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Performance-based design of 100% recycled hot-mix asphalt and validation using traffic load simulator

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ABSTRACT

This paper reports a comprehensive study on application of performance-based design method for design of 100% recycled asphalt wearing course mixture and demonstrates the performance of the optimum composition from mechanical, traffic safety and environmental points of view. An AC8 type mixture was designed by balancing performance in rutting using French rut tester and cracking using semi-circular bend test. Five iterations of different grading and binder content combinations of 100% RAP mixture were tested before achieving the same performance as a traditional AC8 mixture. This optimum mixture design was then validated by producing asphalt slabs for testing using a Model Mobile Load Simulator (MMLS3). Digital image correlation results of the wheel loading demonstrated that performance-optimized 100% recycled asphalt can sustain 2.5 times more load applications compared to the traditional mixture before cracking. This wearing course recycled asphalt mixture was then tested for skid resistance and particle abrasion due to rolling tires and achieved similar results to the reference mixture. The research allows concluding that the proposed mixture design approach can be successfully applied for designing 100% recycled asphalt mixtures that perform similar or better than traditional wearing course asphalt mixtures in all key domains and are safe to the traffic and the environment.

1. Introduction

Asphalt is one of the most used materials in the world. In the quest for a circular economy asphalt has the potential to be a forerunner. In the EU and USA alone more than 123 million tonnes of Reclaimed Asphalt Pavement (RAP) are available annually (EAPA, 2018). When RAP is adequately managed, the mixture is designed using performance-based test methods and modern production technologies are employed, almost all of the available RAP could be re-used for production of new asphalt pavements as demonstrated in Video 1. Moreover, the goal should be to re-use the reclaimed asphalt in the same asphalt layer instead of downgrading the material for use in lower layers. This is because often only the wearing course of asphalt is milled and replaced as part of pavement maintenance efforts. As demonstrated in multiple research studies and road applications, re-using of high content of reclaimed asphalt for surface-courses is certainly possible (Büchler et al., 2018; Valdés et al., 2011; Widyatmoko, 2008). It has even been demonstrated that new asphalt pavements can be produced entirely from reclaimed asphalt without losing performance (Dinis-Almeida et al., 2016; Lo Presti et al., 2016; Zaumanis et al., 2016). Most of the research efforts on 100% recycling, however, have been performed in laboratory scale and do not address important issues like production challenges, traffic and environmental safety.

Video 1: Key principles of high RAP recycling (click link to access video online: https://youtu.be/ig4O05qFl-g).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.jclepro.2019.117679.

Despite the demonstrated successful cases, there is still a lot of skepticism regarding introduction of high content of reclaimed asphalt into practice, especially in surface layers. If pavements fail prematurely they would have to be replaced more often, thus requiring resources, generating greenhouse gasses and causing traffic delays and therefore the advantages of a circular economy would be lost. For this reason the road owners, to be on the safe side, often limit the maximum reclaimed asphalt content to 30%, 20% or even do not allow it at all for high traffic intensity roads. This caution is mostly driven by the fact that RAP binder has aged and is too stiff. As a consequence high RAP mixtures may be prone to cracking (Song et al., 2018; West et al., 2011; You and Goh, 2008)

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and part of the RAP binder is likely not blending with the introduced virgin materials leading to "black rock" effect (Bowers et al., 2014; Kriz et al., 2014; Sreeram et al., 2018). Another problem is the often insufficient homogeneity of RAP which does not allow to have confidence in continuity of the developed mixture design (Valdés et al., 2011; West, 2008; Zaumanis et al., 2018a).

These legitimate concerns must be addressed before widely applying highly recycled asphalt mixtures. One of the most important problems is the development of a reliable mixture design method that would allow designing high content RAP mixtures. The traditional volumetric mixture design methods were developed for characterizing mixtures that are comprised of virgin materials. They cannot capture the aforementioned problems associated with high RAP use and therefore improved methodologies for design and quality control is necessary. Balancing cracking and rutting performance through the use of performance-based test methods is such an alternative that can provide a higher degree of confidence in use of high RAP mixtures (Im et al., 2016; Ozer et al., 2016b; Zaumanis and Valters, 2019; Zhou et al., 2014). The principles of designing asphalt mixture by mainly relying on performance-based test methods are summarized in Fig. 1 as follows (Zaumanis et al., 2018b):

1 Constituent material's requirements and mixture composition are kept to a minimum to allow innovation. Instead, information is collected regarding constituent materials and volumetric properties to aid in optimization of mixture performance.
2 Aging is performed on samples to simulate field aging conditions.
3 The mixture is tested using the chosen performance-based test methods and verified against the specified criteria. In case the requirements are not passed, the composition of constituent materials must be changed.

The choice of performance-based test methods for use in mix design has to be carefully made to account for local climatic conditions, anticipated failure modes, reproducibility of the methods, correlation to field performance, etc. For high-RAP mixture design, cracking is of particular importance due to the presence of aged and

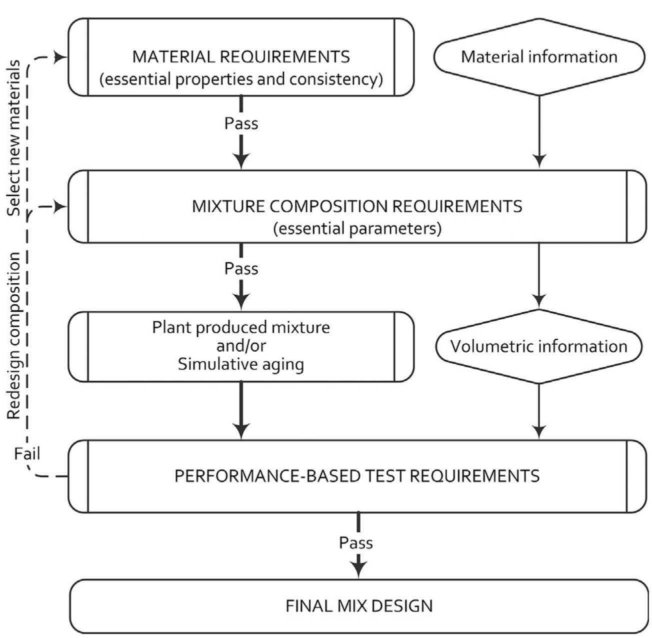

Fig. 1. *Performance mix design framework* (Zaumanis et al., 2018b).

stiff RAP binder. On the other hand overcompensating to improve cracking resistance through the use of softer binder or increase in binder content can lead to rutting. Therefore, the most appropriate test methods must be selected to characterize these two properties. Rutting resistance is often determined by a wheel tracking test. This is also the practice in Switzerland where the French Rutting Tester (FRT) is already used to approve mixture design. Cracking, however, has many test methods that try to capture different aspects, including bottom-up and top-down fatigue, thermal cracking and crack propagation. For practical mixture design purposes it will not be possible to characterize all of these failure modes. Rather it is important to find a cracking test that is sensitive to changes in mixture parameters, has good repeatability and provides reasonable correlation with field performance. Since RAP properties change depending on the age and source of the millings, it is also important that the method is quick to perform so that it can be used in the dynamic environment of asphalt production. Semi-Circular Bend (SCB) is potentially such a test method and the result interpretation using flexibility index (FI) has been demonstrated to have the requested characteristics to be used for mixture design (Ozer et al., 2016b). The combination of the two tests – FRT and SCB – will be used in this study to develop the mixture design.

2. Objective

The objective of the study is to optimize the design of 100% recycled asphalt by balancing performance-based mixture properties and validate the approach by using a traffic load simulator in fatigue testing mode. Since 100% recycling for wearing course layers is an innovative practice, it is also important to ensure that it is safe for the traffic and the environment. For this reason pavement slabs were tested for skid resistance and abrasion of particulate matter PM_{10}.

3. Materials and methods

A flowchart of the experimental program for this study is demonstrated in Fig. 2. Three different aggregate grading curves were used as illustrated with different arrows in the figure. The optimum binder content for the RAP mixtures was then found by performing balanced design using performance-based tests. The requirements for the performance-based tests were set based on the performance of a reference AC8N mixture for roads with design traffic intensity of 300 Equivalent Single Axle Loads (ESAL). For each mixture conventional tests were also performed. The optimum design was then validated using MMLS3 and water susceptibility tests. Finally, safety aspects were evaluated by testing skid resistance and particle abrasion.

3.1. Materials

RAP originating from Switzerland was screened through 11 mm sieve at the RAP processing facility. The RAP had a binder content of 5.6% and penetration of 22 × 0.1 mm. The particle size distribution of the RAP aggregates was close to the Switzerland specification requirements for AC 8 mixtures (see Fig. 3). It was therefore decided to use this RAP gradation as the starting point of the mixture optimization and all mixtures having this gradation are denoted *RAP fine*. Another group of mixture samples were prepared by sieving the RAP through a 5.6 mm sieve and re-grading to achieve a curve as similar as possible to the reference AC8N mixture. This group of mixtures is denoted *RAP coarse* and due to lower fine particle proportion compared to *RAP fine* it has a binder content of 5.1%. This approach assumes that all of the RAP binder is activated. The AC8N plant-produced mixture was selected as a reference. It

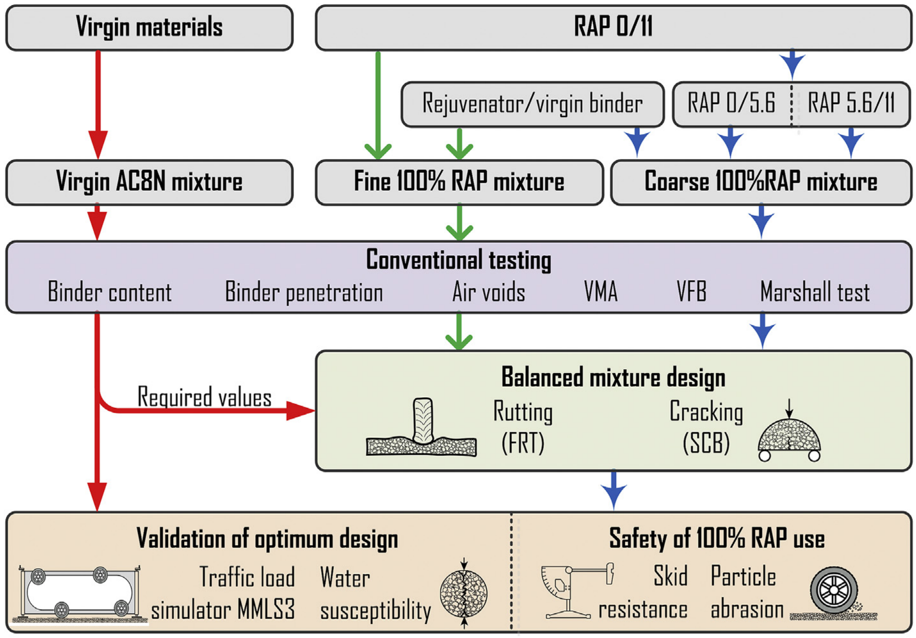

Fig. 2. Experimental program.

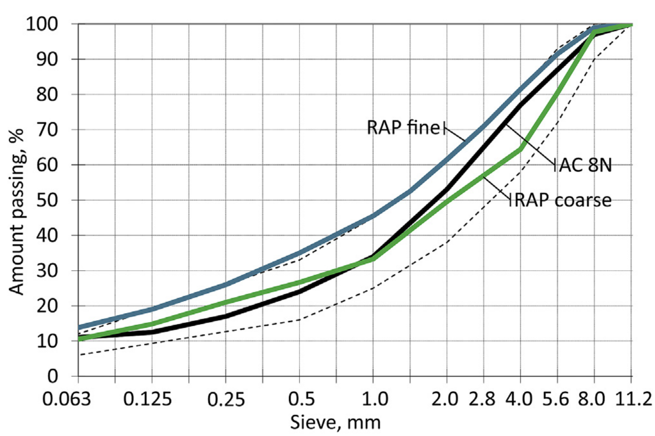

Fig. 3. Gradation of all mixtures.

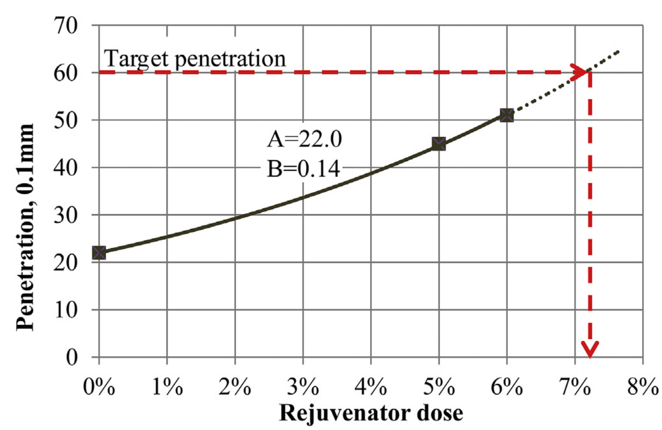

Fig. 4. Rejuvenator dose selection.

has 70/100 grade binder content of 6.2%. The grading curves of all three mixtures are illustrated in Fig. 3.

A commercially available rejuvenator based on distilled tall oil was used for the experiments. It is a by-product of Kraft manufacturing process and has a viscosity of 100 mm^2/s at 20 °C. In a previous paper by the authors this rejuvenator was rated as one of the most resistant to aging and capable of restoring the necessary mechanical properties of RAP binder (Cavalli et al., 2018). Two doses of rejuvenator were added to the RAP binder to determine the optimum dose. The three data points then resulted in an exponential graph demonstrated in Fig. 4. The required rejuvenator dose to reach 60dmm was then determined according to Equation (1) (Zaumanis et al., 2014). This resulted in optimum dose of 7.3% from the RAP binder mass. A target penetration of 60 × 0.1 mm was selected because this is the penetration of 50/70 virgin binder which was used for varying the binder content of mixtures. Such approach then ensures that the mixtures have exactly the same binder penetration, regardless of binder content.

$$\text{Rejuvenator dose, } \% = \frac{log_e \frac{PEN}{A}}{\text{B}} \quad (1)$$

where PEN is the penetration, ×0.1 mm, A is the penetration of RAP binder, ×0.1 mm.

B is the constant calculated by the least squares fit at different dosages of rejuvenator.

For each of the recycled mixtures, two binder contents were used: the original and the original +0.5% bitumen. Either 50/70 grade or highly Polymer Modified Bitumen (PMB) 45/80-80 was added. The final binder+rejuvenator content of the *RAP fine* gradation samples was 6.0% and 6.5% while for the *RAP coarse* samples it was 5.5% and 6.0%.

3.2. Methods

3.2.1. Constituent material tests

The binder was extracted according to EN 12697-1 using toluene and recovered according to EN 12697-3. The binder samples were tested for penetration at 25 °C according to EN 1426. Aggregate gradation was determined in accordance with EN 933-1 after extraction of bitumen.

When a rejuvenator was added to the extracted binder, the samples were prepared as follows. The bitumen samples were heated to softening point temperature plus 80 °C for 40 min as prescribed in EN 1427. The rejuvenator (which was kept at room temperature) was added to the hot binder at the desired dosage and mixed for 1 min in the Speed Mixer™ at 3500 rpm.

3.2.2. Production of mixtures in laboratory

To prepare mixtures in laboratory the materials, except rejuvenator which remained at room temperature, were heated in a laboratory oven to the mixing temperature of 170 °C. The materials were then mixed in an oil-heated laboratory mixer in the following sequence: RAP aggregates were pre blended for 0.5 min after which rejuvenator was introduced at the required dosage and mixed for 1.5 min. Finally, neat binder (if any) was introduced, followed by 3.5 min of mixing. It is considered that rejuvenators should be added directly to RAP, instead of pre-blending with fresh bitumen in order to allow direct contact with the RAP binder. This is expected to facilitate diffusion and activation of RAP binder (Zaumanis et al., 2019).

3.2.3. Sample preparation and conventional tests

Marshall samples were brought to compaction temperature of 145 °C directly after mixing of lab-produced samples and re-heated for plant-produced mixtures. This temperature corresponds to the requirements set in Switzerland National standard (SN 640431-1C-NA) for the binder grades 50/70 and 70/100. Compaction effort of 50 blows to each side was applied. The void characteristics of each mixture were determined according to EN 12697-8. Marshall test was performed by following the procedure of EN 12697-34.

Before running the performance-based tests, the loose mixtures were short term aged in a forced-draft oven at 150 °C for 4 h. This was followed by compaction using the French Roller compactor which was equipped with a steel wheel (developed locally). The slab was compacted at dimensions of 100 mm × 180 mm × 500 mm to a target density equaling that of Marshall specimens.

3.2.4. Rutting

Rutting resistance of the asphalt mixes was evaluated using a French Rutting Tester (FRT) according to EN 12697-22. The FRT was run using a rubber pneumatic test wheel that has a pressure of 0.60 ± 0.03 MPa and a load of 500 ± 5 kN, which was applied to the specimen as the wheel moves across the sample. A preconditioning load was applied at room temperature for 1000 cycles after which the sample was conditioned for about 16 h in a temperature chamber that was set to 60 °C. The test was run for 10,000 cycles for two parallel specimens and rut depth was measured using a gauge after 30, 100, 300, 1000, 3000, and 10,000 cycles at 5 pre-defined points along the length of the rut.

3.2.5. Crack propagation

Crack propagation was measured using a Semi Circular Bend (SCB) test at 25 °C. To prepare the SCB test sample a cylindrical sample was cored from an asphalt mixture slab, trimmed to the required height of 50 mm and cut in half. A notch of 15 mm deep and 3.5 wide was then cut into the half cylinders to control the crack initiation point. During testing the specimen was positioned in a three point testing frame as can be seen in Fig. 5 and load was applied at a monotonic rate of 50 mm/min along the vertical axes. Load and displacement were measured during the test.

The results were expressed in terms of Flexibility Index (FI) (Equation (3)) and fracture energy (Equation (2)) according to AASHTO TP 124-16: “Standard method of test for determining the fracture potential of asphalt mixture using semicircular bend geometry at intermediate temperature”.

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6 \tag{2}$$

where G_f is fracture energy in Joules/m^2, W_f is work of fracture (calculated as the area under the load versus displacement curve) in Joules, $Area_{lig}$ is ligament length in mm^2 multiplied by t, and t is specimen thickness in mm.

$$\mathrm{FI} = \frac{G_f}{|m|} \times A \tag{3}$$

where FI is flexibility index, G_f is fracture energy, m is the post peak slope at the inflection point of the load-displacement curve in kN/mm, and A is a scaling factor (0.01).

3.2.6. Water sensitivity

Water sensitivity was determined according to EN 12697-12. Six cylindrical samples 10 cm in diameter were produced using Marshall compactor by applying compaction energy of 35 blows per side. Half of the samples were kept dry at room temperature while the other half were water conditioned at 40 °C for 3 days. The samples were conditioned for 3 h before testing the indirect tensile strength (ITS) at 22 °C according to EN 12697-22 at 50 mm/min loading speed. The ITS ratio (ITSR) was then calculated as the ratio of wet to dry specimen test results in percent.

3.2.7. Model Mobile Load Simulator (MMLS3)

In order to upscale and validate the results obtained on laboratory samples, an MMLS3 test was performed. 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.

The MMLS3 (illustrated in Fig. 6) is a scaled accelerated pavement testing device used for testing of pavement distresses under the loading of repetitive rolling tires. It applies a downscaled load with four single pneumatic tires that simulates traffic. Each tire has a diameter of 0.3 m and a width of 0.11 m and loads the pavement through a spring suspension system over a 1.2 m path length. In this work, the machine was run at its maximum load (2.1 kN) and speed (9 km/h), allowing approximately 7200 load applications per hour. This corresponds to a loading frequency rate of nearly 2 Hz.

The size of the slab specimens used in this work was 1.6 m × 0.6 m, with a thickness of 4 cm. Each slab was produced from loose material aged for 4 h. Compaction was carried out with a steel roller targeting the density of corresponding Marshal samples. After compaction, a 1 cm deep transverse notch was cut in the center of the bottom face to initiate cracking. The short edges of the slabs were placed on 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 whole setup was fixed onto a stiff concrete plate to anchor the MMLS3 and placed in a container at 20 °C for a controlled loading temperature situation. Two slabs of each mixture type were loaded until failure, i.e. until the crack propagated from the bottom reached the surface of the slab.

The progress of the damage of the slab was followed visually. However, it is difficult to detect the relative movement of the two flanks of the crack with a naked eye. Further, it requires constant visual inspection for a test, which can last for several hours and even days. Therefore, crack formation and propagation was

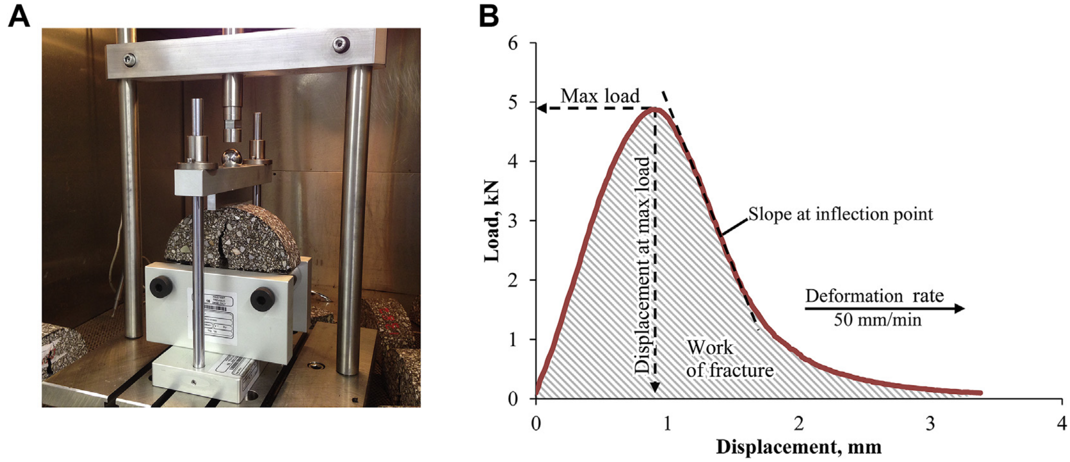

Fig. 5. SCB test setup (a) and typical test result (b).

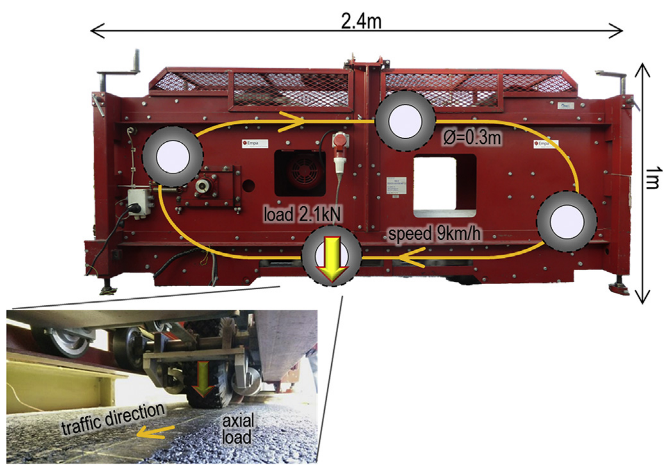

Fig. 6. The MMLS3 applies repetitive loading through four wheels.

monitored in addition by two other means:

(1) Indirectly using 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. 7. Considering that the temperature and the loading speed are maintained constant, any change in the amplitude of the vertical deflection can be attributed to progression of cracking.

(2) Directly using the 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. 7).

3.2.8. Skid resistance

Skid resistance was measured using the pendulum test as described in EN 13036-4 at 20 °C. The test is performed using a standardized pendulum with a standardized rubber mounted at the end of a pendulum arm. The loss of energy as a result of sliding over wet asphalt surface is measured. Two repetitive tests were performed for a given asphalt mixture. The test was performed on asphalt slabs that were prepared for MMLS3 tests using a small scale wheel compactor. The compactor is designed to simulate the field compaction mechanism and therefore can be reasonably assumed to represent the surface characteristics that would be present in the field.

3.2.9. Particle abrasion

In parallel to the mechanical tests described above, particle abrasion measurements were performed in an open environment, the setup is illustrated in Fig. 8. An aerodynamic particle size

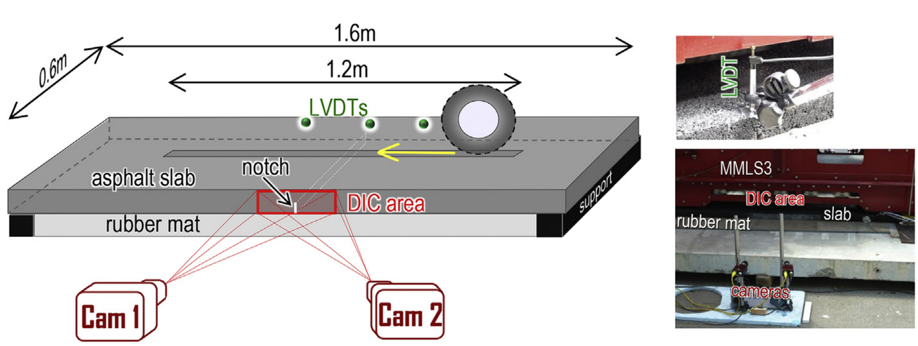

Fig. 7. MMLS3 testing setup.

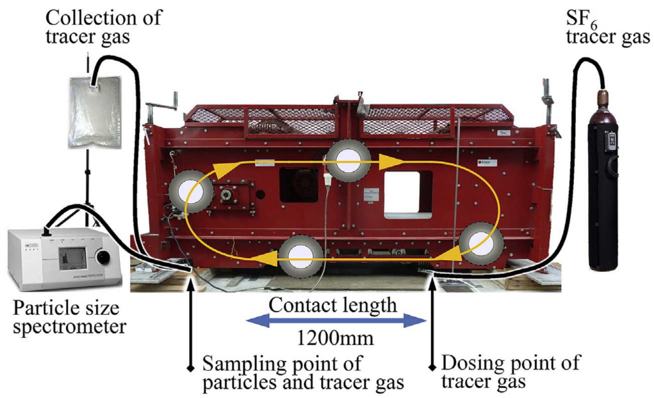

Fig. 8. Setup of the particle abrasion test.

spectrometer (TSI APS Model 3321) was used to count the abraded particles in the range of 0.5–20 μm. To calculate absolute emission factors of the measured particle concentrations, a tracer gas (Sulphurhexafluoride, SF_6) was used. This tracer gas allowed the determination of the air dilution in the induced air flow from the MMLS3 (Gehrig et al., 2010). An SF_6 tracer gas with an amount fraction of 99.7 μmol/mol was used and applied on the front and back side of the MMLS3 with a total flow rate of 50 ml/min. Air samples for the determination of the diluted tracer gas were taken, next to the sampling point for the particle measurements, into gas sampling bags and analyzed offline by gas chromatography with electron capture detection according to Mohn (Mohn et al., 2018). The tracer gas amount fractions were referenced to the SF_6 scale provided by NOAA GMD ESRL. The air flow through the MMLS3 was calculated according to Equation (4) (Gehrig et al., 2010).

$$\dot{V} = \frac{f_{tr} \cdot c_{tr}}{c_{meas}} \tag{4}$$

where f_{tr} – flow of tracer gas injection, ml/min.

C_{tr} – amount fraction of injected tracer gas, ppm.

C_{meas} – measured amount fraction of the sampled tracer gas, ppm.

$\dot{V}$ – Air flow volume through the simulator, m^3/min.

From the measured particle concentrations, the driven wheel distance and the air flow volume through the MMLS3, emission factor can be calculated according to Equation (5). Only particle sizes up to 10 μm were considered (PM_{10}) and as previously reported by Gehrig (Gehrig et al., 2010) it was assumed that the density of the released particles is 1 g/cm^3.

$$EF = \frac{(c_{op} - c_{amb}) \cdot \dot{V}}{d} \tag{5}$$

where EF – Emission factor, mg/km.

C_{op} – Particle concentration during operation, mg/m^3

C_{amb} – Particle concentration of ambient air, mg/m^3

D – Driving distance of the simulator wheels on the pavement per minute, km/min (0.140).

4. Results and discussion

In this section conventional and performance-based test results will be discussed for each test separately to compare the different mixtures, evaluate effects of various parameters on the performance and develop pass/fail thresholds. This will be followed by an explanation of the principles of performance-based mixture design. Finally, validation of the designed mixture will be demonstrated from mechanical, traffic safety and environmental points of view.

4.1. Conventional test results

Conventional volumetric test results along with the requirements according to Swiss road specifications (640 431-1c-NA) are summarized in Table 1. It can be seen that the virgin AC8N mixture passes all requirements while none of the RAP mixtures can fulfill all of them. A typical problem of high RAP mixtures is the low air voids content which has been previously reported in many studies (McDaniel et al., 2012; Mogawer et al., 2013; Ozer et al., 2012; West et al., 2009). As apparent from Table 1, even the use of the coarser grading curve did not allow reaching the required minimum of 2% air voids at the required minimum binder content of 6%.

The Marshall test results are reported in Fig. 9. Marshall stability is indicated with bars and the Marshall flow – with rhombs on the secondary axis. Swiss specifications require Marshall stability of ≥7.5 kN and Marshall flow of 2–4 mm. The AC8N mixture passes both requirements while from the recycled mixtures only *RAP coarse* fulfills the requirements. Other mixtures demonstrate high stability but unacceptably high flow, which can indicate unstable mixtures.

As can be seen, none of the RAP mixtures satisfies all the empirical requirements set out in the Swiss national specifications. At the same time it has to be recognized that even fulfilling these empirical requirements would not ensure the expected mixture performance. As discussed in the introduction, there are many parameters that cannot be captured by these tests, thus the results can serve merely as an information for the mix designer for optimizing the mix for performance-based tests. This study therefore focuses on the performance-based properties to design mixtures and reach conclusions on their performance.

4.2. Rutting

Rutting resistance results are illustrated in Fig. 10 where result range of the test repetitions for each sample is illustrated by error bars. It can be seen that the reference AC8N mixture has 20% rut depth at 10,000 cycles which can be used as an acceptance threshold for the recycled mixtures. This is a relatively low rutting resistance, but, as indicated in the introduction, mixtures designated by "N" are designed for a medium traffic intensity (300 ESAL/day) where rutting resistance is not the primary concern. From the recycled mixtures, only *RAP fine+0.5% bit.* has higher rutting than the reference mixture at 30%. It can be seen that adding 0.5% bitumen for either of the two gradations (*RAP fine* or *RAP coarse*) has resulted in increase of rut depth by approximately 12%. Exchange of 50/70 bitumen to PMB bitumen for the *RAP coarse* mixture has only resulted in statistically insignificant improvement of rutting resistance.

The *RAP fine* mixture without any virgin binder and the *RAP coarse +0.5% bit.* have equal total binder content of 6% and, as

Table 1
Conventional test results and requirements according to Swiss specifications.

Requirement:	Binder content	Air voids, %	VMA, %	VFB, %
	≥6.0	2.0–5.0	N/A	≤86.0
AC8N	6.2	2.8	17.2	83.9
RAP fine	6.0	1.7	16.2	83.5
RAP fine +0.5% bit.	6.5	1.8	17.5	89.5
RAP coarse	5.5	2.9	16.2	82.2
RAP coarse +0.5% bit.	6.0	1.3	15.8	91.6
RAP coarse +0.5% PMB	6.0	1.3	15.7	91.5

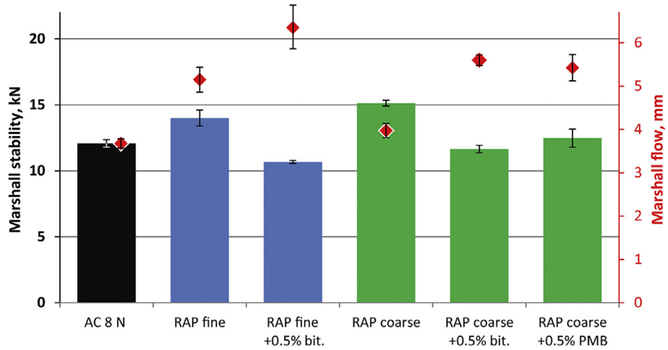

Fig. 9. Marshall stability (bars) and Marshall flow (rhombs) results.

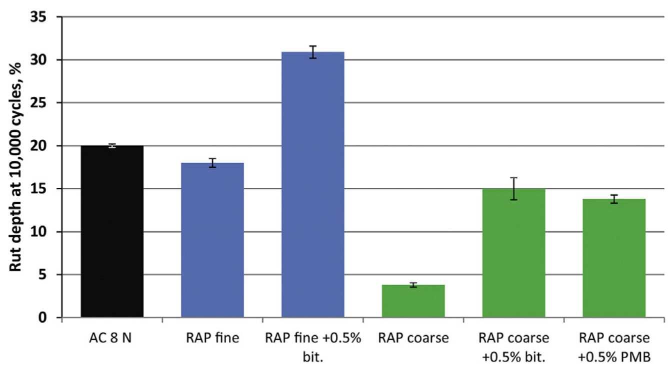

Fig. 10. French rut tester results.

discussed earlier, also the same binder penetration. Therefore, the effect of particle size distribution on rutting resistance can be evaluated. It can be seen that the coarser gradation has slightly improved rutting resistance.

4.3. Crack propagation

The two key parameters in SCB tests are fracture energy (G_f) and Fracture index (FI) (Ozer et al., 2016b). Higher fracture energy indicates asphalt mixtures that can withstand greater stresses with higher damage resistance. This parameter is derived from work-of-fracture (the area under load vs displacement curve) that was refined by RILEM (RILEM, 1985). It was, however, further discussed by Ozer (Ozer et al., 2016b) that the pattern of the load-displacement curve, especially the post-peak part is also important to discriminate cracking potential of mixtures. It was found that estimated crack propagation velocity correlates well with the post peak slope (m) which was therefore used in calculation of the FI.

A correlation of FI with field performance was carried out using results from FHWA (US Federal Highway Administration) test track. Here, seven different mixes with various RAP and RAS (reclaimed asphalt shingles) contents and different warm mix asphalt technologies were placed, using equal structural design and tested for cycles to fatigue threshold. The results of this study correlate well with the results of FI. Based on the study results, FI thresholds for distinguishing between good (FI > 10), acceptable (FI > 6) and bad (FI < 2) performing mixes were proposed, with a note that these should be adjusted based on local circumstances (Ozer et al., 2016a). Based on these results it was concluded that fracture index provides means to identify brittle mixes that are prone to premature cracking and the FI distinguishes between mixtures more clearly than fracture energy.

Based on these findings FI is proposed in this study as a mixture design tool to compare mixes and screen the ones that are prone to cracking. The load displacement curves of all mixtures are demonstrated in Fig. 11 and the FI along with fracture energy in Fig. 12. The following observations can be made:

- An increase in binder content for both RAP gradations lowers the maximum load but flattens the post-peak slope. This results in an increased FI (see Fig. 12) indicating higher cracking resistance. Such effect is what is intuitively expected and somewhat confirms the validity of the test method.
- The reference AC8N has an FI of 5.5 which will be therefore considered as the threshold for pass/fail criteria for the recycled mixtures. Only the *RAP fine+0.5% bit.* mixture has statistically similar performance to the reference mix. As can be seen in Fig. 11 this is due to a much higher post-peak slope compared to the AC8N mixture.
- Another pair of mixtures that should be compared are *RAP fine* and the *RAP coarse+0.5% bit.* These mixtures have equal total binder content and the same binder penetration. The only difference is aggregate gradation. It can be observed that the coarser gradation has improved the FI considerably (from 0.5 to 4). As can be inferred from Figs. 11 and 12 this is due to both higher slope and higher fracture energy.
- It can be observed that the addition of 0.5% PMB instead of paving grade bitumen for the *RAP coarse* mixture has not resulted in statistically significant change of FI, likely due to the relatively small PMB content.
- Finally, it can be observed in Fig. 12 that fracture energy provides similar ranking of the mixtures compared to FI. The difference between the mixtures is smaller for the fracture energy (highest result is 2 times higher compared to the lowest result) than for the FI (highest result is 6.2 times higher compared to the lowest), but the variability of fracture energy is 2.3 times lower (12% compared to 28%).

4.4. Balanced mixture design

The aim of performing the performance-based tests in this study was to develop a mixture design with balanced rutting and cracking performance. The motivation for choosing these particular test methods is that high RAP mixtures depending on the mixture design can be susceptible to cracking on the one end of the spectrum or rutting on the other. In the previous sections performance-based test results were demonstrated and the pass/fail criteria

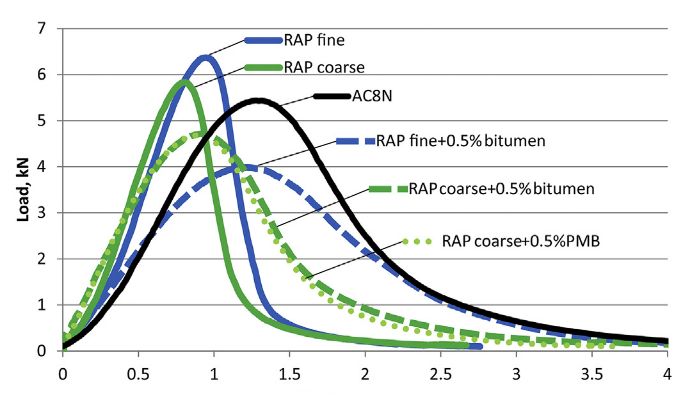

Fig. 11. SCB test load displacement curves.

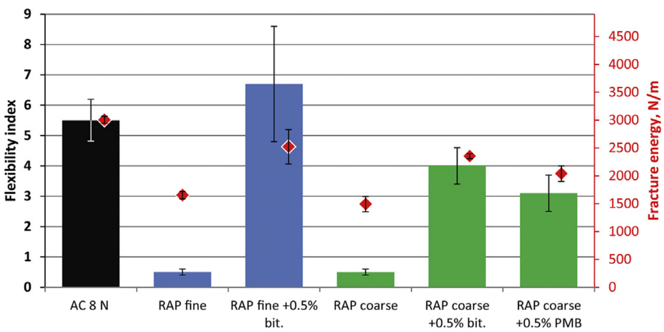

Fig. 12. Flexibility index (bars) and fracture energy (rhombs).

established. Here, balanced design approach to choose the optimum binder content is demonstrated.

Fig. 13 (a) illustrates the results of *RAP fine* gradation with two different binder contents (illustrated on the horizontal axis). Left vertical axis demonstrates rutting tests results while on the right vertical axis the FI results are demonstrated. Two dotted horizontal lines denote the rutting and FI pass/fail criteria based on the reference AC8N results as discussed earlier. Color coding indicates the axes to which the results belong.

It can be seen in Fig. 13 (*a*) that when *RAP fine* gradation was used the ranges of acceptable rutting (<6.1%) and acceptable cracking (>6.35%) do not intersect. This means that an optimum binder content that would allow balancing cracking and rutting results to reach at least the performance of the virgin mixture does not exist. Other changes besides binder content in mixture design are necessary to improve either cracking or rutting performance.

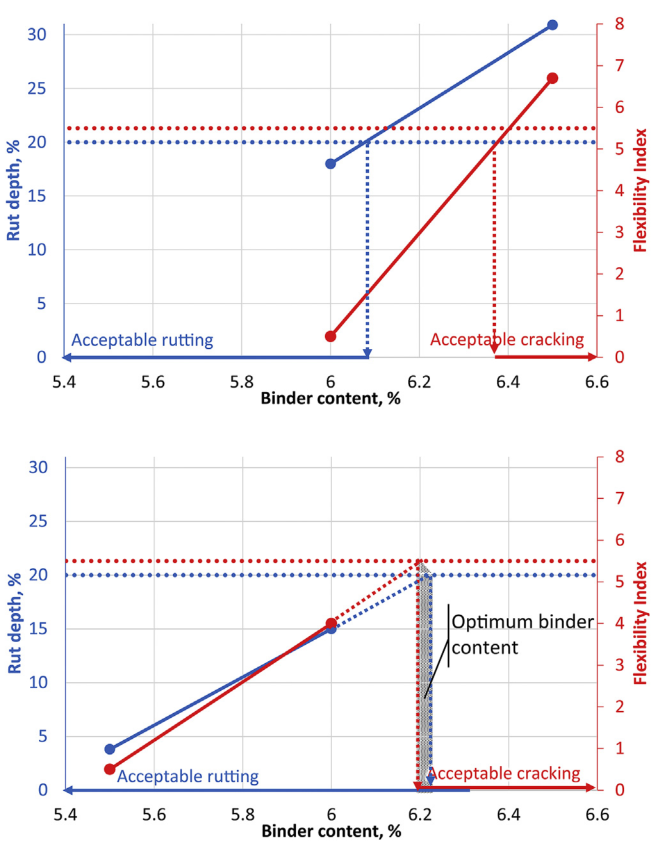

Fig. 13. Balanced design of RAP fine (a) and RAP coarse (b) mixtures.

Such potential improvements include increased fine and coarse aggregate angularity, higher aggregate strength, larger nominal maximum aggregate size, use of PMB, etc. (Zaumanis et al., 2018b).

Unfortunately, unlike for virgin or low RAP mixtures, the potential for changes in mix design for high RAP mixtures is limited because of the necessity to work with the material at hand. Since binder content changes did not provide the necessary performance, the two other key parameters that could be changed are coarseness of grading curve and to a certain extent the grade of the binder (through changing the dosage of rejuvenator). Since the gradation of *RAP fine* mixture was on the limit of the required grading curve of AC 8 mix type, it was decided to re-grade the RAP to make it coarser (see Fig. 3). The performance-based test results of the *RAP coarse* mixture are illustrated in Fig. 13 *(b).* It can be seen that re-grading has allowed obtaining bitumen content (6.2%) where both the rutting and the FI requirements are fulfilled simultaneously. Arriving to 6.2% binder content requires extrapolation of binder content by 0.2% which can be considered acceptably minor. The overlapping area for optimum binder content, however, is relatively narrow, especially considering the inherent RAP variability. Ideally, for an increased confidence, the mixture should be further redesigned to widen the optimum binder content range. For this experiment, however, *RAP coarse* with 6.2% binder content was used for production of the slabs for testing with MMLS3.

4.5. Validation of optimum mixture design and MMLS3 test results

According to the outcome of the balanced mixture design discussed in the previous section, an asphalt mixture with 6.2% binder content with the *RAP coarse* gradation was prepared. The slabs for MMLS3 were compacted to the target density of Marshall samples of the same mixture design. While for the AC8N this was known (2.8%, see Table 1), the 100% recycled asphalt with 6.2% binder was not tested before, so before preparing the slabs for MMLS3 it was determined that the air void content of Marshall samples is 2.3%.

The optimum mixture was also tested for water sensitivity and demonstrated mean indirect tensile strength of dry 100% recycled asphalt samples of 1433 kPa and for moisture-conditioned samples – 1333 kPa. The ratio of wet to dry results (ITSR) is 93% which safely fulfills the requirements of Switzerland specifications of minimum ITSR of 70%. Excellent moisture damage resistance of high RAP mixtures has been previously reported by other authors (Mogawer et al., 2012; Tram et al., 2012).

As described in section 2.2.7, the crack formation and propagation was monitored periodically with visual inspections, LVDTs and using the DIC system. The fatigue limit of the slab was established as the number of MMLS3 load applications when the crack reaches the slab surface, after growing from the notch through the material. Fig. 14 shows a crack that is visible thanks to a large differential movement between each side of the slab, after one MMLS3 tire passing.

An example of the raw data obtained from LVDT measurements are presented in Fig. 15a. The 3 s time frames show the deflections induced by 6 MMLS3 tire passings and measured by three LVDTs located at the center of the slab and 35 cm on each side. The deflection amplitudes at the center of each slab, calculated from the raw data vs. the accumulated MMLS3 cycles are presented in Fig. 15b. This results show that the 100% RAP slabs are much stiffer and durable compared to the slabs produced with standard AC8N material, as they deform less under same loading and temperature conditions.

With the analysis of the images obtained from the DIC system, it was possible to form a more precise assessment of the development of the cracks. Fig. 16 illustrates the displacements in horizontal direction of a region around the notch, when the MMLS3 tire

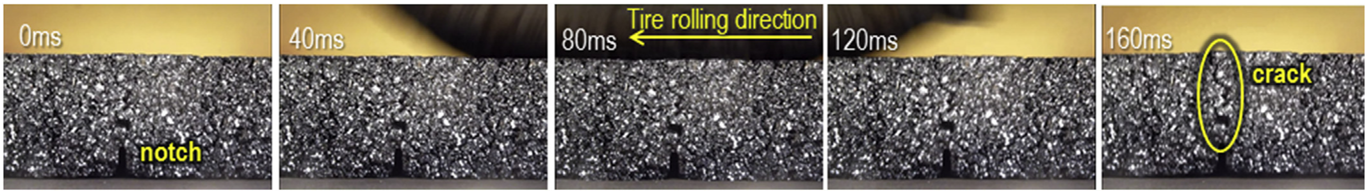

Fig. 14. Consecutive video frames (left to right) showing development of a crack between the notch and the slab's surface.

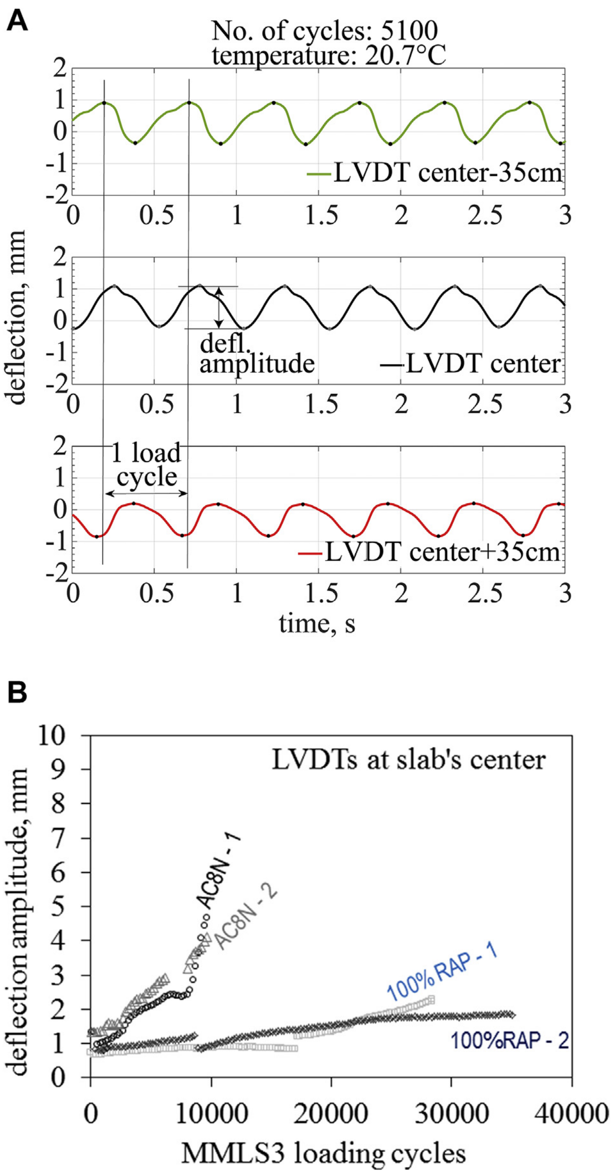

Fig. 15. a) example of the LVDTs records and (b) calculated defl. amplitudes at the center of each slab.

is passing over the center of the slab. Each snapshot was taken after a certain number of load applications, as depicted in the figure. In the situation when the plate bends and no apparent cracks have developed (until 9000 cycles), the colors representing the displacements do not present any discontinuity, i.e. there is a smooth transition between different tonalities. On the contrary, the image corresponding to 12400 cycles present a discontinuity in the colors, suggesting that a crack has initiated in the notch. The following images indicate a progression of the crack until reaching the slab's surface after approximately 30000 load cycles.

The number of MMLS3 load cycles required to produce the slab's failure are summarized in Table 2. It can be observed that the average fatigue limit for the standard AC8N material is reached after 11,000 load cycles whereas the 100% RAP can withstand 28,000 cycles on average, which is 2.5 times more. These results demonstrate good fatigue resistance of 100% RAP mixtures under the repetitive loading of rolling tires.

The asphalt slabs that were prepared for MMLS3 tests were also tested for skid resistance. The British pendulum method showed that the 100% recycled asphalt mixture has a value of 53 and the reference mixture has a value of 54. According to Asi (2007) the required skid resistance for a high traffic road (exceeding 2000 vehicles per day) is at least 55. For all other sites the required value should be at least 45. This indicates that the 100% RAP mixture could be safely used for intermediate traffic intensity roads, like it was intended in this research.

4.6. Particle abrasion

Fig. 17 demonstrates the average particle size distribution during the MMLS3 loading period of 1 h. Before starting the MMLS3 test, the particle distribution in ambient air (background) was collected and these results are also illustrated in the figure. The difference between these two distributions is the amount of abraded particles from asphalt as a result of the MMLS3 wheels passing over slab. It can be seen in Fig. 17 that some particles are being abraded in the air from the asphalt slabs, but the amount is even lower than the amount of particles already in the ambient air. It can also be seen that the amount of particles in ambient air in both cases is similar despite the tests being performed a month apart. This shows that the results are relatively robust.

The calculated emission factors throughout the test period of 60 min are illustrated in Fig. 18. The sampling was performed in 5 min intervals for the 100% RAP and 10 min intervals for the AC8N mixture. The average emission factor for each sampling period is illustrated in the figure. Only one measurement per asphalt type was performed and therefore no statistical evaluation is provided. It was previously reported by Gehrig (Gehrig et al., 2010) that for this test a measurement uncertainty of 30% can be assumed at a 95% confidence interval. It can be seen that the AC8N throughout most of the test has a higher emission factor compared to the 100% RAP. On the average the emission factor of RAP is 0.94 mg/km and for the AC8N mixture it is 5.8 mg/km. The results of the AC8N mixture are similar to what has been reported previously and such emission factors can be generally considered low (Bukowiecki et al., 2010; Gehrig et al., 2010). It can be hypothesized that the recycled asphalt is abrading fewer particles than the AC8N because the mineral aggregates have been encapsulated by the bitumen twice (originally and during recycling) and/or because it has lower air void content of 2.3% compared to 2.8% for the AC8N mixture.

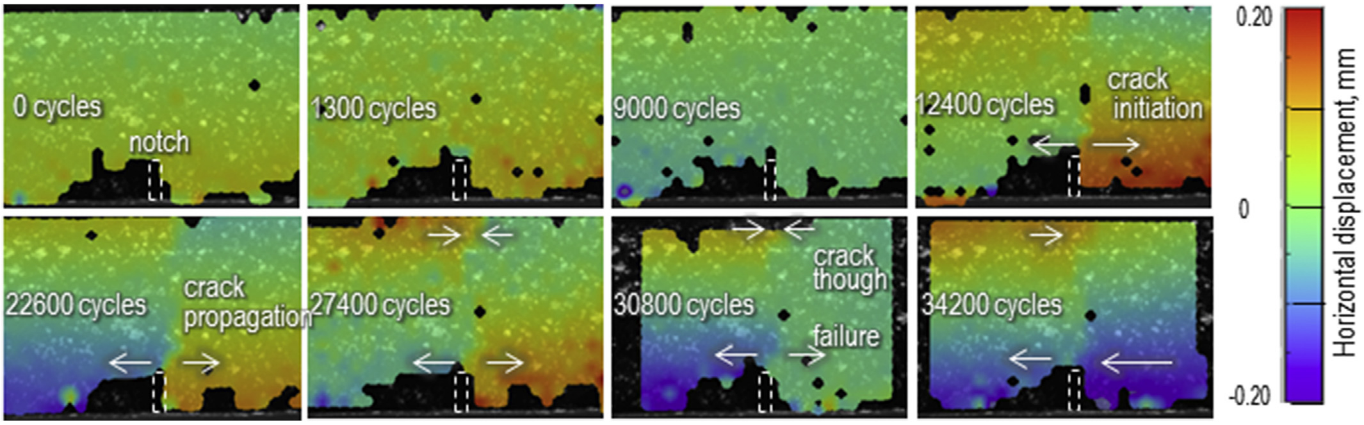

Fig. 16. DIC images at different loading cycles for 100%RAP-2.

Table 2
Fatigue limit of the slabs loaded with the MMLS3.

Material	Cycles to failure	Mean
AC8N-1	12 000	11 000
AC8N-2	10 000	
100% RAP-1	26 000	28 000
100% RAP-2	30 000	

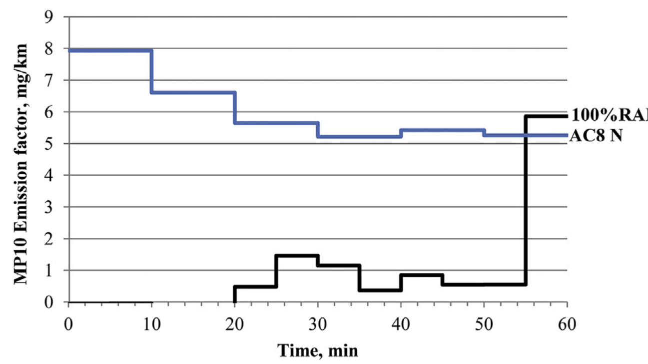

Fig. 18. Emission factor as a function of time.

5. Conslucions

Conventional volumetric mix design procedures cannot ensure the required asphalt pavement performance for mixtures with high recycled asphalt content. This is because of the many unconventional variables including rejuvenator use, blending and diffusion of binders, increased susceptibility to cracking, and others. In this study a 100% recycled mixture was designed by balancing two performance-based properties of asphalt particularly relevant for high RAP mixtures: rutting using French wheel tester and flexibility index using semi-circular bend test. Two different RAP grading curves were used with two binder contents each. For one of the mixtures, a polymer-modified bitumen was also used. The design approach was then validated by testing the optimum mixture design using Model Mobile Load Simulator (MMLS3). Finally the pavement surface was tested for skid resistance and particle abrasion due to moving wheels.

The following conclusions can be drawn from the research:

(1) 100% RAP mixtures could not satisfy the conventional volumetric and Marshall test requirements. However, it is recognized that even correspondence to these requirements would not ensure the required pavement performance.
(2) Performance-based balanced design procedure to balance French rutting test and Flexibility Index from semi-circular bend test was found practical and provided the expected trends as a result of changes in mix design.
(3) It was found by changing different mixture parameters that it is possible to ensure that 100% recycled surface layer asphalt mixture provides similar laboratory rutting and cracking

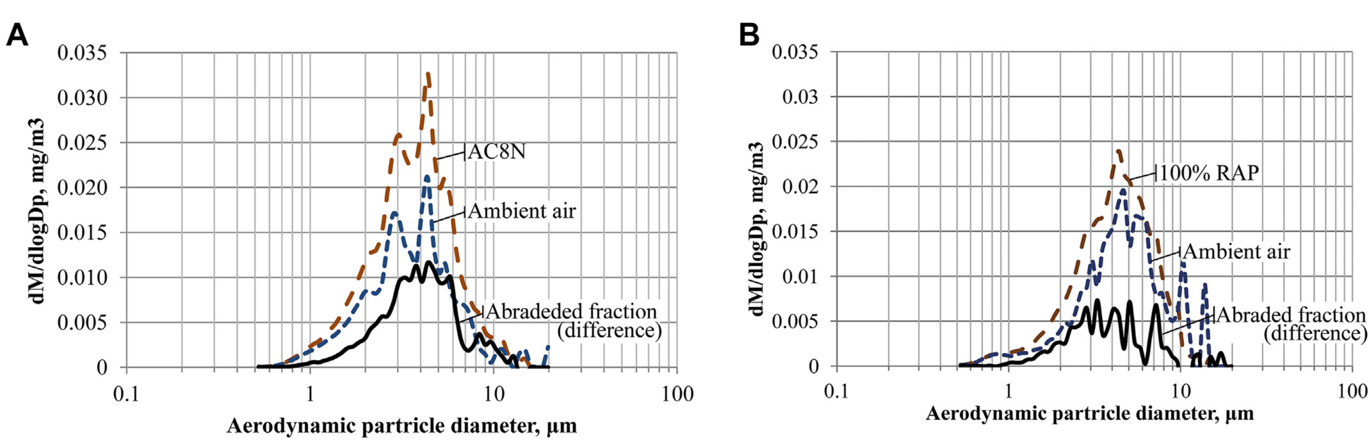

Fig. 17. Average particle size distribution over 1 h of test (a – AC8N and b – 100% RAP).

performance to conventional asphalt intended for roads with design traffic intensity of up to 300 equivalent single axle loads per day.
(4) Testing with MMLS3 demonstrated that the optimum design of 100% recycled mixtures can sustain 2.5 times more wheel passes before fatigue failure compared to the reference AC8N mixture.
(5) Testing of particle abrasion from the asphalt slabs during loading with MMLS3 demonstrated that 100% recycled asphalt emission factor is lower compared to a traditional AC8N mixture. Both emissions factors can be considered low.
(6) Moisture resistance of the 100% recycled asphalt was excellent having 97% tensile strength ratio.
(7) The skid resistance of 100% recycled and virgin mixtures was similar and sufficient for the intended traffic intensity.

Based on the positive experience of using performance-based mixture tests to balance cracking and rutting, it is recommended to consider such an approach as part of the design procedure for mixtures containing high content of reclaimed asphalt. In this study French wheel tester along with Semi-circular bend test flexibility index was found responsive to changes in mixture design, repeatable and simple enough for practical use.

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References

You, Z.-P., Goh, S.-W., 2008. Laboratory evaluation of warm mix asphalt: a preliminary study. Int. J. Pavement res. Technol 1, 34–40. https://doi.org/10.6135/IJPRT.ORG.TW/2008.1(1).34.
Asi, I.M., 2007. Evaluating skid resistance of different asphalt concrete mixes. Build. Environ. 42, 325–329. https://doi.org/10.1016/j.buildenv.2005.08.020.
Bowers, B.F., Moore, J., Huang, B., Shu, X., 2014. Blending efficiency of Reclaimed Asphalt Pavement: an approach utilizing rheological properties and molecular weight distributions. Fuel 135, 63–68. https://doi.org/10.1016/J.FUEL.2014.05.059.
Büchler, S., Falchetto, A.C., Walther, A., Riccardi, C., Wang, D., Wistuba, M.P., 2018. Wearing course mixtures prepared with high reclaimed asphalt pavement content modified by rejuvenators. Transp. Res. Rec. J. Transp. Res. Board. https://doi.org/10.1177/0361198118773193.
Bukowiecki, N., Lienemann, P., Hill, M., Furger, M., Richard, A., Amato, F., Prévôt, A.S.H., Baltensperger, U., Buchmann, B., Gehrig, R., 2010. PM10 emission factors for non-exhaust particles generated by road traffic in an urban street canyon and along a freeway in Switzerland. Atmos. Environ. 44, 2330–2340. https://doi.org/10.1016/J.ATMOSENV.2010.03.039.
Cavalli, M.C., Zaumanis, M., Mazza, E., Partl, M.N., Poulikakos, L.D., 2018. Effect of ageing on the mechanical and chemical properties of binder from RAP treated with bio-based rejuvenators. Compos. B Eng. 141, 174–181. https://doi.org/10.1016/j.compositesb.2017.12.060.
Dinis-Almeida, M., Castro-Gomes, J., Sangiorgi, C., Zoorob, S.E., Afonso, M.L., 2016. Performance of warm mix recycled asphalt containing up to 100% RAP. Constr. Build. Mater. 112, 1–6. https://doi.org/10.1016/J.CONBUILDMAT.2016.02.108.
EAPA, 2018. Asphalt in Figures 2016.
Gehrig, R., Zeyer, K., Bukowiecki, N., Lienemann, P., Poulikakos, L.D., Furger, M., Buchmann, B., 2010. Mobile load simulators – a tool to distinguish between the emissions due to abrasion and resuspension of PM10 from road surfaces. Atmos. Environ. 44, 4937–4943. https://doi.org/10.1016/J.ATMOSENV.2010.08.020.
Im, S., Karki, P., Zhou, F., 2016. Development of new mix design method for asphalt mixtures containing RAP and rejuvenators. Constr. Build. Mater. 115, 727–734. https://doi.org/10.1016/J.CONBUILDMAT.2016.04.081.
Kriz, P., Grant, D.L., Veloza, B.A., Gale, M.J., Blahey, A.G., Brownie, J.H., Shirts, R.D., Maccarrone, S., 2014. Blending and diffusion of reclaimed asphalt pavement and virgin asphalt binders. Road Mater. Pavement Des. 15, 78–112. https://doi.org/10.1080/14680629.2014.927411.
Lo Presti, D., Jiménez del Barco Carrión, A., Airey, G., Hajj, E., 2016. Towards 100% recycling of reclaimed asphalt in road surface courses: binder design methodology and case studies. J. Clean. Prod. 131, 43–51. https://doi.org/10.1016/j.jclepro.2016.05.093.
McDaniel, R.S., Shah, A., Huber, G.A., Copeland, A., 2012. Effects of reclaimed asphalt pavement content and virgin binder grade on properties of plant produced mixtures. Road Mater. Pavement Des. 13, 161–182. https://doi.org/10.1080/14680629.2012.657066.
Mogawer, W., Bennert, T., Daniel, J.S., Bonaquist, R., Austerman, A., Booshehrian, A., 2012. Performance characteristics of plant produced high RAP mixtures. Road Mater. Pavement Des. 13, 183–208. https://doi.org/10.1080/14680629.2012.657070.
Mogawer, W., Austerman, A., Mohammad, L., Kutay, M.E., 2013. Evaluation of high RAP-WMA asphalt rubber mixtures. Road Mater. Pavement Des. 14, 129–147. https://doi.org/10.1080/14680629.2013.812846.
Mohn, J., Zeyer, K., Keck, M., Keller, M., Zähner, M., Poteko, J., Emmenegger, L., Schrade, S., 2018. A dual tracer ratio method for comparative emission measurements in an experimental dairy housing. Atmos. Environ. 179, 12–22. https://doi.org/10.1016/J.ATMOSENV.2018.01.057.
Ozer, H., Al-Qadi, I.L., Kanaan, A., 2012. Laboratory Evaluation of High Asphalt Binder Replacement with Recycled Asphalt Shingles (RAS) for a Low N-Design Asphalt Mixture. Springfield, IL.
Ozer, H., Al-Qadi, I.L., Lambros, J., El-Khatib, A., Singhvi, P., Doll, B., 2016a. Development of the fracture-based flexibility index for asphalt concrete cracking potential using modified semi-circular bending test parameters. Constr. Build. Mater. 115, 390–401.
Ozer, H., Al-Qadi, I.L., Singhivi, P., Khan, T., Rivera-Perez, J., El-Khatib, A., 2016b. Fracture characterisation of asphalt mixtures with high recycled content and using Illinois semicircular bending test method and flexibility index. Transp. Res. Rec. J. Transp. Res. Board 2, 130–137.
RILEM, T.C.S., 1985. Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. Mater. Struct. 18, 285–290.
Song, W., Huang, B., Shu, X., 2018. Influence of warm-mix asphalt technology and rejuvenator on performance of asphalt mixtures containing 50% reclaimed asphalt pavement. J. Clean. Prod. 192, 191–198. https://doi.org/10.1016/J.JCLEPRO.2018.04.269.
Sreeram, A., Leng, Z., Zhang, Y., Padhan, R.K., 2018. Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: an approach using ATR-FTIR and artificial aggregate. Constr. Build. Mater. 179, 245–253. https://doi.org/10.1016/J.CONBUILDMAT.2018.05.154.
Tram, N.H., Taylor, A., Willis, R., 2012. Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents. National Center for Asphalt Technology, Auburn, AL.
Valdés, G., Pérez-Jiménez, F., Miró, R., Martínez, A., Botella, R., 2011. Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP). Constr. Build. Mater. 25, 1289–1297. https://doi.org/10.1016/J.CONBUILDMAT.2010.09.016.
West, R., 2008. Summary of NCAT Survey of RAP Management Practices and RAP Variability. Auburn, AL.
West, R., Kvasnak, A., Tran, N., Powell, B., Turner, P., 2009. Testing of moderate and high reclaimed asphalt pavement content mixes. Transp. Res. Rec. J. Transp. Res. Board 2126, 100–108. https://doi.org/10.3141/2126-12.
West, R., Michael, J., Turochu, R.E., Maghsoodloo, S., 2011. Comparison of virgin and recycled asphalt pavements using long-term pavement performance SPS-5 data. In: Transportation Research Board 90th Annual Meeting. Transportation Research Board, Washington, D.C.
Widyatmoko, I., 2008. Mechanistic-empirical mixture design for hot mix asphalt pavement recycling. Constr. Build. Mater. 22, 77–87. https://doi.org/10.1016/J.CONBUILDMAT.2006.05.041.
Zaumanis, M., Valters, A., 2019. Comparison of two low-temperature cracking tests for use in performance-based asphalt mixture design. Int. J. Pavement Eng. https://doi.org/10.1080/10298436.2018.1549323.
Zaumanis, M., Mallick, R.B., Frank, R., 2014. Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications. Constr. Build. Mater. 69, 155–166. https://doi.org/10.1016/j.conbuildmat.2014.07.035.
Zaumanis, M., Mallick, R.B., Frank, R., 2016. 100% hot mix asphalt recycling: challenges and benefits. In: Transportation Research Procedia, pp. 3493–3502. https://doi.org/10.1016/j.trpro.2016.05.315.
Zaumanis, M., Oga, J., Haritonovs, V., 2018a. How to reduce reclaimed asphalt variability: a full-scale study. Constr. Build. Mater. 188, 546–554. https://doi.org/10.1016/J.CONBUILDMAT.2018.08.137.
Zaumanis, M., Poulikakos, L.D., Partl, M.N., 2018b. Performance-based design of asphalt mixtures and review of key parameters. Mater. Des. 141, 185–201. https://doi.org/10.1016/j.matdes.2017.12.035.
Zaumanis, M., Boesiger, L., Kunz, B., Cavalli, M.C., Poulikakos, L., 2019. Determining optimum rejuvenator addition location in asphalt production plant. Constr. Build. Mater. 198, 368–378. https://doi.org/10.1016/j.conbuildmat.2018.11.239.
Zhou, F., Hu, S., Scullion, T., Lee, R., 2014. Balanced RAP/RAS mix design system for project-specific conditions. In: Journal of the Association of Asphalt Paving Technologists. Association of Asphalt Paving Technologists, pp. 191–196.