Asphalt mixture performance and testing

Towards 100% recycled high-modulus asphalt concrete

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Abstract

Re-use of milled asphalt for production of new asphalt mixtures is continuing to increase. Unfortunately, the efforts are still not sufficient as in many locations piles of Reclaimed Asphalt Pavement (RAP) are accumulating or the material is downgraded for lower value applications. New ways to use RAP should be explored to further increase its consumption in hot mix asphalt. We explore the potential to design 100% recycled High Modulus Asphalt (HMAC). The high resistance to rutting and fatigue of HMAC mixtures is achieved through use of high content of hard binder grade. This is presumably well matched with the properties of RAP – the bitumen in RAP is hard because of aging. Another reason to consider RAP use in HMAC is the requirement to use performance-based test methods for designing this mix type. Performance-based design is recommended for RAP mixtures, since it reduces risks compared to relying on volumetric properties as done in traditional asphalt concrete mix design. Here we designed three different iterations of 100% RAP HMAC mixture in laboratory, but none of them achieved the performance required for a HMAC for stiffness modulus, fatigue and rutting resistance. The reason for the poor performance of 100% RAP HMAC was likely the lacking angularity of RAP aggregates. We thus conclude that a proper RAP management procedure has to be implemented before considering use of high RAP content for design of HMAC mixtures. We intended using the Mobile Load Simulator (MMLS3) to validate if the laboratory fatigue tests can be relied on for design of totally recycled mixtures. Unfortunately, the test setup did not allow making such conclusion because RAP mixtures broke before experiencing fatigue. This indicates that the RAP was more brittle compared to the virgin mix, but does not allow to conclusively comment on the fatigue performance.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

A lot of effort has been put into increasing the use of reclaimed asphalt pavement (RAP) in production of new hot mix asphalt. As a result, RAP recycling rates have been steadily growing [1,2]. In many locations, however, this proves not to be sufficient. RAP stockpiles keep growing or the material is directed towards use in low value applications, for example road base and shoulders. Such approach is not cost effective, because RAP can replace bitumen – the most expensive component of asphalt mixture [3]. At the same time re-using RAP in asphalt is the most sustainable approach because use of RAP reduces the need for non-renewable resources [4,5]. 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.

In this research we explore the potential to use up to 100 % recycled asphalt in High Modulus Asphalt Concrete (HMAC). HMAC, also known by the French abbreviation EME (Enrobés á Module Elevé), was developed in France with the objective to improve mechanical properties of asphalt concrete to provide 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. This is because of their high resistance to both permanent deformation and fatigue. The HMAC 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:

1) RAP binder is aged thus naturally provides the required hard-grade binder for HMAC [6–8];
2) high RAP mixtures often demonstrate low air voids [9–12];
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 [13,14].

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

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 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 RAP processing facility to fractions 0/11 mm and 11/22 mm. The screening was performed on RAP material including bitumen – i.e. "black curve". The binder penetration of 0/11 mm fraction was 22 ×0.1mm while the 11/22 mm fraction had a binder penetration of 28 ×0.1 mm. The RAP binder content and RAP aggregate grading curves are summarized in Table 1.

Based on the test results of RAP aggregate grading (i.e. without bitumen - "white curves") it was only possible to design a 100 % RAP mixture with a maximum aggregate size of 16 mm. Since HMAC 16 C1 is not specified in Switzerland, there was no mixture available to use as reference. Instead, the traditional HMAC 22 C1 from the Swiss specifications was picked up from asphalt plant and used for benchmarking.

Table 1. RAP aggregate grading curves (white curves)

RAP fraction	Binder content,%	Passing through sieve, %											
		0.063	0.125	0.250	0.500	1.0	2.0	4.0	5.6	8.0	11.2	16.0	22.4
0/5.6 mm	5.6	12.8	18	26	33	41	65	84	100	100	100	100	100
5.6/11.2 mm	3.8	7.8	11	15	19	24	31	41	57	95	100	100	100
0/11.2 mm	5.3	13.8	19	26	35	45	6	82	92	99	100	100	100
11.2/22 mm	3.2	4.0	7	10	13	17	23	32	36	44	62	90	100

Two types of virgin bitumen were used for designing the recycled HMAC mixtures:

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

2.2. Methods

2.2.1. Constituent material tests

Softening point was determined according to EN 1427. Binder was extracted from RAP according to EN 12697-1 with toluene and recovered using 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 (so called - white curve).

Flow coefficient of fine portion (0.063-2 mm) of the aggregates was tested according to EN 933-6.

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 Equation 1. The penetration of the blend of RAP and virgin binders with the natural bitumen was estimated using an equation provided by the suppliers of the natural bitumen (Equation 2).

$$logP_{blend} = \frac{AlogP_{RAP}+BlogP_{virg}}{100} \tag{1}$$

P_{blend} – penetration of the blend of RAP and virgin binder, 0.1×mm
P_{RAP} – penetration of RAP binder, 0.1×mm
$P_{virg.}$ – penetration of virgin binder, 0.1×mm
A – percentage of RAP binder, %
B – percentage of virgin binder, %

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

P – penetration of final binder in mixture, 0.1×mm
P_{blend} – penetration of the blend of RAP and virgin binder, 0.1×mm
C – percentage of natural binder, %

2.2.2. Mixture production

Laboratory mixtures were prepared using a heated batch mixer at 175 °C. This temperature was chosen according to the recommendations from Swiss specifications for the binder grades in use.

2.2.3. Sample preparation

Marshall samples were prepared at 175 °C and 50 blows from each side according to EN 12697-34. Void characteristics for each mixture were determined according to EN 12697-8. The determined bulk density from Marshall samples was then used as the target to calculate the necessary mixture mass for slab samples. The slabs with dimensions of 18×50×10 cm were prepared using a French roller compactor. For stiffness and fatigue tests four 100 mm samples were then cored from each slab and 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 followed by fatigue test on the same specimens was performed using indirect tensile test according to EN 12697-24 on cylindrical shaped specimens (CIT-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 at 10 °C. The load level was chosen to induce horizontal strains in the specimen in the range between 0.05 and 0.10 ‰. Three replicate specimens for each mixture were tested. Fatigue test was performed at 10 °C by applying a sinusoidal repeated loading at 10 Hz frequency. The conventional failure criterion ($N_{f/50}$) of 50 % loss of initial stiffness modulus was used. Strain levels were chosen to induce failure of the specimens at three distinct levels (~10^5, ~$10^{5.5}$, ~10^6). This allows calculating another conventional failure criterion – the strain at 1 million cycles (denoted ε_6). It is calculated according to Equation 3 (EN 12697-24).

$$Log(N_f) = a + \frac{1}{b} \cdot Log(\varepsilon) \tag{3}$$

where ε is the amplitude of the tensile strain repeatedly applied, N_f is the number of load applications to failure. a and b are determined from plotting a regression line between fatigue failure criteria $LogN_{f/50}$ and applied strain amplitude $Log\varepsilon_i$. 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 study has recently finished where the requirements were proposed and they are going to be used in this article [15].

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 rut resistance requirements are set for samples prepared using pneumatic wheel. However, a steel wheel compactor was used in this research. A comparison of rutting test results prepared using steel wheel and pneumatic wheel was made for an AC mixture having the same density 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 around 40 % can be deducted from the steel wheel sample results to arrive to the pneumatic wheel sample results.

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 Figure 1) is a one-third scaled accelerated pavement testing device used for testing of pavement distresses under the loading of repetitive rolling tires. The slabs 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 hours at 150 °C. 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. [16].

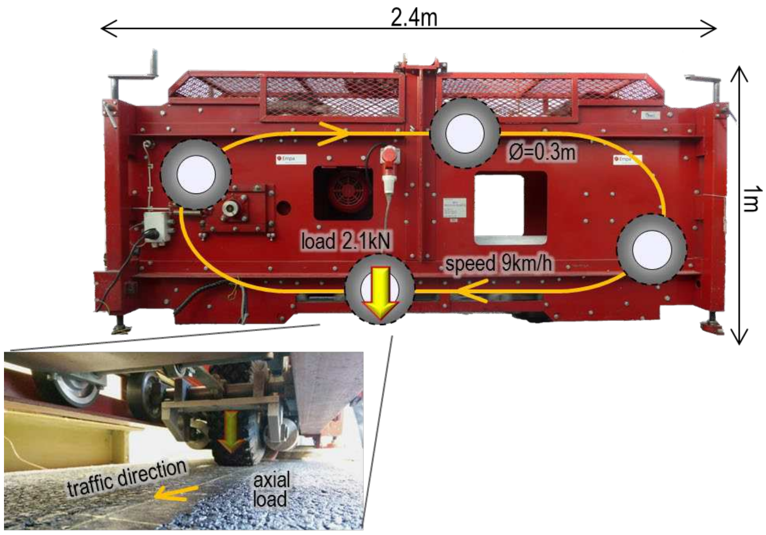


Figure 1. MMLS3

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, simulating the subgrade. The crack propagation was monitored by two means (Figure 2):

1) Indirectly using Linear Variable Differential Transducer Sensors (LVDTs)
2) Directly using the Digital Image Correlation (DIC) device.

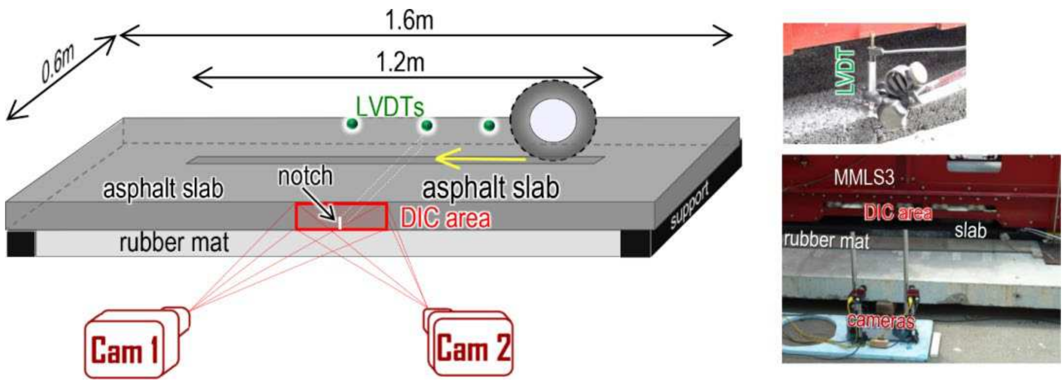


Figure 2. MMLS3 testing setup

3. RESULTS AND DISCUSSION

An iterative approach was used for designing three distinct 100 % recycled HMAC C1 mixtures (denoted C1-A; C1-B, C1-C). Grading curves of the mixtures are illustrated in Figure 3 and the mix composition along with the test results and requirements according to requirements in Switzerland (SC 640 431-1c-NA) are summarized in Table 2. The fatigue results are visualized in Figure 4 and a conventional HMAC 22 C1 mixture (C1-Ref.) is added to provide a reference of a mixture that passes the requirements.

3.1. Mixture designs

C1-A mixture was designed using two fractions of RAP (black curves of 0/11 mm and 11/22 mm) delivered by the asphalt producer. Virgin binder content to be added was chosen to satisfy the requirements for Richness modulus (calculated according to Equation 4 (SC 640 431-1c-NA)) 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×mm. The performance-based test results for C1-A mixture design demonstrated very high modulus and a very low fatigue. It also had lower than required void content. Because of these unsatisfactory results, rutting resistance was not tested for the C1-A mixture.

$$M_R = \frac{B_{GK}}{\alpha \cdot \sqrt[5]{\frac{0.25\cdot(100-a)+2.3\cdot(a-b)+12\cdot(b-c)+150\cdot c}{100}}} \tag{4}$$

M_R – Richness modulus
B_{GK} – Binder content, %
$\alpha = 2.65/\rho_a$, where ρ_a is density of aggregates, $Mg\cdot m^{-3}$
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 does not get activated and acts as part of the rock [17,18]. It was arbitrary assumed that the "active" portion of the binder in this case 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 reduction of modulus. The cause for fatigue improvement can be depicted from Figure 4 where C1-B demonstrates significantly higher strain amplitude compared to C1-A mixture thus shifting the line right. However, the fatigue resistance is still somewhat lower than required and the modulus is significantly higher than minimally required.

C1-C mixture was designed with the same RAP fraction as C1-B but aimed to further increase fatigue resistance and reduce modulus. To do this filler was removed and binder content was increased to 5.58 %. The proportions between other materials remained constant. These changes resulted in 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 existing RAP and therefore C1-C mixture was tested for rutting resistance where it demonstrated 6.8 % proportional rut depth. This is higher than the requirement (≤5.0 %), but as discussed in methods section, the sample preparation differed from the requirement likely resulting in around 40 % higher rutting. If 40 % are deducted from the proportional rut depth, the results are within the required range.

At the same time it has to be considered that the RAP aggregates are not angular enough. A flow coefficient test on extracted RAP 0.063-2mm fraction particle size aggregates and 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. Rounded aggregates reduce the friction between the particles and increase deformations per wheel pass.

Likely as a combination of high binder content and rounded, well compacting aggregates, the C1-C mix has air voids that are 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 testing using MMLS3.

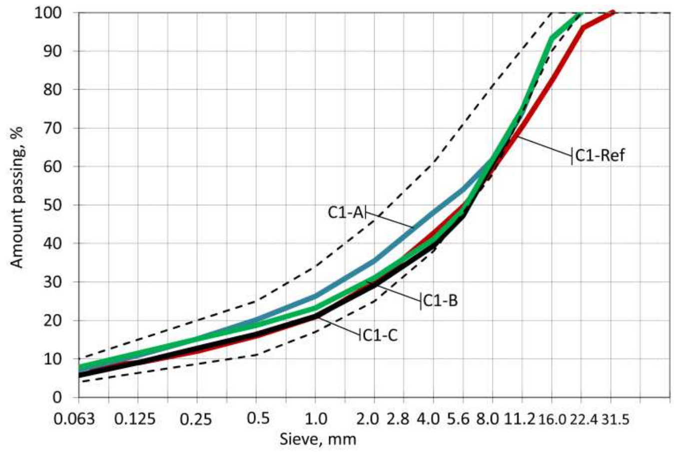


Figure 3. Gradation of C1 mixtures

Table 2. HMAC C1 design and test results

Parameter	C1-A	C1-B	C1-C	Required
RAP 0/5.6, %	-	13.3	10.5	-
RAP 5.6/11, %	-	20.5	21.0	-
RAP 0/11, %	32.8	-	-	-
RAP 11/22, %	66.5	64.8	66.3	-
Filler, %	-	2.6	-	-
Virgin bitumen, %	0.7	1.75	2.1	-
Natural bitumen, %	0.07	-	-	-
Total binder content (RAP+virgin), %	4.70	5.14	5.58	≥4.60
Estimated binder penetration, 0.1×mm	16	21	21	15-25
Richness modulus	2.87	3.11	3.57	≥2.70
Richness modulus @ 85 % binder activation	2.39	2.70	2.87	-
Air voids, %	2.2	2.0	2.0	3.0-6.0
Modulus, MPa @ 10°C, 10Hz	25,151	22,646	20,850	≥19,000
Fatigue strain at 10^6 cycles ε_6 @ 10°&10Hz, µm/m	13.9	46.7	45.8	≥50
Proportional rut depth @30,000 cycles, %	-	-	6.8*	≤5.0

*sample preparation differed from the standard method, likely resulting in by approx. 40 % higher rut depth

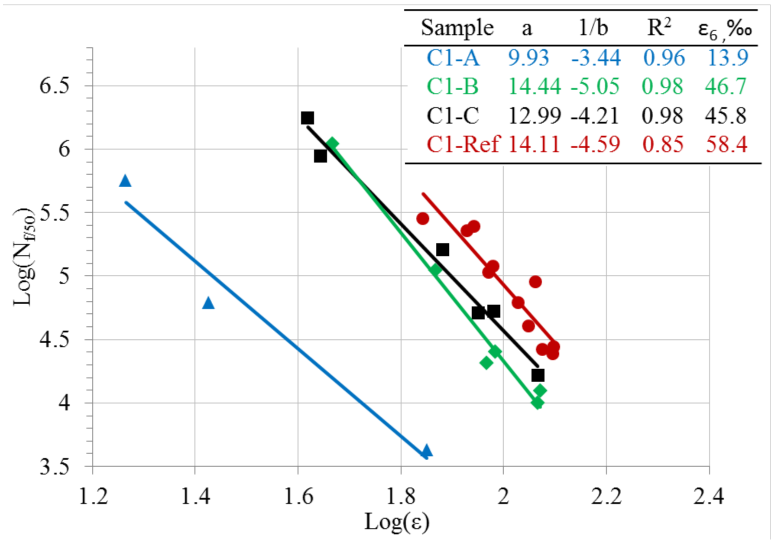


Figure 4. Fatigue diagram showing failure criteria $N_{f/50}$ versus applied strain amplitude ε for C1 mixtures

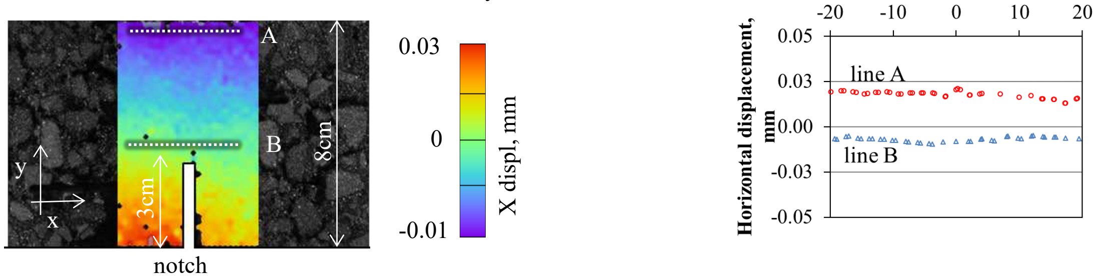
3.2. Validation of optimum mixture using MMLS3 vehicle simulator

MMLS3 tests were intended to demonstrate the fatigue performance where the fatigue limit was defined as the number of MMLS3 load applications when the crack reaches the specimen's surface, after growing from the notch upwards through the thickness of the slab. The cracks might be visible at first sight thanks to a large differential movement between the crack edges produced by a MMLS3 tire passing. However, it was evident that the stiffness of the 80 mm thick slabs and the strong interlocking between the crack walls produced a relatively small deflection under load. Therefore, it was difficult to visualize crack initiation with a naked eye. Consequently, it was only evident after post-processing of Digital Image Correlation (DIC) results when and where the cracks developed.

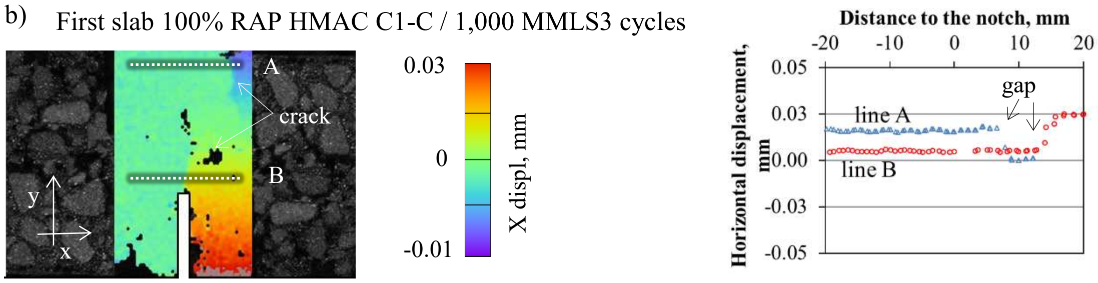
Figure 5 shows the results of the DIC analysis on the three tested slabs. The color maps illustrate the relative displacements in horizontal direction of a region around the notch when the MMLS3 tire is passing over the center of the slab. These displacements are relative to the unloaded state, when no tire is touching the surface of the specimen. In the situation where there is bending without cracks, the color maps should not present any discontinuity, i.e. there should be a smooth transition between different tonalities. This is true for the slab produced with the standard HMAC 22 C1 mixture, even after 310,000 loadings, as presented in Figure 5 (a). Instead, as it can be observed in the Figure 5 (b) and (c) corresponding to slabs with 100 % RAP HMAC C1 mixture, a discontinuity in the colors suggests the presence of a crack after just 1000 load cycles.

On the right side of Figure 5, 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 horizontal displacements at 1,000 cycles. The formation of a crack at the beginning of the loading suggest that the slabs were not tested under a fatigue regime, but they reached the breaking limit just after starting of loading, thus showing a brittle behavior. On the other hand, the slab HMAC 22 C1 presented no fatigue damage even after several days of loading

a) Slab HMAC 22 C1 / 320,000 MMLS3 cycles



b) First slab 100% RAP HMAC C1-C / 1,000 MMLS3 cycles



c) Second slab 100% RAP HMAC C1-C / 1,000 MMLS3 cycles

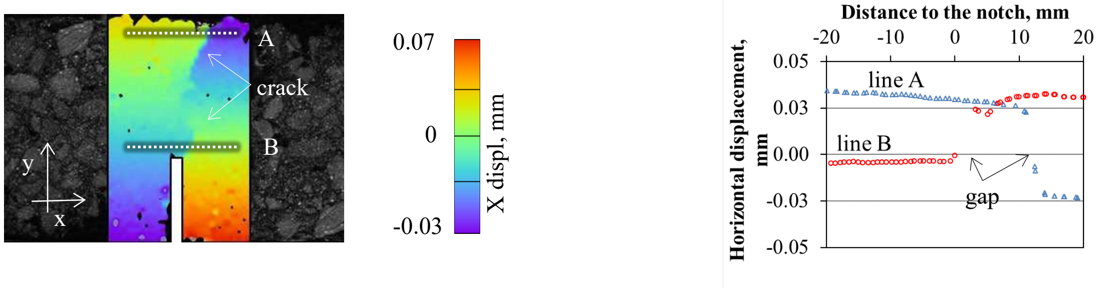


Figure 5. Fatigue diagram showing failure criteria $N_{f/50}$ versus applied strain amplitude ε for C1 mixtures

The DIC results were confirmed by the Linear Variable Differential Transducer Sensor (LVDT) measurements. The analysis of this type of data is based on the calculation of the deflection amplitudes from the raw data vs. the accumulated MMLS3 cycles, as shown in Figure 6. Ideally, the deformation of a bending plate on an elastic foundation should produce a steady grow of the deflection in the center of the span due to accumulating micro cracking. The micro cracks will eventually start producing a dramatic reduction of the stiffness. This is observed as an increase of the deflection amplitudes until the slab is completely broken and behaving as two separate plates. This behavior was not observed in the 100 % RAP nor in the virgin mixture.

Both 100 % RAP HMAC C1 slabs cracked suddenly after the first load applications. Although the slab was completely broken, the interlocking of aggregates in the crack allowed a load transfer between both parts of the slab. On the other hand, the HMAC 22 C1 slab showed no sign of cracking even after more than 310,000 load applications, which corresponds to 43 hours of uninterrupted MMLS3 operation. As the machine cannot run unattended, the loading was stopped during the night. These breaks are revealed as discontinuities in the deflection amplitude vs. load cycles curve of Figure 6. However, it is evident that the curve does not produce the expected sudden increase in deflection amplitude.

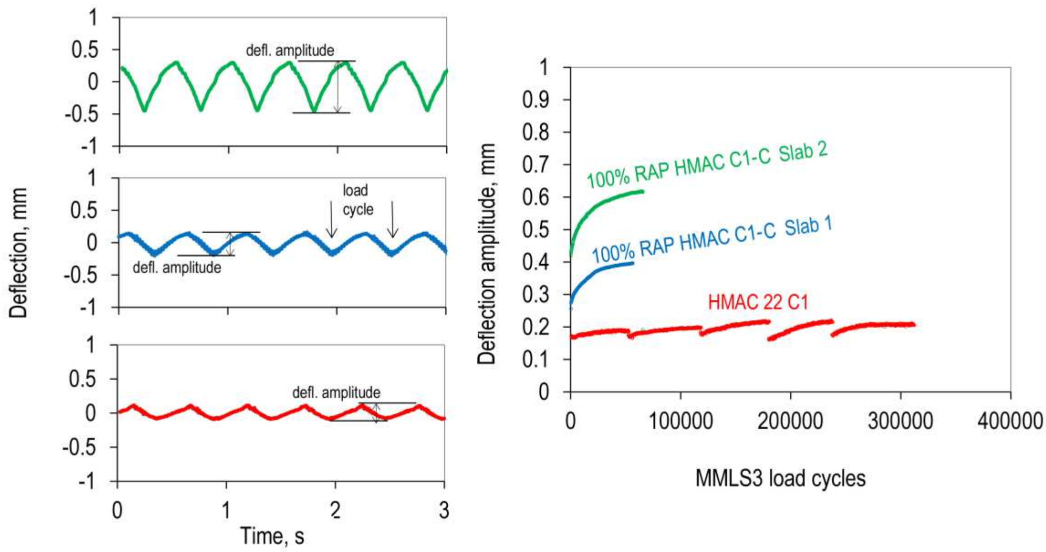


Figure 6. Raw deflection data of the plates (left) and calculated deflection amplitude vs. accumulated number of MMLS3 load cycles (right)

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 RAP mixture, the slabs broke right after start of loading while for the virgin mixture the load was not high enough to induce fatigue damage. It is therefore impossible to make any conclusions regarding fatigue limit. Unfortunately, repeating the test at different conditions was not possible due to time constraints. It is, however, possible to state that since loading conditions were the same in both conditions, the RAP mixture is more brittle compared to the virgin mixture.

4. CONCLUSIONS

The design principle of HMAC is a good match for using high RAP content, because of requirement to test mixture performance 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 presents 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 % recycled HMAC C1 mixture to pass the performance-based test requirements. This is likely due to the presence of aggregates having low angularity in the RAP. This indicates that, although the binder may fit HMAC mixtures, implementation of management procedure of the RAP is necessary based on the properties of the aggregates as well.
2) 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.
3) The Mobile Model Load Simulator (MMLS3) results did not allow making conclusions regarding fatigue resistance of either the RAP or the virgin mixtures. They did, however, allow concluding 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.
4) 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, it proved difficult to design 100 % recycled 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.

Acknowledgements

This contribution is part of a Swiss national project titled "Sustainable Fully Recycled Asphalt Concrete" funded by the Swiss federal office for the environment grant No. UTF489.19.14/IDM2006.2423.487. The authors are grateful to F.Piemontese for assisting with the MMLS3 measurements and H.Kienast, C.Meierhofer, R.Takacs, and S.Küntzel from EMPA road engineering laboratory for performing tests.

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