiffness, in this case, only three specimens for each mixture were tested.

Fatigue test was performed at 10 °C by applying a sinusoidal repeated loading at 10 Hz frequency on cylindrical samples (CIT-CY). The conventional failure criterion \( N_{f/50} \) of 50% loss of initial stiffness modulus (at 100 cycles) was used. Strain levels were chosen to induce failure of the specimens at three distinct levels \((-10^3, -10^5, -10^6)\). The standard requires three replicates at each strain level, however this was not always followed. If after testing of several first samples of a particular mixture, it was deemed that the results would not satisfy the criteria, the subsequent samples were not tested. Testing at different conditions allows calculating another conventional failure criterion – the strain at 1 million cycles (denoted \( \varepsilon_0 \)). This is calculated according to Eq. (3).

\[
\log(N_f) = a + \frac{1}{b} \log(\varepsilon)
\]  
(3)

where \( \varepsilon \) is the amplitude of the tensile strain repeatedly applied, \( N_f \) is the number of load applications to failure. The values \( a \) and \( b \) are regression constants, determined from plotting a regression line between fatigue failure criteria \( \log(N_{f/50}) \) and applied strain amplitude \( \log(\varepsilon) \). The value \( a \) is the ordinate of the regression and \( 1/b \) is the slope. The fatigue and modulus requirements using CIT-CY test are currently not specified in Switzerland but a recent study proposed the requirements used in this article [36].

### 2.2.5. Rutting

Rutting resistance of the asphalt mixes was evaluated using French Rutting Tester (FRT) at 30,000 cycles according to EN 12697-22. The rutting resistance requirements are set for samples prepared using a pneumatic wheel. However, a steel wheel compactor was used in this research. This method allows ensuring more homogeneous density throughout the slab which is important when cores are drilled for stiffness and fatigue tests. Since it was desired to use the same sample preparation procedure for both rutting and fatigue tests, the steel wheel was preferred for both tests.

A comparison of rutting test results on slabs prepared using steel wheel and pneumatic wheel was made for an AC8 type mixture having the same porosity of around 4%. At 10,000 cycles the results demonstrated 5.9% proportional rut depth for steel wheel samples and 3.5% rut depth for the pneumatic wheel samples indicating that sample preparation with the standard method could result in a somewhat lower rutting than reported in this paper.

#### 2.2.6. Mobile model load simulator (MMLS3)

In order to upscale and validate the results obtained on laboratory samples, an MMLS3 test was performed at 20 °C. The MMLS3 (illustrated in Fig. 2) is a downscaled accelerated pavement loading device used for testing of pavement distresses under the load of repetitive rolling tires. The slabs used for the tests were 1.6 m long and 0.6 m wide with a thickness of 8 cm and they were made from laboratory-mixed loose material which was short-term aged for 4 h at 150 °C in a forced-draft oven. The virgin reference mixture was not aged because it was sampled from an asphalt plant where short term aging already had occurred. More information on the test device and slab preparation can be found in Zaumanis et al. [37].

Since cracking is the major concern for high content RAP mixtures, the MMLS3 was used to determine the mechanical resistance of slab specimens under rolling tire loading regime against fatigue crack formation and propagation. To do this, the short edges of the slabs were laid onto steel profiles (supports) to induce bending under load. Between the steel profiles and below the slab, a thin rubber mat was placed to model a soft elastic foundation. The slab–mat system simulates the condition of a flexible pavement, in which the asphalt layers have a continuous support of the subgrade and bottom up cracking of asphalt pavement layers arise from repeated tensile strains due to traffic loading. A thermocouple was installed inside the slab through a small hole drilled at one side. Considering that mechanical friction produced by the rolling tires increases the temperature in the slab [38], air temperature was adjusted so that the slab was always at 20 ± 1 °C. To initiate a crack, a 35 mm deep transverse notch was cut at the center of the slab from the bottom side. The notch allows to control the location at which the crack starts to propagate through the slab. The detection and monitoring of the crack progression was made by two means (Fig. 3):

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**Fig. 2.** MMLS3 [37].

**Fig. 3.** MMLS3 testing setup [37].
1. Digital image correlation (DIC) device: this non-contact optical technique measures the deformation of a body under loading by tracking and correlating the displacements of random speckle patterns applied to the surface of the specimen. The movement is calculated from digital images obtained from 2 cameras positioned in front of the area of interest; in this case, around the notch of the slabs (DIC area in Fig. 3).

2. Linear variable differential transducer sensors (LVDTs): because of initiation and progression of micro and visible cracks, the stiffness of the slabs decreases. This leads to an increase in bending deformation under load. The vertical deflection was measured through the use of LVDTs, as illustrated in Fig. 3. Considering that the temperature and the loading speed are maintained constant, any change in the amplitude of the vertical deflection can be attributed to a change in the slabs' stiffness due to cracking.

3. Results and discussion

Two types of mixtures were designed – HMAC C1 and HMAC C2. The major difference between the two is the higher fatigue resistance and higher modulus requirements for the HMAC C2 mixture. An iterative approach was used for designing the mixtures with each subsequent design denoted by a new letter (A, B, C, D). The respective iterations of each mix type (C1 and C2) were designed in parallel.

3.1. Design of 100% RAP HMAC C1 mixture

Three distinct designs of 100% RAP HMAC C1 mixtures were developed and tested (denoted C1-A; C1-B, C1-C). Grading curves of the mixtures are illustrated in Fig. 4 and the mix composition along with the test results and requirements according to requirements in Switzerland (SN 640 431-1c-NA) are summarized in Table 2. The fatigue results are visually illustrated in Fig. 5 and a conventional HMAC 22 C1 mixture (C1-Ref.) is added to provide a reference of a mixture that passes the requirements.

C1-A mixture was designed using two fractions of RAP (0/11 mm and 11/22 mm) delivered by the asphalt producer. The added virgin binder content was chosen to satisfy the requirements for Richness modulus (calculated according to Eq. (4), Richness modulus is conceptually similar to calculation of binder film thickness and results in minimum binder content for the specific gradation). Two binder types were selected – 10/20 penetration class bitumen and natural bitumen – at a proportion to provide resultant penetration close to the average requirement of 15 0.1 /C2

Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C1-A</th>
<th>C1-B</th>
<th>C1-C</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP 0/5.6, %</td>
<td>–</td>
<td>13.3</td>
<td>10.5</td>
<td>–</td>
</tr>
<tr>
<td>RAP 5.6/11, %</td>
<td>–</td>
<td>20.5</td>
<td>21.0</td>
<td>–</td>
</tr>
<tr>
<td>RAP 0/11, %</td>
<td>32.8</td>
<td>–</td>
<td>32.2</td>
<td>–</td>
</tr>
<tr>
<td>RAP 11/22, %</td>
<td>66.5</td>
<td>64.8</td>
<td>66.3</td>
<td>–</td>
</tr>
<tr>
<td>Filler, %</td>
<td>2.6</td>
<td>–</td>
<td>2.6</td>
<td>–</td>
</tr>
<tr>
<td>Virgin bitumen, %</td>
<td>0.7</td>
<td>1.75</td>
<td>2.1</td>
<td>–</td>
</tr>
<tr>
<td>Natural bitumen, %</td>
<td>0.07</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total binder content (RAP + virgin), %</td>
<td>4.70</td>
<td>5.14</td>
<td>5.58</td>
<td>&gt;4.60</td>
</tr>
<tr>
<td>Estimated binder penetration, 0.1 × mm</td>
<td>16</td>
<td>21</td>
<td>21</td>
<td>15–25</td>
</tr>
<tr>
<td>Richness modulus</td>
<td>2.87</td>
<td>3.11</td>
<td>3.57</td>
<td>≥2.70</td>
</tr>
<tr>
<td>Richness modulus @ 85% binder activation</td>
<td>2.39</td>
<td>2.70</td>
<td>2.87</td>
<td>–</td>
</tr>
<tr>
<td>Air voids, %</td>
<td>2.2</td>
<td>2.0</td>
<td>2.0</td>
<td>3.0–6.0</td>
</tr>
<tr>
<td>Modulus, MPa @ 10°C, 10 Hz</td>
<td>25,151</td>
<td>22,646</td>
<td>20,850</td>
<td>≥19,000*</td>
</tr>
<tr>
<td>Fatigue strain at 10⁶ cycles, μm/m</td>
<td>13.9</td>
<td>46.7</td>
<td>45.8</td>
<td>≥50⁰</td>
</tr>
<tr>
<td>Proportional rut depth @30,000 cycles, %</td>
<td>–</td>
<td>–</td>
<td>6.8⁰</td>
<td>≤5.0</td>
</tr>
</tbody>
</table>

* Requirement based on the recommendation of a research project [38].
** Sample preparation differed from the standard method, likely resulting a somewhat higher rut depth.
It also had lower than required void content. Because of these unsatisfactory results, rutting resistance was not tested for the C1-A mixture.

\[
M_R = \frac{B_{GC}}{M} \left( 0.25 \left( 100 - a \right) + 2.1 \left( b - c \right) + 12 \left( b - c \right) - 150c \right)
\]

where:
- \(M_R\) – Richness modulus.
- \(B_{GC}\) – Binder content, %.
- \(a\) – mass of aggregates passing through 4.0 mm sieve, %.
- \(b\) – mass of aggregates passing through 0.25 mm sieve, %.
- \(c\) – mass of aggregates passing through 0.063 mm sieve, %.

C1-B mixture was designed to increase the void content, increase fatigue resistance and reduce modulus. It was done by re-sieving the 0/11 mm RAP fraction into 0/5.6 mm and 5.6/11 mm fractions. This allowed developing a gradation closer to the lower requirement of the grading envelope in an attempt to increase air voids. At the same time, higher binder content was required to increase fatigue resistance and reduce modulus. It has been long discussed that part of the RAP binder film is not activated and acts as part of the rock [33, 39, 40]. To account for this effect, in the C1-B and consecutive mixtures, we arbitrarily assumed that the “active” portion of the binder is 85%. This then required to increase the binder content to 5.14% in order to ensure the Richness modulus of ≥2.7. Filler was added to increase the surface area of the aggregates. As can be seen in Table 2 these changes in mix design resulted in a significant increase in fatigue resistance and a reduction of modulus. The cause for fatigue improvement can be depicted from Fig. 5 where C1-B demonstrates significantly higher strain amplitude compared to the C1-A mixture, thus shifting the fatigue line to the right. However, the fatigue resistance is still somewhat lower than the reference and the modulus is significantly higher than the required value.

C1-C mixture was designed to further increase fatigue resistance and reduce modulus. To do this, filler was removed and binder content was increased to 5.58%. The proportions of other materials remained constant. These changes resulted in a slight decrease in modulus and almost unchanged fatigue resistance. The fatigue resistance was about 10% lower than the requirement and approximately 20% lower than that of the reference mixture, indicating a shorter life cycle of the pavement. Nevertheless, it was considered that it is impossible to further improve the performance using the available materials. Further fatigue improvements could possibly be achieved by introduction of new additives. The C1-C mixture was tested for rutting resistance where it demonstrated 6.8% proportional rut depth. This is higher than the required ≤5.0%. As discussed in the Methods section, the sample preparation differed from the requirement and it is possible that sample preparation with a standard method would result in a somewhat lower rutting. This mix had air voids that were 1% lower than the requirement. However, since the main goal of the study was to verify the performance-based properties of the mixtures, it was decided to use this mixture design for performance validation of using MMLS3.

### 3.2. Design of 100% RAP HMAC C2 mixture

Four different 100% RAP HMAC C2 mixtures were designed (denoted C2-A; C2-B; C2-C; C2-D) and their gradations are illustrated in Fig. 6. To ensure a distinct difference compared to the HMAC C1 mixtures, only two RAP fractions, 0/11 and 11/22 mm, were used. Because of this, the gradation was finer compared to the C1 mixture but still corresponded to the 16 mm maximum aggregate size. The mixture design proportions along with the test results are summarized in Table 3. Fatigue test results are illustrated in Fig. 7 and a conventional HMAC 22 C1 mixture (C2-Ref.) is added to provide a reference of a mixture that passes the requirements.

C2-A mixture was designed by adding virgin 10/20 penetration class bitumen and natural bitumen in amount and proportions to ensure the required richness modulus of 3.3 and penetration close to the minimum requirement of 10 0.1 × mm. This resulted in high modulus and unsatisfactory fatigue. The air void content, although lower than that of HMAC C1, was within the required range.

C2-B mixture was designed slightly coarser to increase air voids and the content of natural bitumen was reduced to increase binder penetration. As with the HMAC C1 mixtures, binder content was increased to reach the required Richness modulus assuming that only 85% RAP binder is activated. The results indicate slight increase in fatigue resistance and no reduction in stiffness.

C2-C mixture was designed similar to C2-B with two differences: (1) no natural bitumen was added to make the mixture softer and (2) crumb rubber was added at 10% of virgin binder mass. The crumb rubber (particle size of <600 μm) was first blended with the hot virgin bitumen and then added to the mix with the intention of increasing the fatigue resistance. As shown in Fig. 7, this did not happen and instead the slope of the regression became steeper reducing the strain at 10⁶ cycles (\(e_{10^6}\)). The modulus reduced slightly compared to C2-B mixture.

C2-D mixture was designed by removing the filler, and increasing the binder content to 6.5%. This resulted in reduction of air voids and modulus, and increase in fatigue resistance. It was considered that it is not possible to design a mixture with better fatigue resistance using the existing RAP without adding any virgin aggregates or new additives so the rutting resistance was tested. The FRT results demonstrate unacceptably high proportional rut depth at 18.3% compared to permitted 7.5%. The reason for this is likely two-fold. First, the binder content for this iteration is very high, reducing the interaction between the aggregates. Second, the RAP aggregates are not angular enough, and the friction between the particles is reduced resulting in an increase of the permanent deformations per wheel pass. A flow coefficient test performed on extracted RAP 0.063–2 mm fraction particle size aggregates produced a result of 29.5. Such result corresponds to the lowest category in EN 13043 standard and can be considered insufficient for high rut resistance requirements, like HMAC mixtures. A visual inspection of the RAP >2 mm fraction confirmed that it also has rounded shape which could further contribute to weak rutting resistance.

Since both the fatigue and rutting test results were not satisfied, it was concluded that design of this mixture is not successful and it...
was not tested using MMLS3 traffic load simulator. A re-design of the mixture gradation and addition of portion of angular virgin aggregates would be necessary to improve the performance.

3.3. Validation of C1-C mixture using MMLS3 vehicle simulator

The 100% RAP HMAC C1-C mixture design was selected for validation using MMLS3 traffic load simulator. Even though this mixture did not pass all the requirements for a conventional HMAC mixture, it demonstrated the best performance from all the 100% RAP HMAC C2 mix types in the performance-tests. The performance of any of the 100% RAP HMAC C2 mixtures was too poor using the performance-based tests to warrant testing using the resource-intensive MMLS3 test.

MMLS3 tests were intended to demonstrate the fatigue performance of the mixtures. The fatigue limit was defined as the number of MMLS3 load applications when the bottom-up crack reaches the specimen’s surface, after growing from the notch upwards through the thickness of the slab. In some cases, the cracks might be visible to a naked eye thanks to a large differential movement between the crack edges produced by an MMLS3 tire passing. However, it was evident that the stiffness of the 80 mm thick slabs and the strong interlocking between the aggregates on both sides of the crack produced a relatively small deflection under load. Therefore, it was difficult to see crack initiation with an unaided eye. Consequently, only after post-processing of the result it became evident when the cracks developed.

Fig. 8 shows the results of the DIC analysis on the three tested slabs of 100% RAP HMAC C1-C mixture. The color maps illustrate the relative displacements in horizontal direction of a region around the notch when the MMLS3 tire is passing over the center of the slab. These displacements are relative to the unloaded state, when no tire is touching the surface of the specimen. In the situation where there is bending without cracks, the color map would present no discontinuity, i.e. there would be a smooth transition between different tonalities. As seen in Fig. 8(a), this is the case for the slab produced with the reference HMAC 22 C1 mixture even after 320,000 loadings. On the contrary, as it can be observed in the Fig. 8(b) and (c) corresponding to slabs with 100% RAP HMAC C1-C mixture, a discontinuity in the colors suggests the presence of a crack after just 1,000 load cycles. This means the slab is cracked already very early during the test.

On the right side of Fig. 8, the horizontal displacements of two lines A and B are plotted to show the crack width produced at the specific number of passes. Both 100% RAP slabs present a gap in the line with horizontal displacements at 1000 cycles. The formation of a crack at the beginning of the loading means that the slabs were not actually tested under a fatigue regime. Rather, they cracked soon after starting of loading, thus showing a brittle behavior of the material. On the other hand, the horizontal displacements of the HMAC 22 C1 reference mixture present a continuous line even after several days of loading (320,000 cycles) indicating no fatigue damage.

The DIC results were confirmed by the LVDT measurements. The analysis of data collected from LVDTs is based on the calculation of the deflection amplitudes from the raw data vs. the accumulated MMLS3 cycles, as shown in Fig. 9. It can be expected that a deformation of a bending plate on an elastic foundation should produce a steady growth of the deflection in the center of the span due to accumulation of micro cracks. The micro cracks will eventually start producing a dramatic reduction of stiffness, revealed as an inflection of the curve. This is observed as an increase of the deflection amplitudes until the slab is completely cracked and acting as two separate plates. This behavior was not observed in the 100% RAP nor in the reference mixture.

The reference HMAC 22 C1 slab showed no sign of cracking even after >320,000 load applications, which corresponds to 43 h of uninterrupted MMLS3 operation. Since the machine cannot run unattended, the loading was stopped during the night while air temperature was maintained at 20 °C. These breaks in testing appear as discontinuities in the deflection amplitude vs. load cycles curve in Fig. 9 and are probably due to small temperature differences inside the slab and due to crack healing, typically produced in asphalt materials during resting periods [41]. At the same time...
Fig. 8. Pavement response due to repeated loading of MMLS3 for a) reference mixture, b) and c) 100% RAP HMAC C1-C mixture.

Fig. 9. Raw deflection data of the plates (left) and calculated deflection amplitude vs. accumulated number of MMLS3 load cycles (right).
it is evident that the curve does not produce the sudden increase in deflection amplitude which would characterize a crack. As evident from analysis of the DIC results, both 100% RAP HMAC C1-C slabs cracked suddenly after the first few load applications. The test was not discontinued at this point, but rather the data was accumulated up to around 60,000 cycles. Although the slabs were completely cracked, the interlocking of aggregates in the crack allowed a load transfer between both parts of the slab. Just like with the reference mixture, no inflection point is observed. In fact, without the DIC results, an observer of the LVDT results might erroneously conclude that there is no crack. This signifies the importance of using DIC when performing MMLS3 tests.

It can be seen in the Fig. 9 that the RAP slabs exhibit a higher deflection amplitude compared to the reference slab, but this is likely not related to the stiffness of the mixture. The stiffness of 100% RAP and the reference mixture are actually relatively similar according to mixture design results (Table 2). The higher deflection amplitude of 100% RAP slabs can be explained by the fact that the slab is cracked shortly after the beginning of the loading.

The MMLS3 tests were intended as a validation of fatigue resistance of the mixture. Unfortunately, in none of the cases fatigue endurance was actually measured. In the case of 100% RAP mixtures, the slabs broke shortly after start of loading while for the virgin mixture the load was not high enough to induce fatigue damage. It is therefore not possible to make any conclusions regarding fatigue behavior with this set up. Unfortunately, repeating the test at different test conditions was not possible due to time constraints.

While the objective to evaluate the fatigue resistance was not achieved, an important conclusion can be made from the MMLS3 test results. The results demonstrated that with the same loading conditions for the RAP and reference mixtures, the RAP mixture was much more brittle compared to the reference mixture. This is despite the fact that the performance-based test results (most importantly modulus and fatigue) were actually relatively similar for the 100% RAP and reference mixture. A likely explanation for the differences in the MMLS3 test results is then the difference in resistance to crack propagation. Note that the notch in the center of slab is an artificial crack, intended to initiate crack propagation whereas fatigue tests that were performed as part of mixture design only consider the formation of microcracks. They do not characterize the second stage of material failure – crack propagation. When loading was applied to this artificial crack using MMLS3, the crack in 100% RAP mixtures propagated much faster than that in the reference mixture. This indicates that for high-RAP HMAC mixtures measuring the crack propagation might be an important mix design consideration. Because of the small sample size in this study, this conclusion needs to be further addressed in another research.

In an actual pavement, the two parameters – crack initiation and crack propagation are related. For a stiffer mixture, like the RAP mixture used in this research, the development of micro cracks may be delayed because of ability of the material to absorb strain energy before they start to have tensile failures [32,34]. Once initial micro cracks have formed networks, resistance to crack propagation plays an important role. In our study, the fatigue test characterized crack initiation while the MMLS3 reflects crack propagation because the slabs had an artificial notch. Based on the test results, we can see that the performance in each of these tests for the 100% RAP was very different as compared to the reference mixture.

4. Conclusions and recommendations

In theory, the design principle of HMAC is a good match for using high RAP content in mixtures. This is because of the requirement to test the mixture using performance-based tests instead of relying mostly on volumetric properties like it is done for asphalt concrete (AC) type mixtures. The aged, hard binder of reclaimed asphalt also often matches requirements for hard binder grade in high modulus asphalt concrete mixtures (HMAC). This study presented the design of HMAC mixture made from 100% reclaimed asphalt. The following conclusions can be drawn from the study:

1) It was not possible to design a 100% RAP HMAC C1 or C2 mixture to pass the performance-based test requirements. This is likely due to the presence of aggregates having low aggregate angularity in the RAP (either because of low angularity materials used in the original mixture design or due to degrading during milling and processing). This indicates that, although the binder may fit HMAC mixtures, implementation of management procedure of the RAP is necessary to also control the properties of the aggregates.

2) The Model Mobile Load Simulator (MMLS3) results did not allow making conclusions regarding fatigue resistance of either the RAP or the virgin mixtures because the selected loading conditions did not induce fatigue failure. However, the results did allow to conclude that at the conditions imposed by the test, the RAP mixture was much more brittle than the virgin mixture. Such results were not expected based on the laboratory mix design results, demonstrating the importance of upscaling the laboratory results before allowing such pavements into practice.

3) The failure of the existing mix design procedure to capture the dramatically insufficient resistance to crack propagation of HMAC mixtures, suggests that performance-based mix design methods might need to be re-evaluated when using high RAP mixtures. One parameter that could aid characterization of high RAP mixtures is testing of susceptibility to crack propagation as part of mix design.

4) In order to improve fatigue performance, 100% recycled mixtures required higher binder content than normally found in HMAC mixtures. This is likely because of not fully activated RAP binder. However, in this study, even increasing of binder content did not allow fulfilling the fatigue requirements and therefore use of additives should be considered in mixtures containing high content of RAP.

5) Sieving of RAP into three fractions as opposed to using two fractions allowed more flexibility to design the mixture resulting in a better performance.

6) Use of linear variable differential transducer sensors did not allow detecting propagation of crack in the MMLS3 slabs. The use of digital image correlation was the preferred option.

In general, the results of this work demonstrate the difficulty in designing 100% RAP HMAC mixtures. However, it has to be considered that HMAC mixtures are used for high-performance pavements on highways but the RAP used in this study was from an unknown origin with low quality aggregates. An appropriate management of the RAP might enable using the material in HMAC in very high content. Another potential approach is to use high content of RAP in HMAC mixtures designed for intermediate and low traffic intensity roads as a replacement to conventional asphalt concrete mixtures to reduce pavement layer thickness, increase pavement life expectancy, and reduce costs. Further research on pavement design, and cost effectiveness is encouraged to verify this.

CRediT authorship contribution statement

M. Zaumanis: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing -