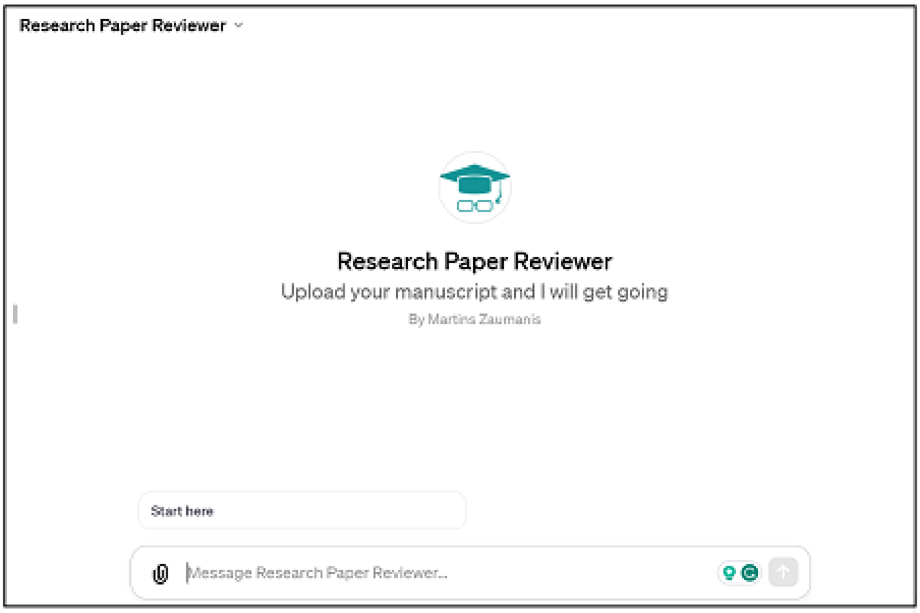
# Research Paper Review by ChatGPT



Research Paper Reviewer

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By Martins Zaumanis

**Research Paper Reviewer**

## Manuscript Review: "Asphalt recycling in polymer modified pavement: A test section and recommendations"

Title

- **Summary**: "Asphalt recycling in polymer modified pavement: A test section and recommendations"
- **Comments**: The title is specific and descriptive, clearly indicating the focus on asphalt recycling in polymer-modified pavements and implying practical application through a test section and recommendations.
- **Suggestions**: The title is well-constructed, but could potentially include a specific result or finding for greater impact.

Abstract

- **Summary**: Discusses the acceleration of Reclaimed Asphalt Pavement (RAP) recycling, particularly in polymer-modified pavement, and presents findings from a test section with 30%-50% RAP showing good performance. Recommendations for RAP use in polymer-modified layers are provided.

- **Comments**: The abstract effectively summarizes objectives, methods, key findings, and implications. It maintains clarity and avoids jargon, focusing on significance and potential implications.
- **Suggestions**: The abstract is comprehensive; however, ensure that it stays within the typical word limit for the target journal.

## Introduction

- **Summary**: Highlights the increasing use of RAP in asphalt production, the challenges in using RAP in polymer-modified mixtures, and the research gap in understanding the blending of aged and virgin binders. The study addresses these gaps through a case study.
- **Comments**: Provides necessary background, significance, and research gaps. The research problem is well articulated.
- **Suggestions**: Further emphasize the potential impact of the study's findings.

## Objective

- **Summary**: Design polymer-modified mixtures with high RAP content, construct a full-scale test section, and offer recommendations for RAP use in polymer-modified mixtures.
- **Comments**: Clear and concise objective, accurately presenting the paper's focus.
- **Suggestions**: None; the objective is well-stated.

## Methods

- **Summary**: Detailed description of research methodology, including mixture design, rejuvenator selection, performance-based mixture design, and various testing methods for binder and mixture properties.
- **Comments**: Methodology is well-documented, allowing for reproducibility. Ethical considerations are not explicitly mentioned but may not be applicable.
- **Suggestions**: Consider adding a flowchart or table summarizing key steps if not already included.

## Results

- **Summary**: Results include detailed data on mixture and binder properties, performance of extracted binder, and performance of various mixtures in test sections.
- **Comments**: Results are thoroughly presented with quantitative descriptions. Data visualizations would enhance understanding.
- **Suggestions**: Ensure results are presented in a logical sequence.

### Discussion

- **Summary**: Analyzes the test results, comparing them with reference mixtures and discussing implications for RAP use in polymer-modified pavements.
- **Comments**: Discussion ties back to objectives, interprets results, and acknowledges limitations. Aligns and contrasts with existing literature.
- **Suggestions**: Discuss any unexpected results or alternative explanations more explicitly.

### Conclusions

- **Summary**: Summarizes findings on the viability of high RAP content in polymer-modified pavements, noting performance similarities with lower RAP mixtures and making recommendations for RAP use.
- **Comments**: Conclusions effectively summarize findings and restate the problem and methodology. Implications and recommendations are clear.
- **Suggestions**: Consider using bullet points for clearer presentation of key conclusions.

### Appendix

- **Comments**: The presence of an appendix with additional data or supporting evidence is not mentioned.
- **Suggestions**: If there is supplementary material, consider sharing it in an online repository or as an appendix.

## Overall Assessment

- The paper is well-written and thoroughly addresses the categories outlined. It presents significant findings in the field of asphalt recycling.
- Next Steps:
  - Confirm the title of the scientific journal for submission to provide a scope recommendation.

- Inquire if a review of the manuscript's compliance with the journal's author's guide is needed.

Would you like to provide the name of the journal for scope assessment? Should I review the manuscript's compliance with the journal's author guide?

**You**

International Journal of Pavement Research and Technology

**Research Paper Reviewer**

The manuscript "Asphalt recycling in polymer modified pavement: A test section and recommendations" is suitable for submission to the *International Journal of Pavement Research and Technology*. The journal aims to promote the exchange of ideas in pavement engineering, encompassing a wide range of topics including pavement recycling, which aligns well with the subject of your manuscript.

To ensure compliance with the journal's submission guidelines, here are key points to consider:

1. **Double-Blind Review and Anonymization**: The journal follows a double-blind review process. Ensure that the manuscript and associated materials do not contain identifying information like author names or affiliations. A separate title page should be submitted containing this information along with acknowledgments, disclosures, or funding information.
2. **Manuscript Format and Length**: Manuscripts should be submitted in Word or LaTeX format, using a normal, plain font like 10-point Times Roman. The text should be concise, ideally within 15 single-spaced pages.
3. **Abbreviations**: Define all abbreviations at their first mention and use them consistently throughout the manuscript.
4. **References**: Use square brackets for in-text citations. The reference list should be numbered consecutively, include only works cited in the text, and be formatted according to APA version 7 guidelines. Include full DOI links where available.
5. **Tables**: Number all tables using Arabic numerals and cite them in consecutive order in the text. Supply a caption for each table, and identify any previously published material.

6. **Artwork and Figures**: Submit all artwork electronically. For vector graphics, use EPS format, and for halftones, use TIFF format. Name figure files appropriately (e.g., Fig1.eps). Figures should be numbered using Arabic numerals, cited in consecutive order in the text, and accompanied by concise captions included in the text file of the manuscript, not in the figure file.

Before submitting, ensure that the manuscript aligns with these guidelines. Would you like assistance in assessing the manuscript's compliance with these specific requirements of the *International Journal of Pavement Research and Technology*?

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Great, let's proceed with assessing the compliance of your manuscript, "Asphalt recycling in polymer modified pavement: A test section and recommendations," with the submission guidelines of the *International Journal of Pavement Research and Technology*. I'll review aspects such as formatting, abbreviations, citation style, figure and table formatting, and other relevant items based on the journal's guidelines.

Please give me a moment to conduct this review.

After reviewing your manuscript "Asphalt recycling in polymer modified pavement: A test section and recommendations," here are some key points regarding its compliance with the submission guidelines of the *International Journal of Pavement Research and Technology*:

1. **Anonymization for Double-Blind Review**: The manuscript should not contain author names or affiliations within the main text or figures to comply with the double-blind review process.
2. **Manuscript Format**: Ensure the manuscript is formatted correctly (e.g., font size, spacing) as per the journal's guidelines.
3. **Abbreviations**: All abbreviations seem to be defined at their first mention, in line with the journal's requirements.
4. **References**: The referencing style should follow the journal's specific format, including the use of square brackets and proper citation of all authors up to 20.

5. **Tables and Figures**: Tables and figures are properly numbered and cited. Ensure that all tables have captions and any supplementary material is properly referenced.
6. **Length of Manuscript**: The manuscript appears concise. However, ensure it aligns with the journal's preference for a length of fewer than 15 single-spaced pages.
7. **Title Page and Abstract**: Ensure the title page is separate and contains all required information. The abstract should be within 150 to 250 words, and keywords are appropriately provided.

Please make any necessary adjustments to ensure full compliance with the journal's guidelines. Do you need any further assistance with this process?

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no

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Alright, if you have any more questions or need further assistance in the future, feel free to ask. Good luck with your manuscript submission!

**You**

offer alternative titles and a list of keywords for your paper

**Research Paper Reviewer**

Certainly! Here are six alternative titles and a list of six keywords for your manuscript "Asphalt recycling in polymer modified pavement: A test section and recommendations":

## Alternative Titles

1. "High RAP Content in Polymer-Modified Asphalt: Performance and Guidelines"
2. "Evaluating Recycled Asphalt Pavement in Polymer-Modified Mixes: A Practical Approach"
3. "Innovative Utilization of Reclaimed Asphalt in Polymer-Modified Pavements"

4. "Advancing Sustainable Road Construction: Polymer Asphalt Mixes with High RAP"
5. "Optimizing Polymer-Modified Asphalt: Incorporating High RAP Ratios"
6. "Sustainable Pavement Solutions: High RAP in Polymer-Modified Asphalt"

## Keywords

1. Reclaimed Asphalt Pavement (RAP)
2. Polymer-Modified Asphalt
3. Sustainable Road Construction
4. Asphalt Recycling
5. Pavement Performance
6. Asphalt Mix Design

These titles and keywords are designed to be descriptive and to enhance the visibility and searchability of your paper in academic and industry-related research databases.

# ASPHALT RECYCLING IN POLYMER MODIFIED PAVEMENT: A TEST SECTION AND RECOMMENDATIONS

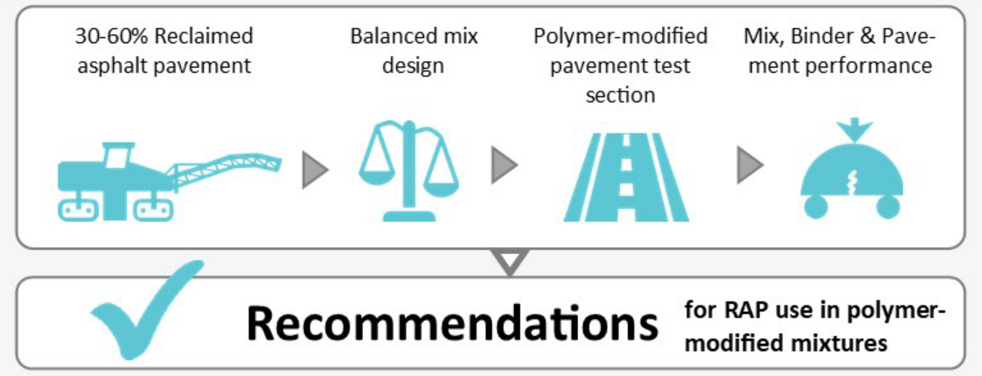
Martins Zaumanis, Lily Poulikakos, Martin Arraigada, Bernhard Kunz, Urs Schellenberg, Christoph Gassmann

## 1. ABSTRACT

While recycling of Reclaimed Asphalt Pavement (RAP) is accelerating, road owners still often restrict the use of RAP in polymer-modified pavement. Here we used a balanced mixture design for preparing polymer-modified asphalt mixtures for wearing and binder courses having 30 % to 60 % RAP content. Findings from the paved test section show that it is possible to design polymer-modified mixtures with 30 % to 50 % RAP that have a good crack propagation resistance, high fatigue resistance, acceptable stiffness, and sufficient rutting resistance. Based on the findings, recommendations for RAP use in polymer-modified layers are provided.

**Keywords:** RAP; polymer-modified binder; trial section; case study; performance-based tests; balanced mix design; reclaimed asphalt pavement; asphalt recycling; in-situ performance, asphalt re-use

### Graphical abstract



### Highlights:

- Up to 50 % reclaimed asphalt can be used in polymer-modified pavements
- Polymer-modified wearing coarse was constructed with 30 % RAP
- 65% RAP used in unmodified binder course—with good performance
- Recommendations for PmB mixture design with RAP are provided

## 2. INTRODUCTION

Re-use of reclaimed asphalt in the production of new asphalt mixtures provides environmental and economic benefits. For this reason, the use of Reclaimed Asphalt Pavement (RAP) in asphalt production is steadily increasing. For example, in the USA the average percentage of RAP used in asphalt production has increased from 15 % in 2009 to 22% in 2021 [1]. As a consequence, the total amount of RAP used in asphalt mixtures in the same period increased by 68.9% (the amount of produced asphalt increased by only 20.6 %).

While asphalt re-use and recycling are increasing, the use of reclaimed asphalt pavement in polymer-modified asphalt mixtures is still relatively poorly explored. Although there are studies on the use of reclaimed asphalt used together with styrene-butadiene-styrene (SBS) [2,3], poly butadiene rubber (PBR) [4], and even waste PBR [5], there are still many open questions. In particular there is insufficient understanding of the blending of the aged and virgin binders and concerns about the long-term performance of recycled asphalt mixtures, especially the elastic performance and cracking resistance [6–13]. There is also a lack of information about the mixture performance since most research studies only report the binder properties after full blending of extracted RAP binder and virgin Polymer Modified Binder (PmB) (full blending does not occur in mixtures). Finally, there is lack of published results on full-scale research on the use of RAP in polymer modified mixtures. This further limits the ability to make evidence-based decisions on the RAP use in PmB containing asphalt mixtures.

For the abovementioned reasons, the use of RAP in polymer-modified mixtures is often restricted (e.g. in Florida to 20% [11]) and the RAP use in wearing courses is not permitted by many road authorities (e.g. in Switzerland an agreement must be made between the road owner and the contractor to use above 0% RAP [14]).

Polymer-modified mixtures are typically paved on high traffic intensity roads and on wearing courses. Considering that good practices for efficient road maintenance often only require the regular replacement of the surface layer (i.e. wearing coarse), permitting the RAP use in such high value application would enable to efficiently re-use the milled material (as opposed to RAP downcycling for use in lower, non-PmB-modified layers).

In this case study, we aimed to explore the boundaries of RAP re-using in PmB layers (including surface courses) using the technology and materials available for an economically viable construction of large-scale road pavements in Switzerland. To do this, we designed three mixture types with RAP contents between 30 and 60 %. Such RAP content was hypothesized to be at or slightly beyond the boundary of what is currently possible to ensure the properties expected from PmB-containing mixtures. These mixtures were then paved on a high traffic intensity road and sampled for testing the performance of extracted binder as well as mixture performance.

### 2.1. Objective

The objective of the research was to design polymer-modified mixtures with high RAP content, to construct a full-scale test section for determining the mixture performance and to offer recommendations for RAP use in polymer-modified mixtures.

## 3. METHODOLOGY

The research methodology is summarized in Fig. 1. The constituent materials for designing the mixtures were sampled from the BHZ AG asphalt plant. A highly polymer-modified virgin binder (Styrol-Butadien-Styrol (SBS) content ≥6 %) was used to compensate for the lack of polymers in the RAP.

After determining the optimum recycling agent content, a balanced mixture design was performed to optimize the binder content and binder type using semi-circular bend (SCB) test and cyclic compression (CC) test. According to the approach described by Zaumanis et al. [15], conventional mixture properties (air voids, gradation, and binder content) and binder properties were used to facilitate design optimization.

For construction of the test section, the prepared recipes (abbreviated with "HighRAP" in the rest of the paper) were handed to the asphalt producer who, based on the RAP routine testing results, made the final adjustments to account for the binder content and gradation of materials available at the time of production. The virgin binder and the RAP used in the production differed from the materials used during mixture design while the recycling agent was the same at both stages.

During construction, asphalt samples were gathered for extended laboratory testing of the mixture and extracted binder properties according to the methods summarized in Fig. 1. In addition, road cores were sampled from the pavement for determining air voids, and testing with SCB test.

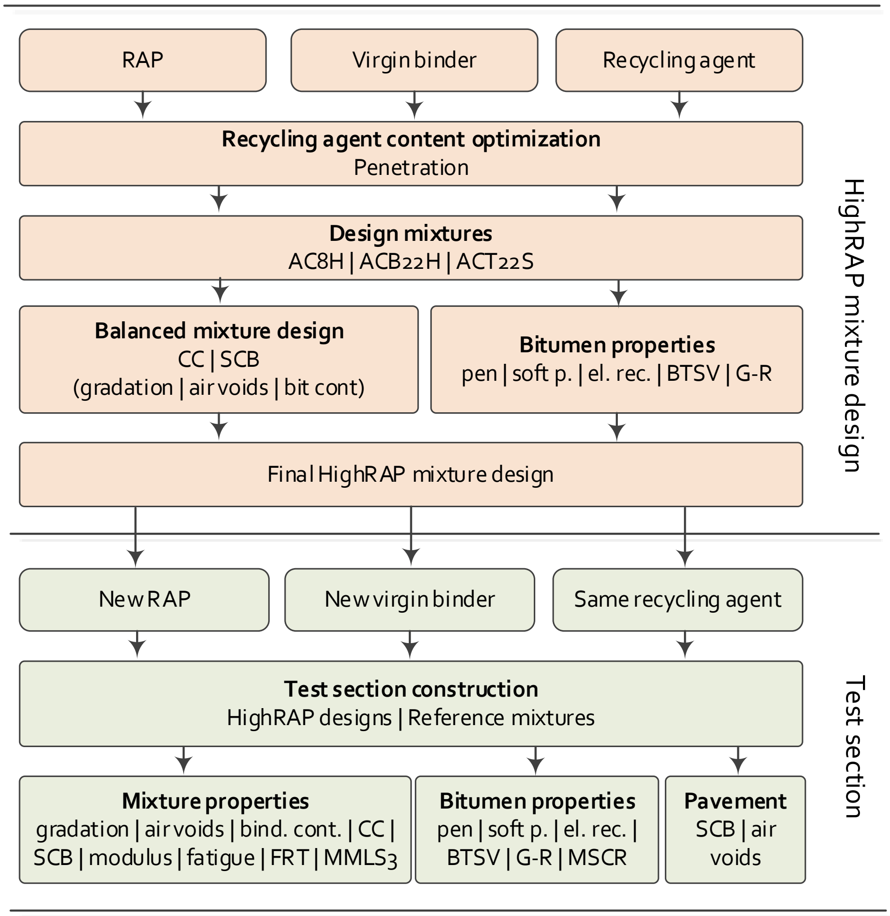


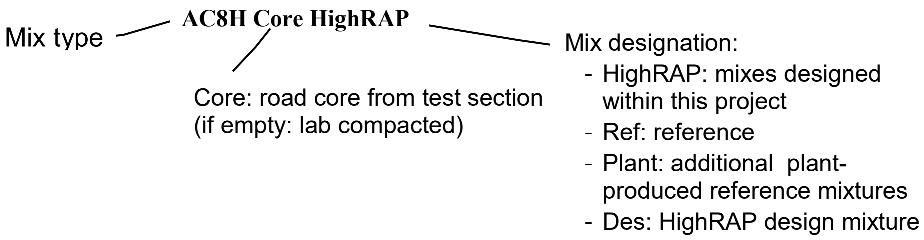
*Fig. 1 Research methodology and test methods (CC-Cyclic Compression, SCB-Semi-Circular Bend; BTSV-Binder fast characterization test; G-R-Glower-Rowe parameter; FRT-French Rut Tester; MSCR-Multiple Stress Creep Recovery; MMLS3-Model Mobile Load Simulator)*

## 3.1. Target mixtures

The following three mixture types from the test section were evaluated:

- AC8H 30 % RAP mixture with a target PmB grade of 45/80-80 was compared to the reference 0 % RAP mixture with a target grade of 45/80-80.
- ACB22H 60 % RAP mixture with a target PmB grade of 45/80-80. Using the available RAP at the time of mix design, this target grade could not be reached so the design target grade was modified to 45/80-65. This mixture was compared to the reference 30 % RAP mixture having the target grade 45/80-80.
- ACT22S 80% RAP mixture with a target non-PmB grade of 50/70. Because the RAP properties at the time of construction were different from the properties at the design phase, the recipe was modified and two mixtures, having 65 % RAP and 75 % RAP were paved instead. These mixtures were compared to the reference 65 % RAP with a target grade of 50/70.

The mixtures are abbreviated as follows:



## 3.2. Bitumen tests

### 3.2.1. Extraction, recovery, and conventional binder tests

Bitumen extraction was performed using toluene according to EN 12697-1. This procedure was also used to determine the binder content.

Penetration was determined according to EN 1426, Softening point according to EN 1427, and Elastic recovery according to EN 13398. The mean of two softening point tests, two elastic recovery tests, and three penetration tests is reported.

### 3.2.2. Multiple Stress Creep Recovery Test (MSCR)

The Multiple Stress Creep Recovery Test (MSCR) is used to determine the creep performance of asphalt binders. The MSCR was performed according to the EN 16659 on unaged samples. This test is performed using Dynamic Shear Rheometer using 25 mm plate-plate geometry with 1 mm gap. In this research the test was performed at 60 °C. During the test, stress is applied for one second, followed by a 9 seconds rest period. This cycle is repeated 10 times at 0.1 kPa stress, followed by 10 more cycles at 3.2 kPa stress. Two main results are expressed from the test are:

- The percent recovery demonstrates the elastic response of binders and can be used to assess the effect of polymers in the binder.
- The non-recoverable creep compliance (Jnr) serves as an indicator of the sensitivity to permanent deformations of the binder under repeated load.

### 3.2.3. Binder fast characterization (BTSV) test

The BTSV test was performed according to DIN 52050 on unaged samples. The test is performed using a Dynamic Shear Rheometer (DSR) with 25 mm diameter plates having 1 mm gap under a constant shear stress of 500 Pa at 10 rad/s frequency. During the test, the temperature is increased by 1.2 °C/min between 20 °C and 90 °C. The temperature at which the complex shear modulus reaches 15 kPa is determined ($T_{BTSV}$) and the phase angle at this temperature is calculated ($\delta_{BTSV}$). For each binder, two samples were tested to ensure that the variability does not exceed the range specified in the standard.

### 3.2.4. Glover-Rowe (G-R) parameter

The Glover-Rowe parameter was calculated to characterize the susceptibility of a binder to cracking. The test was performed using a DSR using on unaged binder samples using 8 mm diameter plates with 2 mm gap. During the test, a frequency sweep is carried out at 5 °C, 15 °C, 25 °C, 35 °C, and 45 °C. The collected results are then used to construct a master curve at 15 °C using the time-temperature superposition principle. The master curve shape was calculated according to the sigmoidal model proposed by Witczak [16] and the Williams-Landel-Ferry relationship was used for calculating the shift factors [17].

The master curve was used to determine the phase angle ($\delta$) and complex shear (G*) modulus at 0.005 rad/s and 15 °C. The determined values were then used to calculate the Glover-Rowe (G-R) parameter according to Equation 1.

$$\boldsymbol{G\text{-}R} = \boldsymbol{G}^{*}((\boldsymbol{cos\delta})^{2}/\boldsymbol{sin\delta}) \qquad \text{Equation 1}$$

To set the G-R parameter damage thresholds, Rowe proposes using the relationship that Kandhal had derived between age-related cracking of pavement and the binder ductility [18,19]:

- G–R ≤ 180 kPa – no cracking (corresponding to more than 5 cm ductility)
- G–R = 180-450 kPa – crack development (corresponding to 3 cm to 5 cm ductility)
- G–R ≥ 450 kPa – significant cracking (corresponding to less than 3 cm ductility)

## 3.3. Mixture tests

For laboratory mixing the component materials (except recycling agent which remained at room temperature) were heated in an oven at 155 °C for AC8H and ACB22H, and at 145 °C for ACT22S mixture for 3 hours. Laboratory mixing was performed in an oil-heated laboratory mixer as follows: RAP aggregates were pre-blended for 0.5 minutes after which recycling agent was introduced at the specified dosage and mixed for 1.5 minutes. Finally, neat binder and virgin aggregates were introduced, followed by 3.5 minutes of mixing.

The plant-produced asphalt samples were collected at the asphalt plant during production.

The sample preparation method for each mixture test method is summarized in Tab. 1. Before laboratory compaction, the mixtures were reheated to 155 °C for AC8H and ACB22H mixtures and to 145 °C for the ACT22S mixture. The target air void content was geometrically calculated and varies depending on the sample preparation method to reach the air final void content of the test samples (surface-saturated dry method) in the range defined by the standard SN EN 13108-1 (3-6 % for AC8H type mixtures and 4-7 % for the other mixtures).

*Tab. 1 Sample preparation for mixture tests (for road cores, the compaction does not apply but the remainder is the same)*

| **Test method** | **Sample preparation** |
|---|---|
| Marshall test | Marshall compactor (2x50 blows) |
| Semi-circular bend test | Gyratory compactor to target air voids (8%) + trimming + cutting + notch |
| Cyclic compression test | Marshall compactor (2x 50 blows) + plan parallel polishing |
| Stiffness and Fatigue | Gyratory compactor to target air voids (7.5%) + cutting |
| French Rut Tester | Roller compactor with steel wheel to target air voids (4%) |
| Model Mobile Load Simulator (MMLS3) | Large-scale slab compactor to target air voids (5%) + notch + painting for DIC |

### 3.3.1. Conventional mixture tests

The maximum density was determined according to EN 12697-5 using pyknometers and toluene. Bulk density of the samples was determined using saturated surface dry method according to EN 12697-6 and the volumetric properties were then calculated according to EN 12697-8.

The Marshall test was performed according to EN 12697-34.

### 3.3.2. Semi-circular bend (SCB) test

The Semi Circular Bend (SCB) test was performed at 25 °C according to AASHTO TP 124-16 to determine susceptibility to crack propagation.

For the SCB test, a 50 mm thick half-cylindrical specimen having a notch on the flat side is positioned in a three-point testing frame and load is applied at a monotonic rate of 50 mm/min along the vertical axis. Load and displacement are measured during the test and the Flexibility Index (FI) is calculated according to Equation 2. For AC8H mixture due to the small aggregate size and hence better repeatability four samples were tested. For the other mix types six parallel samples were tested and the mean result is reported.

$$FI = \frac{G_f}{|m|} \times A \qquad \text{Equation 2}$$

, where FI is the flexibility index, $G_f$ is fracture energy calculated according to Equation 3, 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).

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6 \qquad \text{Equation 3}$$

, 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.

### 3.3.3. Cyclic Compression (CC) test

Susceptibility to plastic deformations was determined using the cyclic compression test according to the procedure described in the German standard TP Asphalt-StB Part 25 B 1. The test was performed at 60°C since preliminary testing demonstrated that tests at the standard 50 °C barely induce any damage and thus it would not be possible to distinguish between the performance of different mixtures.

In the test, a cylindrical asphalt sample is subjected to 5,000 load cycles. Each cycle consists of 0.2-second haversine pulse load followed by a 1.5-second rest period. The maximum pulse stress is 350 kPa and during the rest period, 0.035 kPa stress is applied. The loading plate diameter was 150 mm.

The lab-compacted mixture specimens were prepared by using 100 mm Marshall moulds. The road cores were cut to 100 mm diameter. Both the Marshall samples and the road cores were polished plan-parallel to 60 mm height.

During the test, the cumulative permanent deformation was measured as a function of load cycles and the creep rate ($f_c$) between 2,500 and 5,000 cycles was calculated according to Equation 4. Two replicates were tested for each material.

$$f_c = \frac{\varepsilon_{n1} - \varepsilon_{n2}}{n_1 - n_2} \times 10{,}000 \qquad \text{Equation 4}$$

where

$n_1$; $n_2$ is the number of repetitive loading cycles;

$\varepsilon_{n1}$; $\varepsilon_{n2}$ is the cumulative axial strain after 2,500 and 5,000 cycles.

### 3.3.4. Rutting resistance

Rutting resistance of the asphalt mixes was evaluated using a French Rutting Tester (FRT) according to EN 12697-22. The FRT runs using a rubber pneumatic test wheel that has a pressure of 0.60±0.03 MPa and a load of 500±5 kN. A preconditioning load is applied at room temperature for 1,000 cycles after which the sample is conditioned for about 16 hours in a temperature chamber at 60°C. 30,000 loading cycles are applied to two parallel specimens and rut depth is measured using a gauge after 30, 100, 300, 1000, 3000, 10,000, and 30,000 cycles at 5 pre-defined points along the length of the rut.

### 3.3.5. Stiffness modulus

The stiffness modulus was determined by applying Cyclic Indirect Tension on Cylindrical samples (CIT-CY) according to the German standard AL Sp-Asphalt 09. The specimen diameters were 150 mm for ACB22H and ACT22S, and 100 mm for AC8H. All samples were prepared using the Gyratory compactor using 150 mm molds, followed by coring to 100 mm diameter if necessary. All samples were cut on top and bottom to increase sample homogeneity. The height of the 150 mm diameter samples was 60 mm, and the height of the 100 mm diameter samples was 40 mm.

The samples were tested at 10°C by applying sinusoidal load at 0.1 Hz, 1 Hz, and 10 Hz loading frequencies. Three replicates were tested for each material.

### 3.3.6. Fatigue

Fatigue testing was performed according to AL Sp-Asphalt 09 standard on samples that were prepared identically to the samples for stiffness modulus testing. The fatigue test was performed at 10 °C by applying a sinusoidal repeated loading at 10 Hz frequency.

The failure criterion defined in the German standard AL Sp-Asphalt 09 is reached at the number of cycles when the energy ratio reaches the maximum value. Energy ratio is the product of the number of cycles and the corresponding stiffness modulus.

The standard requires testing of three replicates at three strain levels, however due to the large number of mixtures, the total number of repetitions was reduced to four per mixture. The stress was selected in such a way to ensure that for two test results, the maximum energy ratio is reached in the approximate range between 30,000 cycles and 100,000 cycles and for the other two – between several hundred thousand to a million cycles. If the results did not satisfy the variability requirements (coefficient of determination >0.9) further specimen were tested.

### 3.3.7. Model Mobile Load Simulator (MMLS3)

The MMLS3 (operation principle illustrated in Fig. 2 and further explained in [20]) is a scaled accelerated pavement testing device used for testing of pavement distresses under the loading of repetitive rolling tires. In this research, the machine was run at its maximum load (2.5 kN) and speed (4.5 km/h), corresponding to loading frequency rate of nearly 1 Hz.

The size of the slab specimens used in this research was 1.6 m x 0.45 m, with a thickness of 6 cm. Compaction was carried out with a steel roller. After compaction, a 3 cm deep transverse notch was cut across the center of the bottom face to initiate cracking. The short edges of the slabs were placed on steel profiles 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 whole setup was placed in a temperature chamber at 20 °C. One slab per mixture was loaded until complete failure, i.e. until the crack propagated from the bottom to the surface of the slab.

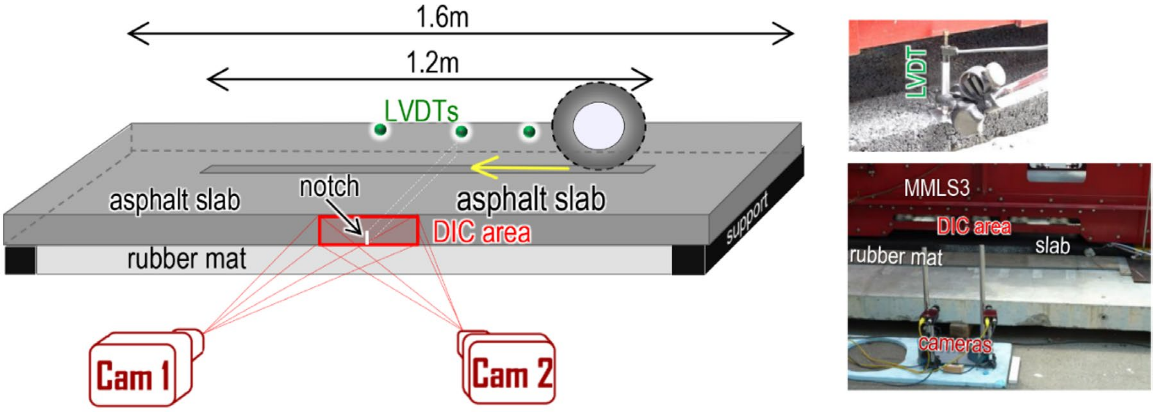


*Fig. 2 MMLS3 testing setup*

The crack formation and propagation was monitored by using linear variable differential transducer sensors (LVDTs) and by using the Digital Image Correlation (DIC) device.

## 4. MIXTURE DESIGN

The mix design approach is summarized in Fig. 1. At first, we determined the optimum recycling agent dosage. This was followed by testing various mixture compositions to achieve the desired performance, as explained in the following sections.

### 4.1. Recycling agent Selection and Dosage

A tall oil based recycling agent (a by-product of paper production) was used in the mixtures. Fig. 3 demonstrates the measured penetration at three trial recycling agent contents and the target penetration for the three mixtures used in the test section. The target values were set based on the penetration of the virgin binders used in the reference mixtures.

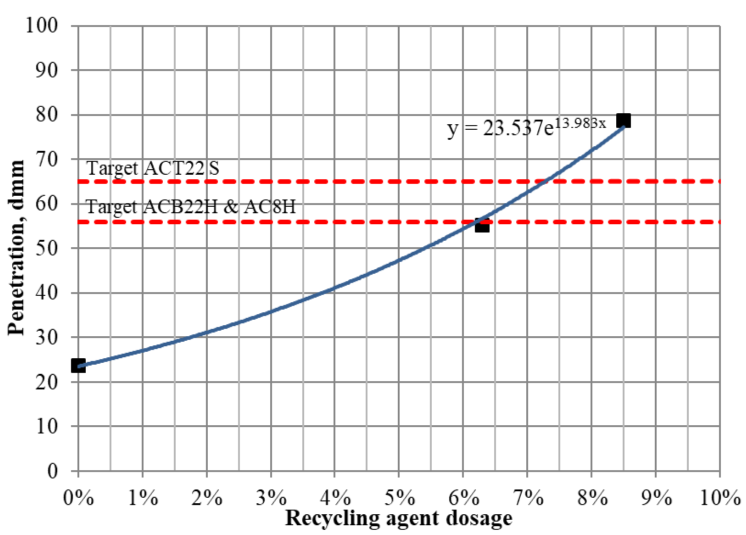


*Fig. 3 Recycling agent dosage determination (as a percent of RAP binder)*

The recycling agent dosage, in percent of RAP binder, that allowed to reach the target values was determined using Equation 5 [21]. A spreadsheet with the a calculator for the estimation of recycling agent dosage is available in https://doi.org/10.5281/zenodo.7441761 [22].

The final recycling agent dose was 6.2 % for the AC8H and ACB22H mixtures and 7.3% for the ACT22S mixture. After testing the first trial mixture, the recycling agent dosage for the second production of ACT22S mixture was reduced to 6.2 %.

$$\boldsymbol{Dose} = \frac{\boldsymbol{log_e \frac{PEN}{A}}}{\boldsymbol{B}} \qquad \text{Equation 5}$$

where

Dose – dose of the recycling agent, % from RAP binder

PEN – penetration, ×0.1 mm

A – penetration at 0 % dose (y-intercept of the exponential function), ×0.1 mm

B – constant calculated by least squares fit through data points

Before selecting a specific recycling agent, the aging resistance of the recycling agent plus binder blend should be determined as well. For the selected recycling agent, the results demonstrated 0.4% mass change after the Rolling Thin Film Oven Test (RTFOT) (acceptability limit is <0.8% according to EN 1291). The retained penetration after RTFOT aging as well as two cycles of Pressure Aging Vessel (PAV) was similar or larger compared to the reference virgin binder. Based on these results, we considered the recycling agent to have acceptable aging resistance and therefore it was used in the test section.

## 4.2. Performance-based mixture design

The mixtures were designed using performance-based mixture design framework described in [15]. The following test methods were used to determine the optimum mixture composition:

- **Cracking characterization.** Semi-Circular Bend (SCB) test using the Flexibility Index (FI) has been demonstrated to possess sensitivity to mix design parameters, including binder grade, binder content, and aging [15,20,23,24]. This test has also proven to be punishing the use of elevated RAP content, if appropriate measures have not been taken to compensate for the stiff RAP binder [25].
- **Characterization of plastic deformations.** The goal to improve mixture cracking resistance through the use of recycling agents, softer binder, or the increase in binder content can lead to plastic deformations (rutting). Therefore, along with the cracking test, it is important to use a test that characterizes plastic deformations. The cyclic compression test (CC) was selected due to a relatively simple sample preparation, permitting to test various different combinations of mix designs.
- **Volumetric properties and constituent material properties.** The volumetric properties (air voids, gradation, and binder content) and binder properties were used to facilitate decision-making.

## 4.3. Example Mixture Design ACB22H Mixture

Here we provide an example mix design approach for the ACB22H mixture. Considering the target RAP content, the reclaimed asphalt was combined with the sampled virgin aggregates in a gradation that mimics the gradation of the reference mixture as close as possible.

At first, two virgin binder grades with 4% binder content were used to attempt achieving the required acceptance criteria for the flexibility index and creep rate:

- Mixture A: PmB 90/150-80 without any recycling agent
- Mixture B: PmB 45/80-80 with 6.2 % recycling agent content

The cyclic compression creep rate and the flexibility index results of these two mixtures are summarized in Fig. 4. On the horizontal axis, the two mixtures are displayed while the primary and secondary vertical axes show the test results. The acceptable result range for each of the test results is shown in the figure as well (defined in [26]).

It can be seen that both mixtures pass the creep rate requirement but only the mixture with 6.2% recycling agent content (mixture B) passes the flexibility index (FI) requirement.

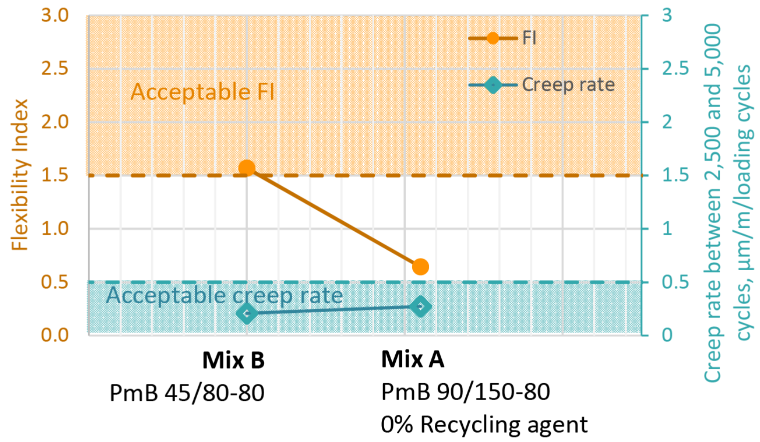


*Fig. 4 Optimization of bitumen type and recycling agent content for ACB22H mixture*

Since the results of the mixture B only barely pass the FI requirement, we prepared another mixture (C) with a higher binder content. This C mixture contains 4.2% rather than 4.0% binder content. The FI and creep rate results are shown in Fig. 5. In this case, the horizontal axis demonstrates the bitumen content of the mixtures.

As expected, a higher bitumen content increases the flexibility index and also increases the creep rate. Even at the higher bitumen content, both requirements are fulfilled thus we put forward mixture C as the best of the three designs.

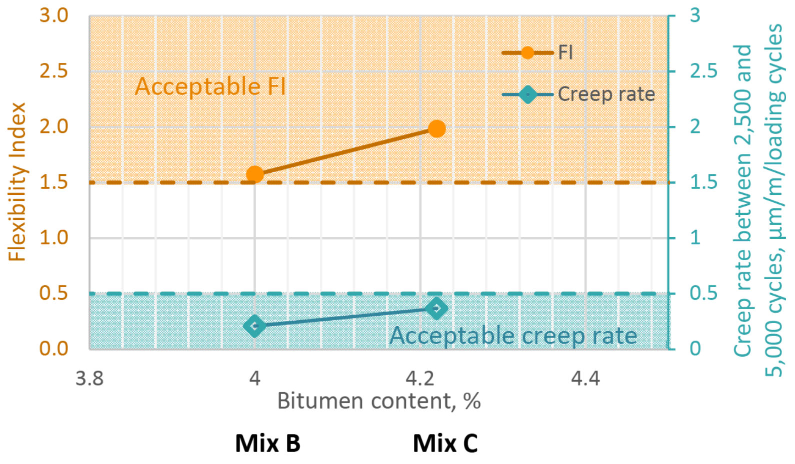


*Fig. 5 Optimization of bitumen content for ACB22H mixture*

According to the performance-based mix design principles described in [15], we used volumetric and conventional tests to enable better decision-making when optimizing the mixture design. Tab. 2 summarizes the design parameters, Marshall air void content, and recovered bitumen properties of the three ACB22H mixture designs.

All ACB22H mixtures fulfill the requirements set by the road agency for Marshall air voids, recovered penetration, and elastic recovery, but none of the mixtures fulfills the requirements for the recovered softening point. Considering that the RAP binder has a softening point of 62.4 °C, the likely reason for the inability to reach the required 70 °C softening point, is the elevated RAP content (60%). The added virgin binder can not compensate for this despite having a softening point of 100.5 °C for the PmB 45/80-80 and 86.8 °C for the PmB 90/150-80.

In such a situation, one solution would be to lower the RAP content and repeat the mix design procedure. Another solution could be to select a different virgin binder, perhaps with a higher polymer content. In this case, however, with the acceptance of the road agency, it was decided to change the target binder grade from PmB 45/80-80 to PmB 45/80-65. For the PmB 45/80-65, the recovered binder softening point requirement of 60°C is fulfilled by all the HighRAP mixtures.

Based on the aforementioned discussion, the final design used in the Uster test section mixtures is design C.

*Tab. 2 Design parameters and test results of the three ACB22H design mixtures*

| Mix | Added binder | Binder cont, % | Rec. agent, % | Marshall air voids, % | Penetration, 0.1mm | Softening point, °C | Elastic recovery, % | G-R, kPa | BTSV temp, °C | BTSV, phase angle, ° |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 4.0% 90/150-80 | 4.0 | 0 | 4.55 | 26 | 68.7 | 64 | 167 | 67.8 | 65.0 |
| B | 4.0% 45/80-80 | 4.0 | 6.2 | 4.05 | 32 | 66.5 | 61 | 54 | 63.6 | 64.4 |
| C | 4.2% 45/80-80 | 4.2 | 6.2 | 4.22 | 37 | 64.8 | 61 | 37 | 60.8 | 65.7 |
| Requirement | | | | ≥4.0 | 30…65 | ≥70*<br>≥60** | ≥60 | | | |
| | *for target grade 45/80-80 ** for target grade 45/80-65 | | | | | | | | | |

The mixture design process for all other mixtures was similar and for brevity, it will not be reported here. All the test results of each final design mixture (abbreviated with "Des") are included in the following sections along with the results from the test section.

## 4.4. Design Parameters of all mixtures

Tab. 3 summarizes the main mixture design parameters of the AC8H, ACB22H, and ACT22S mixtures. The table lists the mixtures from the test section (highlighted in bold) as well as the reference mixtures that were used throughout the study for comparison. The reader is reminded that the plant-produced mixtures (abbreviated with "HighRAP") contained RAP that was different from the RAP used in the design stage. The virgin binder and recycling agent content for these mixes were adapted based on the regular RAP quality control results available before production.

As shown in Tab. 3, the ACB22H and ACT22S mixtures also include reclaimed aggregates. This material is produced by exposing the coarser fractions of RAP to high mechanical impact, which separates the bulk of mortar from the coarse RAP aggregates. The resultant "reclaimed aggregates" contain less than 1 % binder and can be used as a substitute for virgin materials in the asphalt production process. In this way, the total amount of recycled material that is used in the mixtures for the base and binder layers is higher than the RAP content. In this paper, however, when referring to the RAP content, only the RAP is considered, without including the "reclaimed aggregates".

It can be seen in Tab. 3 that the RAP content of the ACT22S design mixture was 80 % while for the mixtures paved in the test section it is 65 % and 75 %. The reason for this is that the RAP gradation that was available at the time of construction was finer than that of the RAP that was used during the mixture design phase and it did not allow to fulfill the particle size distribution requirements. Moreover, it has been reported that the use of fine RAP can have a detrimental effect on the mixture cracking resistance [11].

*Tab. 3 Design parameters of the mixtures*

| Abbreviation | Sample preparation method* | RAP content and fraction**, mm | Reclaimed aggregates and size**, mm | Recycling agent content, % of RAP binder | Design binder content, %*** | Target binder grade |
|---|---|---|---|---|---|---|
| AC8H Lab | Lab-Lab | 0% | 0% | none | 6.0 | PmB E 45/80-65 |
| **AC8H Des** | **Lab-Lab** | **30% 0/11** | **0%** | **6.2** | **6.0** | **PmB E 45/80-80** |
| **AC8H HighRAP** | **Plant-Lab** | **30% 0/11** | **0%** | **6.2** | **6.0** | **PmB E 45/80-80** |
| **AC8H Ref** | **Plant-Lab** | **0%** | **0%** | **none** | **5.9** | **PmB E 45/80-80** |
| AC8H Plant1 | Plant-Lab | 20% | 0% | N/A | 6.0 | PmB E 45/80-80 |
| AC8H Plant2 | Plant-Lab | 0% | 0% | N/A | 6.0 | PmB E 45/80-65 |
| **ACB22H Des** | **Lab-Lab** | **60% 0/16** | **10% 11/16,16/22** | **6.2** | **4.2** | **PmB E 45/80-80** |
| **ACB22H HighRAP** | **Plant-Lab** | **60% 0/16** | **10% 11/16,16/22** | **6.2** | **4.3** | **PmB E 45/80-80** |
| **ACB22H Ref** | **Plant-Lab** | **30% 0/16** | **≤20% 11/16,16/22** | **none** | **4.1** | **PmB E 45/80-80** |
| ACB22H Plant1 | Plant-Lab | 50% | 10% | N/A | 4.0 | PmB E 45/80-80 |
| ACB22H Plant2 | Plant-Lab | 30% | N/A | N/A | 4.0 | PmB E 25/55-65 |
| **ACT22S Des** | **Lab-Lab** | **80% 0/16, 16/22** | **10% 11/16,16/22** | **7.3** | **4.1** | **50/70** |
| **ACT22S HighRAP 65%** | **Plant-Lab** | **65% 0/16, 16/22** | **15%11/16,16/22** | **7.3** | **4.0** | **50/70** |
| **ACT22S HighRAP 75%** | **Plant-Lab** | **75% 0/8, 8/22** | **10% 4/8, 8/11, 11/16,16/22** | **6.2** | **4.0** | **50/70** |
| **ACT22S Ref** | **Plant-Lab** | **65%** | **≤20%** | **none** | **4.0** | **50/70** |
| ACT22S Plant1 | Plant-Lab | 65% | 15% | N/A | 4.0 | 50/70 |
| ACT22S Plant2 | Plant-Lab | 50% | N/A | N/A | 4.0 | 50/70 |

*the first word refers to the mixing location and the second word refers to the compaction method

**the aggregate size of mixtures designated with "Lab" and "Plant" is not known since these where not paved in the test section

*** binder + virgin binder + recycling agent content

## 5. CONSTRUCTION OF A TEST SECTION

The test section is located in Uster, between Aathalstrasse houses No.81 and No.41 on the right lane going towards the city center. The reference mixture AC8H was paved on the left lane of the same street while the ACT22S and ACB22H reference mixtures were paved on the connected Sulzbacherstrasse. Fig. 6 shows the location of the test site and the asphalt plant.

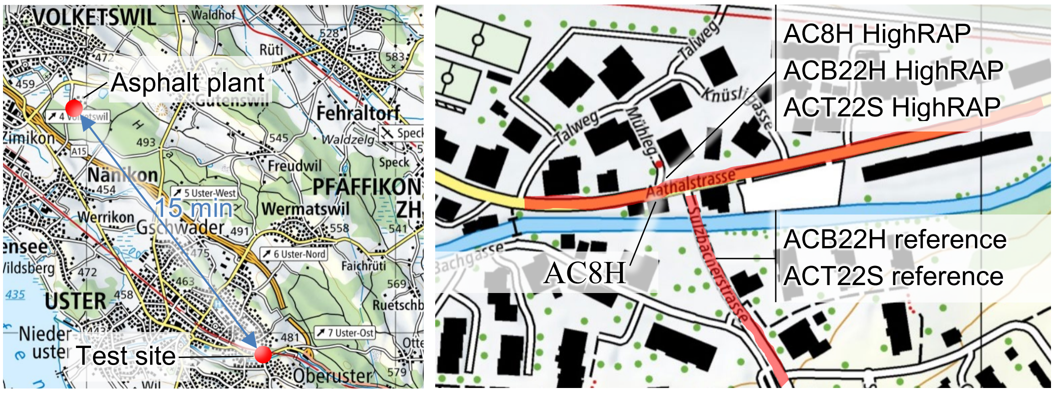


*Fig. 6 Location of the test section (highlighted in red) and the asphalt plant*

The construction of all test section mixtures, except for the ACT22S HighRAP 75%, took place between September and October 2021. The construction of ACT22S HighRAP 75 % took place in April 2022.

The asphalt production was carried out using an Ammann Schweiz batch asphalt plant with a dedicated RAP heating drum. A production temperature that is conventionally used for the particular asphalt mixture types could be ensured for all the mixtures regardless of the RAP content.

Recycling agent was added in the mixer via an integrated additive dosage system. The dosage was calculated based on the pre-determined RAP binder content.

Samples of the mixture were gathered on each day of production at the asphalt plant.

Photos from the construction are shown in Fig. 7 and a video is shown in Fig. 8.

*Fig. 7 Construction of the test section in Uster*

*Fig. 8. Video from the test section construction (scan the QR code or follow this link: https://youtu.be/MvyCwyrMNOs)*

A highly SBS polymer-modified virgin binder (polymer content ≥6%) was used in the study. The binder producer, however differed in the design and construction phases. It can be seen in Tab. 4 that even though both binders are classified as 45/80-80, their properties substantially differ. For example, the softening point temperature differs by 20 °C and the penetration differs by 21 0.1mm. Because of these differences, the properties of the extracted binder and the mixtures used in the construction should not be expected to be the same as those from the mixture design phase.

*Tab. 4 Properties of the PmB that were used in the design and construction phases of the project*

| Material | Mixtures | Penetration, 0.1mm | Softening point, °C | Elastic recovery, % | BTSV | | MSCR | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $T_{BTSV}$, °C | $\delta_{BTSV}$, ° | $R_{3.2kPa}$, % | $J_{nr\ 3.2kPa}$, kPa$^{-1}$ |
| PmB Rec* | AC8H Des<br>ACB22H Des | 54 | 100.5 | 98 | 53.6 | 55.4 | 98.7 | 0.007 |
| PmB Prod** | AC8H HighRAP<br>AC8H Ref<br>ACB22H HighRAP<br>ACB22H Ref | 75 | 79.7 | 97 | 51.1 | 56.8 | 97.0 | 0.024 |

*Binder used in the mixture design

**Binder used in plant production of mixtures for the test section

The reclaimed asphalt (abbreviated as RAP1) for mixture design was sampled in October 2020 while the reclaimed asphalt (RAP2) that was used in production was sampled on the first day of production of the test section mixtures in October 2021. The properties of these two RAP materials are summarized in Tab. 5 and it can be seen that the only major difference is the binder content. The reclaimed asphalt (RAP3) that was used in the trial of ACT22S HighRAP 75% was not tested.

*Tab. 5 Properties of the three RAP materials that were used in the design and construction phases of the project*

| **RAP** | **Mixture where the RAP was used** | **Binder content, %** | **Penetration, 0.1mm** | **Softening point, °C** | **BTSV** | |
|---|---|---|---|---|---|---|
| | | | | | **$T_{BTSV}$, °C** | **$\delta_{BTSV}$, °** |
| RAP1<br>0/16 mm | ACB22H Des<br>ACB22S Des | 4.4 | 24 | 62.4 | 62.9 | 74.9 |
| RAP2<br>0/16 mm | AC8H HighRAP<br>AC8H Ref<br>ACB22H HighRAP<br>ACB22H Ref<br>ACT22S HighRAP 65%<br>ACT22S Ref | 6.0 | 26 | 62.6 | 62.8 | 73.3 |
| RAP3<br>0/22 mm | ACT22S HighRAP 75% | N/A | N/A | N/A | N/A | N/A |

## 6. PERFORMANCE OF EXTRACTED BINDER

The binder test results reported here include results from all final mixture designs, the results from extracted binder from mixtures paved in the test section, as well as the reference mixtures from projects unrelated to the test section (designated with "Lab" and "Plant").

### 6.1. Conventional binder properties

The penetration results are summarized in Fig. 9. The agency's minimum requirements for the recovered binder for the respective target grade are illustrated in the figure as well. It can be seen that all the HighRAP mixtures fulfill the requirements.

The penetration of both plant-produced ACT22S HighRAP mixtures differ substantially from the binder properties in the design mixture (ACT22S Des). The binder properties substantially differ also between the plant-produced HighRAP mixtures with 65 % and 75 % RAP content. These two mixtures were produced on separate occasions using different RAP. The recycling agent dosage for the production of 75 % RAP mixture was slightly reduced based on the test results of the 65 % RAP mixture. The reduction of recycling agent from 7.3 % to 6.2 % should not, however, have caused a reduction of penetration from 52 0.1mm to 26 0.1mm. Such a large penetration change indicates the likelihood that the RAP binder properties had changed between the two production instances. At an elevated RAP content, any changes in the RAP binder properties would significantly affect the properties of the final mixture.

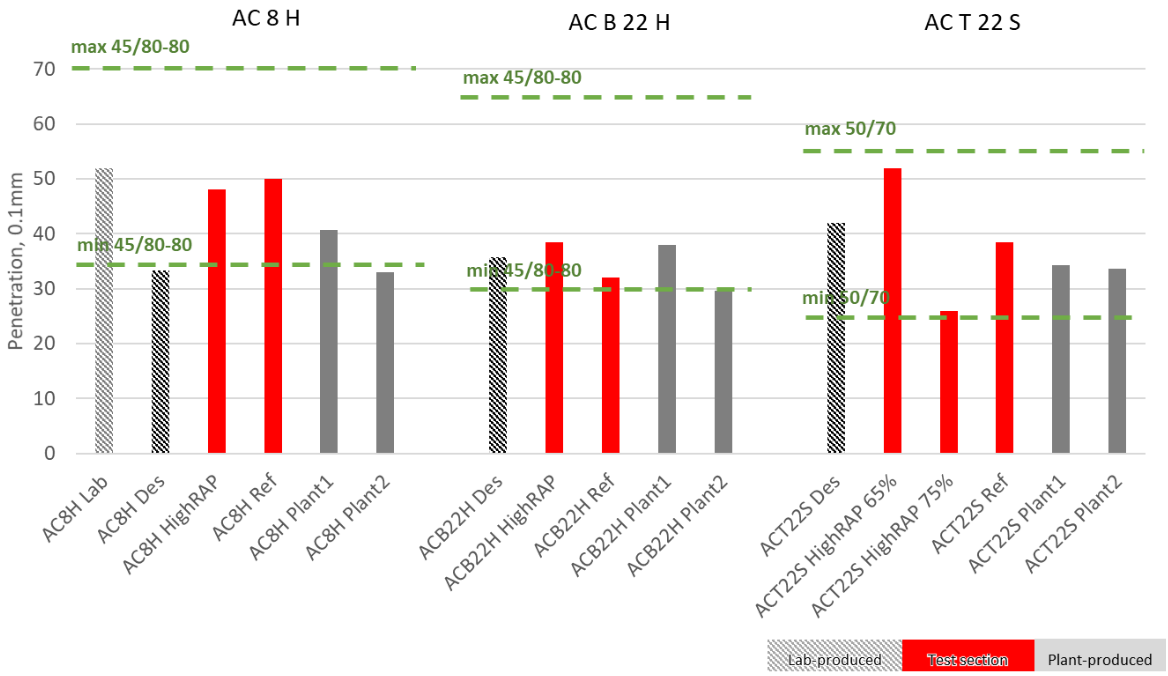


*Fig. 9. Penetration results*

The softening point results are summarized in Fig. 10. It can be seen in the figure that the AC8H HighRAP mixture nearly fulfills the softening point requirements. Use of a binder with a higher softening point (similar to one used in the AC8H Des mixture (see **Tab. 4**)) would likely allow ensuring correspondence to the requirement.

The binder extracted from the ACB22H HighRAP mixture does not fulfill the softening point requirement for PmB 45/80-80 grade. This was expected for the reasons discussed in section 4.3. However, the softening point requirements of PmB 45/80-65 are fulfilled.

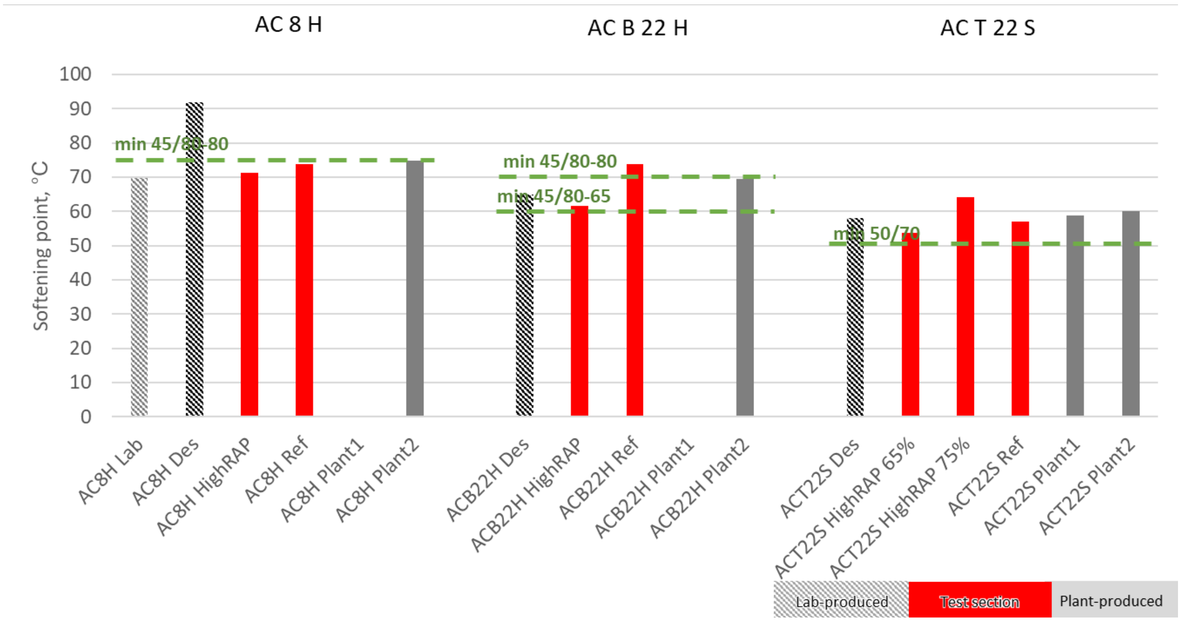


*Fig. 10. Softening point results*

The elastic recovery results are summarized in Fig. 10. It can be seen that the requirement for the minimum elastic recovery by binder extracted from both mixtures is fulfilled. Due to the higher RAP content, the elastic recovery of the ACB22H binder is lower. For the ACT22S testing of elastic recovery is not required since this mixture does not contain PmB.

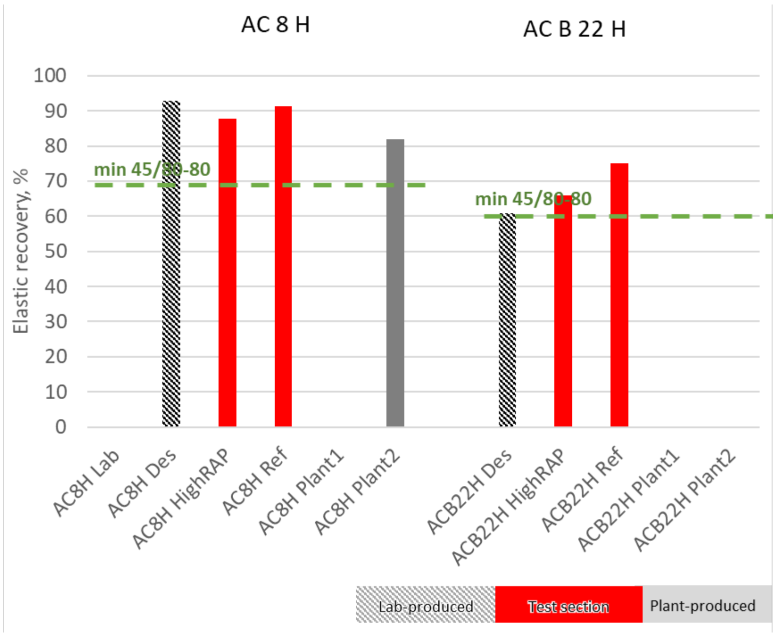


*Fig. 11. Elastic recovery results*

## 6.2. Multiple Stress Creep Recovery (MSCR) test results

The MSCR test results are summarized in Fig. 12. The results of the virgin PmB that was used in the mixtures are also included in the figure: the "PmB Rec" binder was used in the mixture design stage and the "PmB Prod" was used in the production of the mixtures for the test section.

In the figure, the percent recovery is displayed on the vertical axis and the creep compliance (Jnr) is shown on the horizontal axis. The gray line in the figure signifies the threshold according to the USA standard AASHTO R 92–18. Binders above this line are considered sufficiently elastic due to the presence of elastic polymers. In the USA, the provided threshold would apply for tests performed at the performance grade (PG) grade high temperature. Here the test temperature of 60 °C was used.

It can be seen that indeed the tested polymer-modified binders are above this line while the non-polymer modified binders fall below the line. This concurs with the findings of Yan et al. [10] who showed sufficient elastic response in the MSCR test for PmB mixtures with up to 40% RAP content. The binder from the ACB22H HighRAP mixture is on the border of the threshold because, due to the RAP content (60%), the polymer content in the binder is diluted. From this, it can be inferred that the 60% RAP binder is at the borderline of the maximum amount of this particular RAP that can be added to still ensure a sufficient elastic response at 60°C. A smaller RAP content (e.g. 50%) or a higher polymer content in the virgin binder are recommended to provide a margin of safety for ensuring sufficient elastic response [6,8]. Testing of the elastic response using MSCR is recommended in either case.

The Jnr value (horizontal axis) has been proposed as an indication of a binder's resistance to rutting (AASHTO 332 standard in the USA). The results demonstrate the expected trend: the binders with a higher polymer content overall have a lower Jnr than the binders with smaller or no polymer content. Based on the Jnr value, AC8H HighRAP mix has a similar performance to the reference mixture, while the ACT22S HighRAP and ACB22H HighRAP designs have a lower resistance to rutting compared to the corresponding reference materials. This is likely due to the use of recycling agents to soften the binder (for the ACT22S mixture) and a smaller polymer content (for the ACB22H mixture). Similar reduction of Jnr for PmB containing mixes holding RAP has been reported by Bernier et al. [6].

The ACT22S mixture with 75% RAP has a lower Jnr value compared to the reference which is, as by penetration results, likely a result of the harder binder present in this mixture.

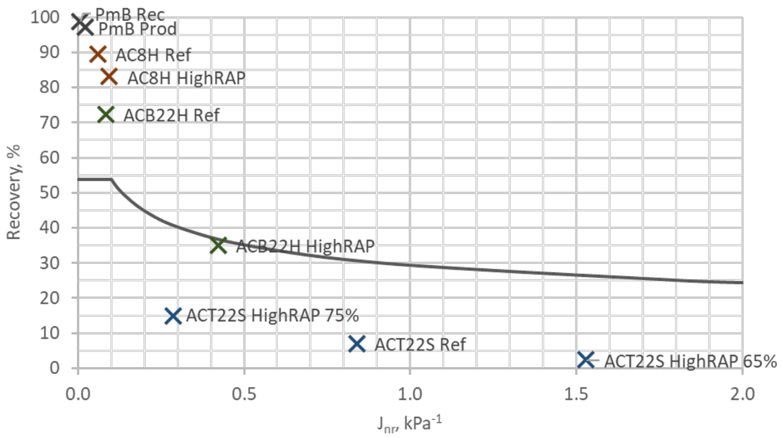


*Fig. 12 MSCR results of binder from all mixtures. The gray line signifies the threshold according to the USA standard AASHTO R 92–18*

## 6.3. BTSV Results

The BTSV test results are illustrated in Fig. 13 through Fig. 15. The figures also contain the rectangles that, based on the research at Braunschweig University [27], demonstrate result range for binders from select binder grades.

The BTSV test results of AC8H in Fig. 13 demonstrate that the BTSV temperature for the binder extracted from the AC8H Ref and AC8H HighRAP mixtures is similar. The phase angle results of all the mixtures is in a similar range of results compared to the reference mixtures from other jobsites (shown with gray rhombs).

Compared to the other binders, the AC8H Des binder has a notably higher BTSV temperature and lower phase angle, which supports the observation from the softening point test discussed earlier. The lower phase angle is likely a result of higher polymer content in the binder.

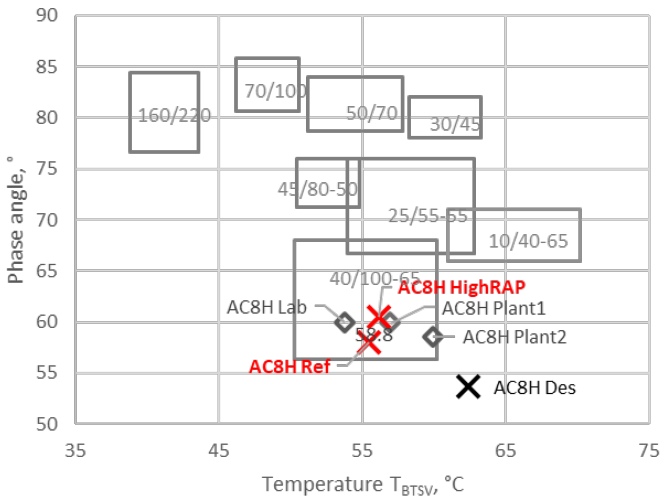


*Fig. 13 BTSV results of binder from AC8H mixtures (in red – samples from test section)*

The BTSV results of the ACB22H binders in Fig. 14 show that the binder from the reference mixture has a higher BTSV temperature and a lower phase angle compared to the binder form the HighRAP mixture and the design mixture (Des). This was expected considering the elevated RAP content, and the observations from the previous test methods.

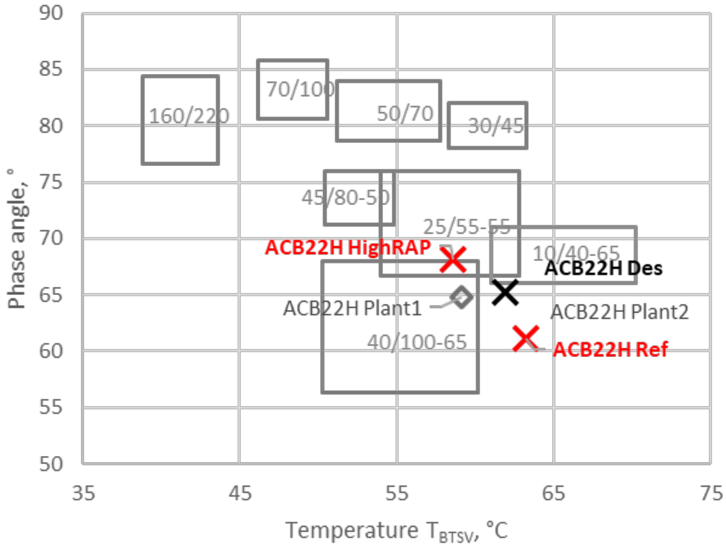


*Fig. 14 BTSV results of binder from ACB22H mixtures (in red – samples from test section)*

The BTSV results of the ACT22S binders in Fig. 15 demonstrate that the mixtures from the test section (in red) have a similar phase angle but the reference mixture has by about 3 °C higher BTSV temperature. The design mixture has by approximately 5 ° lower phase angle compared to the plant-produced mixtures.

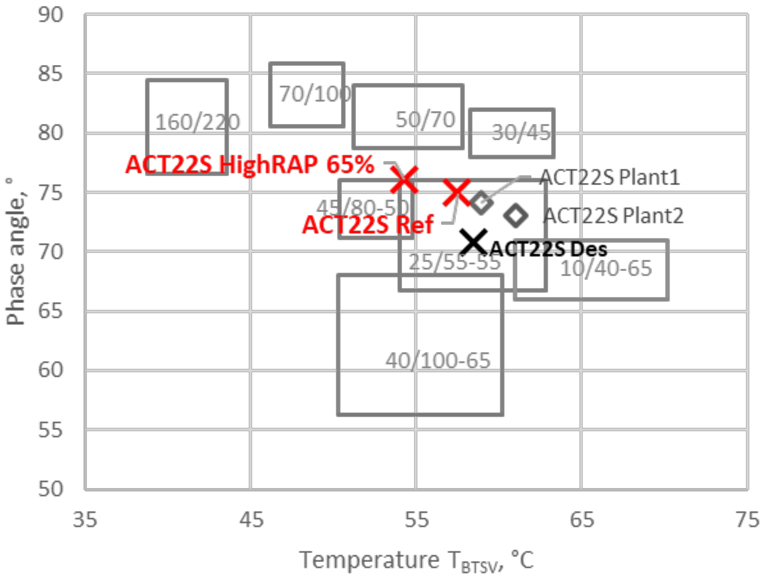


*Fig. 15 BTSV results of binder from ACT22S mixtures (in red – samples from test section)*

The binder results from ACT22S mixtures despite not being polymer-modified in Fig. 15 are positioned in the boxes where polymer-modified binder results would be expected. The reason for this is that typically RAP binder containing recycling agent has a lower phase angle compared to the source virgin binders [27,28]. For this reason, the BTSV results of a binder containing recycling agent can be similar to PmB results. The use of BTSV test alone therefore does not allow to decisively classifying binders based on polymer content.

### 6.4. Glover-Rowe Parameter Results

The G-R results of AC8H binder in Fig. 16 shows that the results of the plant-produced reference and HighRAP mixtures are nearly identical. This suggests that the binder from the HighRAP mixture can be considered similarly resistant to cracking compared to all other tested binders despite the 30 % RAP content.

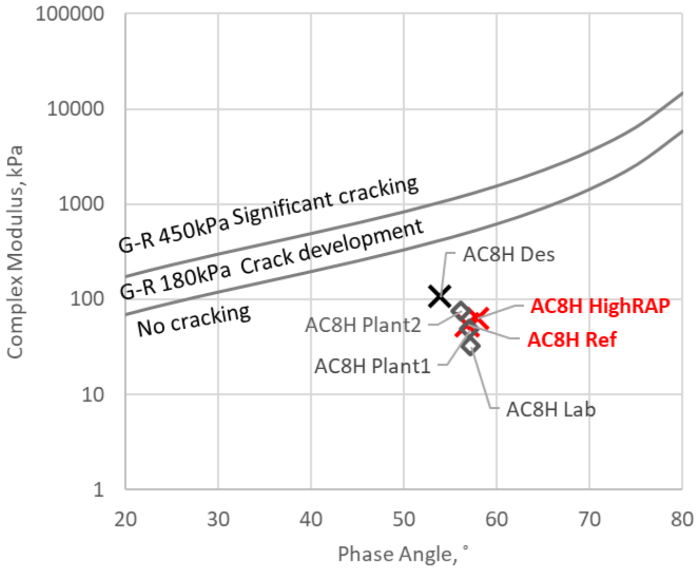


*Fig. 16 Glover-Rowe parameter results for binder extracted from AC8H mixtures (in red-samples from test section)*

The G-R results of ACB22H binder in Fig. 17 show that the HighRAP mixture has a lower G-R parameter (16 kPa) compared to the reference mixture (58 kPa) and the design mixture (52 kPa). This shows that the HighRAP binder has a superior crack resistance compared to the other binders. This result is likely related to the softer binder that was present in this mixture compared to the design mixture (evident also in other test results).

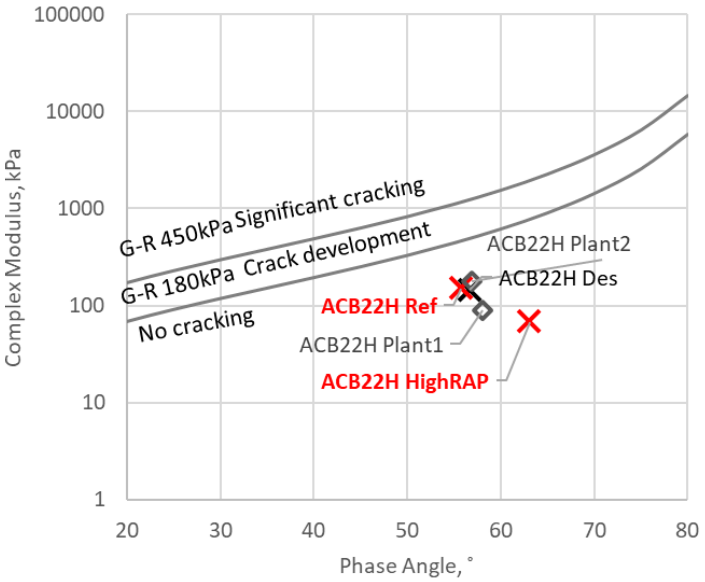


*Fig. 17 Glover-Rowe parameter for binder extracted from ACB22H mixtures (in red-samples from test section)*

The G-R results for the binder extracted from ACT22S mixtures in Fig. 18 shows that the binder from ACT22S HighRAP 65% has a lower G-R parameter (5 kPa) compared to the binder from the reference mix (17 kPa). This demonstrates that the use of recycling agent has allowed to reduce the cracking susceptibility despite the 65 % RAP content. The HighRAP 75% RAP binder, however, has a higher G-R parameter (89 kPa) compared to any other binder. This is likely related to the harder RAP binder in this mixture (due to RAP inhomogeneity). It can be seen in the figure that the binder is still not in the crack danger zone but with aging the G-R parameter will continue to increase and it will likely arrive in the damage zone sooner than any of the other tested binders. Similar negative effect of RAP on the G-R parameter has been reported by Zhou et al. [29].

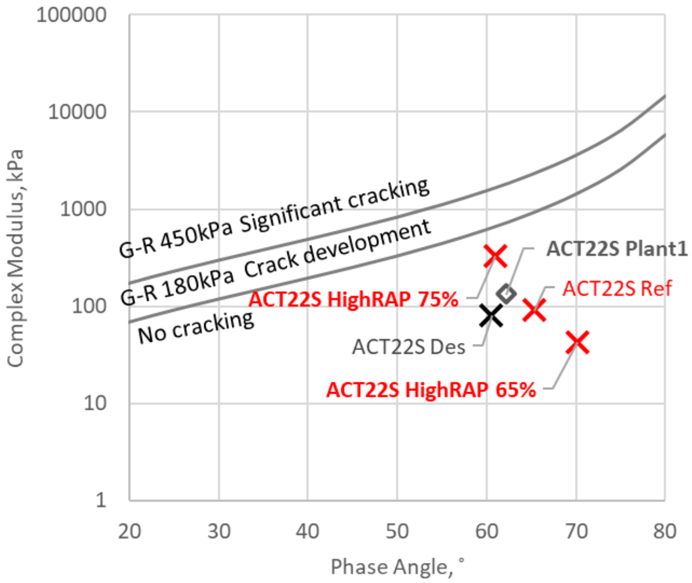


*Fig. 18 Glover-Rowe parameter for binder extracted from ACT22S mixtures (in red-samples from test section)*

## 7. PERFORMANCE OF MIXTURES

The volumetric properties of all test section samples as well as the corresponding HighRAP mix designs are summarized in Tab. 6. It can be seen that in some instances the minimum air void requirement is not achieved. However, the focus of this research is on the evaluation of mixture performance properties.

The bitumen content of the HighRAP and the respective reference mixture is relatively close (difference <0.3 %) in all cases, except for ACT22S HighRAP 75% mixture (for this mixture the binder content is 3.9 % compared to the 4.5 % for the reference). This consistency in bitumen content will allow interpreting the following performance-based test results simpler, since the bitumen content, except for the ACT22S HighRAP 75%, should not significantly impact the test results.

The bitumen content of the HighRAP mixture designs, however, is always smaller than that of the test section mixture results. This is related to the lower RAP binder content in the RAP that was used in the mix design (4.4 %) versus the RAP that was used in production (6 %).

*Tab. 6. Volumetric properties of asphalt mixtures*

| Mixture | Air voids*, % | Bitumen content, % | Max density, t/m$^3$ |
|---|---|---|---|
| AC8H Des | 5.1 | 5.5 | 2.472 |
| AC8H HighRAP | 2.2 | 6.4 | 2.440 |
| AC8H Core HighRAP | 3.1 | - | - |
| AC8H Ref | 4.8 | 6.1 | 2.447 |
| AC8H Core Ref | 5.2 | - | - |

| | | | |
|---|---|---|---|
| *Requirement* | *3.0…6.0* | *≥5.8* | - |
| ACB22H Des | 4.3 | 3.7 | 2.532 |
| ACB22H HighRAP | 4.7 | 4.2 | 2.534 |
| ACB22H Core HighRAP | 2.4 | - | - |
| ACB22H Ref | 5.3 | 4.5 | 2.529 |
| ACB22H Core Ref | 4.3 | - | - |
| *Requirement* | *4.0…7.0* | *≥4.0* | - |
| ACT22S Des | 5.2 | 3.7 | 2.547 |
| ACT22S HighRAP 65% | 3.0 | 4.4 | 2.53 |
| ACT22S Core HighRAP 65% | 3.2 | - | - |
| ACT22S HighRAP 75% | 4.7 | 3.9 | - |
| ACT22S Ref | 2.3 | 4.5 | 2.513 |
| ACT22S Core Ref | 2.5 | - | - |
| *Requirement* | *4.0…7.0* | *≥4.0* | - |

*the air voids for road cores refer to the core test results after cutting the respective layer, while for all other samples these are the air voids after Marshall compaction. Requirements are according to the relevant cantonal standard

The gradation of the mixtures is provided in Fig. 19 along with the respective limits for each mix type. It can be seen that the AC8H and ACB22H mixtures correspond to the respective requirements of each mixture type and the differences between the reference and the HighRAP curves for each particular mix type are not substantial. Due to a combination of a higher RAP content and RAP inhomogeneity, the ACT22S HighRAP mixtures diverge from the reference mix gradation slightly more

Mixtures with high content of RAP typically have a high filler content. However, it can be seen in the figure that in this case the requirement toward mass passing the 0.063 mm sieve have been fulfilled in each case. This shows the effectiveness of the crushing and sieving approach used in the plant (see Tab. 3).

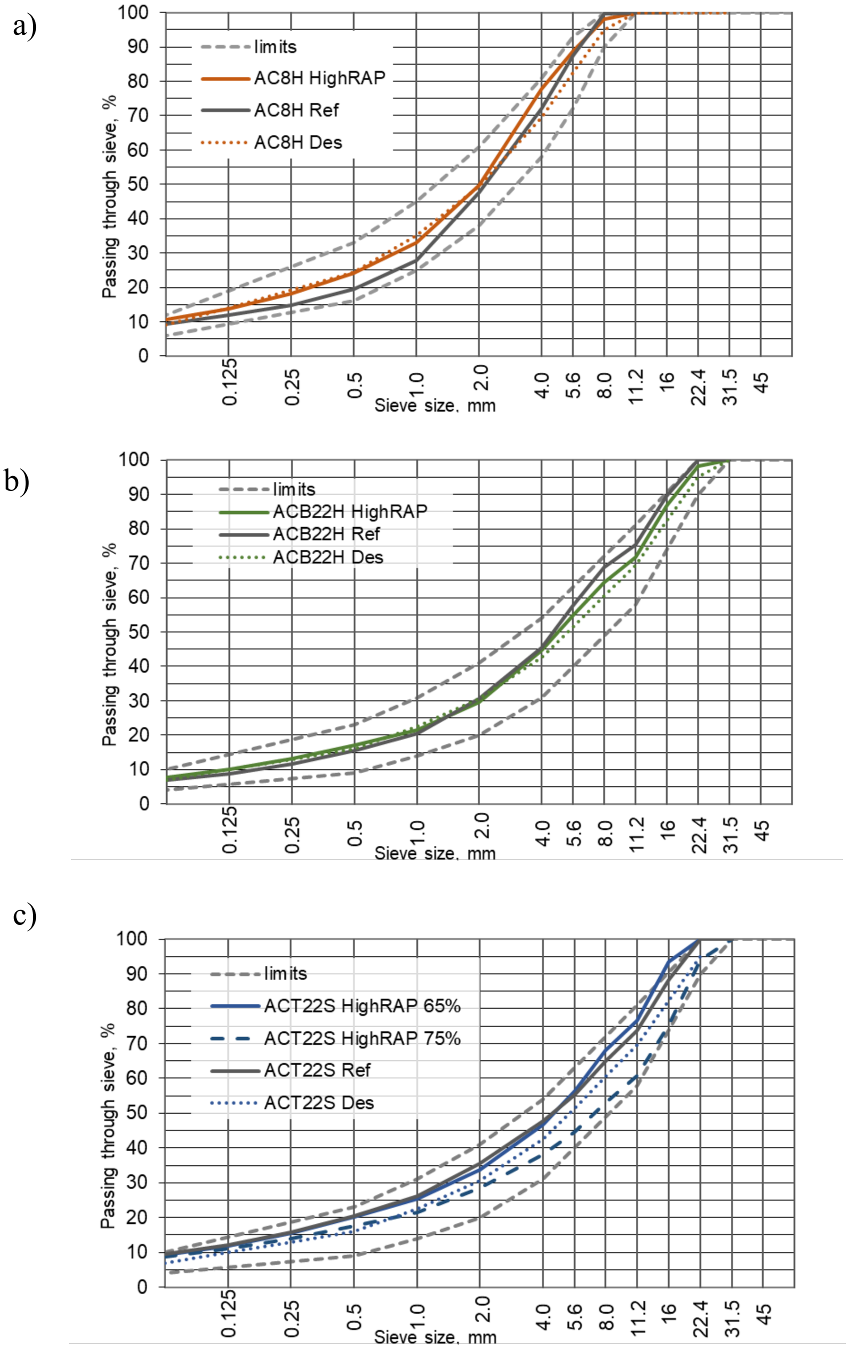


*Fig. 19 Gradation of AC8H (a), ACB22H (b), and ACT22S (c)mixtures*

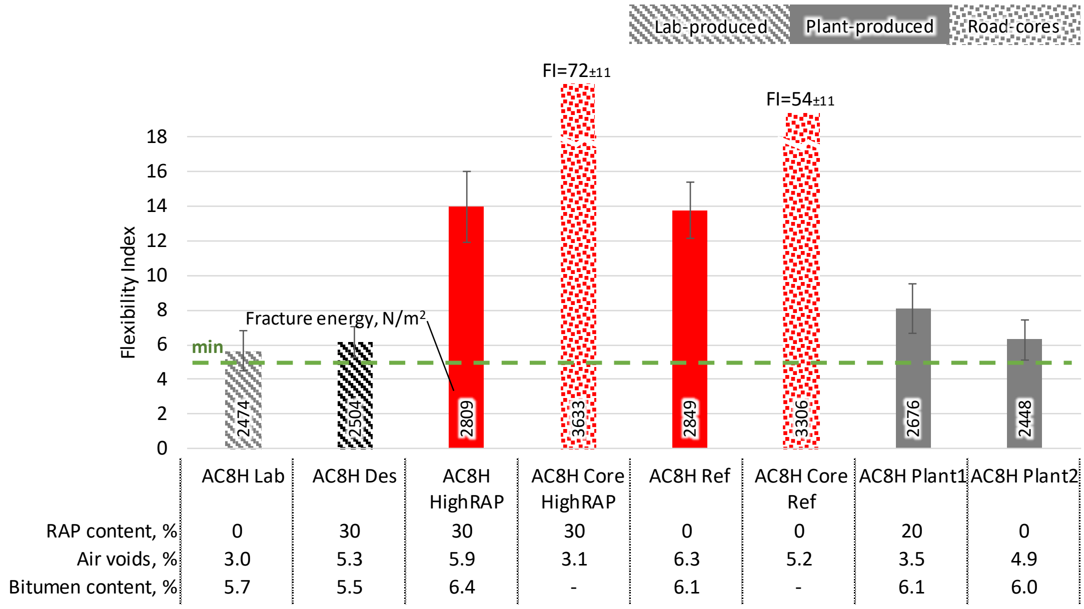
## 7.1. Crack Propagation Resistance

The Flexibility Index (FI) and fracture energy results from SCB are illustrated in Fig. 20 through Fig. 22 along with air void content and binder test results. The minimum target value for FI as defined in [26], is displayed in the figures as well.

The results in Fig. 20 show that both the HighRAP and the Reference AC8H mixtures have an FI of approximately 14 which is considerably higher than the proposed requirement of 5.

These and the following results concur with the findings of Zhou et al. [30] who showed an overall high FI of polymer-modified mixtures for RAP contents up to 50 %.

The FI of the cored samples is 72 for the HighRAP mixture and 54 for the reference. The core results are significantly higher because, due to the pavement layer thickness, the sample thickness was approximately 30mm instead of the 50mm of the laboratory-compacted samples. A thinner sample increases the compliance and thus reduces the angle of the post-peak slope, which in turn increases the FI index [31].



| | AC8H Lab | AC8H Des | AC8H HighRAP | AC8H Core HighRAP | AC8H Ref | AC8H Core Ref | AC8H Plant1 | AC8H Plant2 |
|---|---|---|---|---|---|---|---|---|
| RAP content, % | 0 | 30 | 30 | 30 | 0 | 0 | 20 | 0 |
| Air voids, % | 3.0 | 5.3 | 5.9 | 3.1 | 6.3 | 5.2 | 3.5 | 4.9 |
| Bitumen content, % | 5.7 | 5.5 | 6.4 | - | 6.1 | - | 6.1 | 6.0 |

*Fig. 20 Flexibility Index of AC8H type mixtures. Dash line indicates min required FI, the numbers in columns refer to fracture energy (the error bars represent one standard deviation)*

The FI of the ACB22H mixtures, illustrated in Fig. 21, demonstrates that all the samples fulfill the FI requirement of 1.5. The FI results of cores are considerably higher than the results of the lab-compacted mixtures (in this case, the sample dimensions were equivalent between the two). One possible explanation for the discrepancy is the aging of asphalt mixture in storage (for organizational reasons the testing was performed approximately a year after sample collection).

The results between the reference samples and the respective HighRAP samples (either cores or mixtures) are similar, thus demonstrating a similar crack propagation resistance.

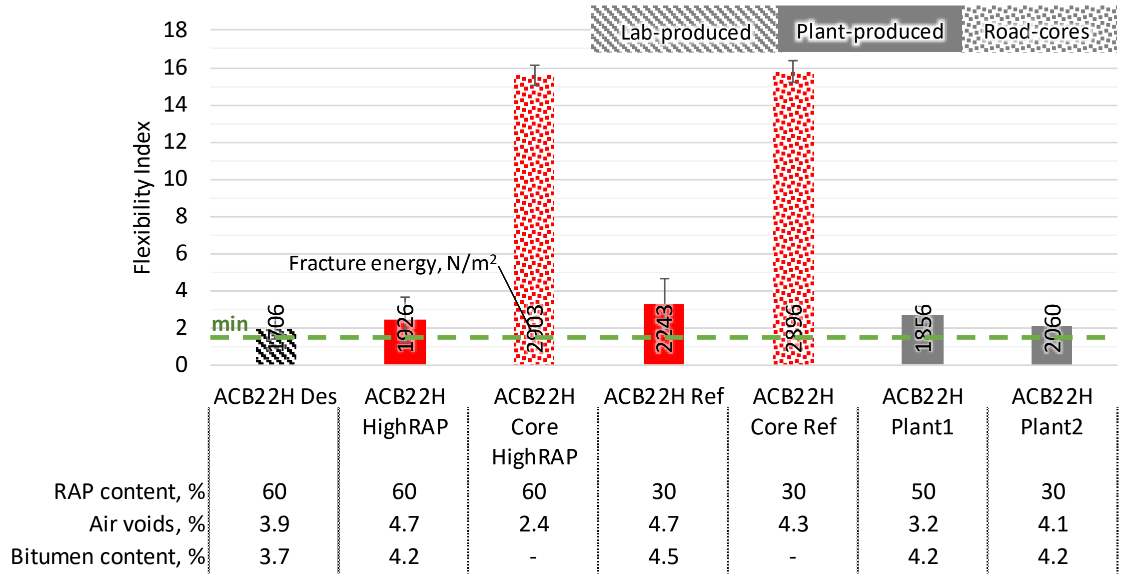


**Fig. 21** Flexibility Index of ACB22H type mixtures. *Dash line indicates min required FI, the numbers in columns refer to fracture energy (the error bars represent one standard deviation)*

The FI of the ACT22S mixtures, illustrated in Fig. 22, shows a slightly better crack propagation resistance of the reference mixtures as compared to the HighRAP mixtures having 65% RAP content. All of them exceed the FI threshold of 1.5.

The HighRAP mixture with 75% RAP content proved to be very brittle with the SCB sample exhibiting a brittle failure during the test. For this reason, the FI of this sample is zero. The probable cause of the poor performance of this mixture in this test is the hard binder that was present in the mixture.

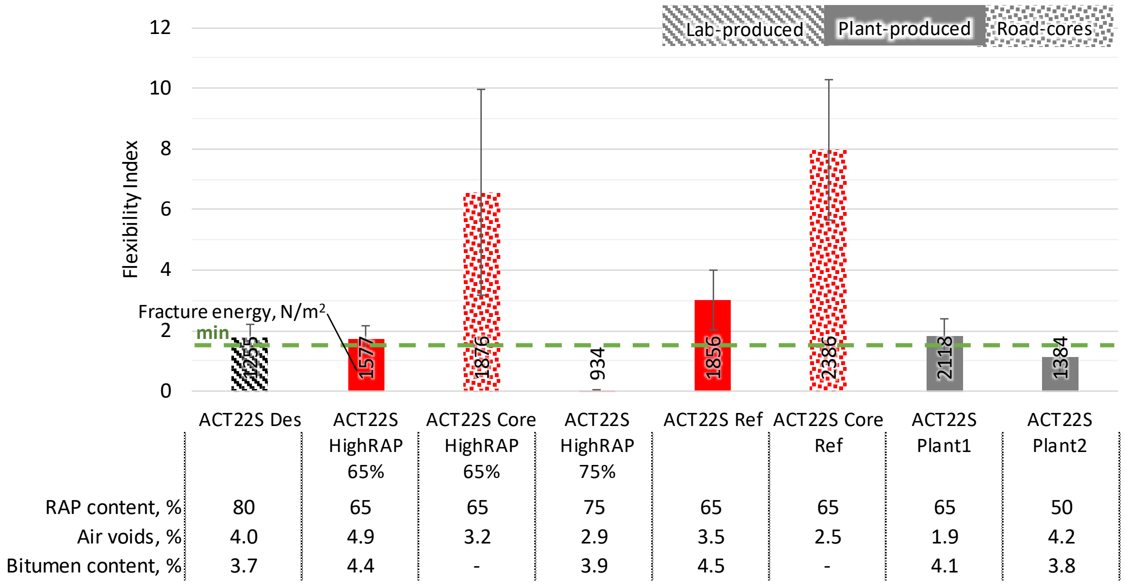
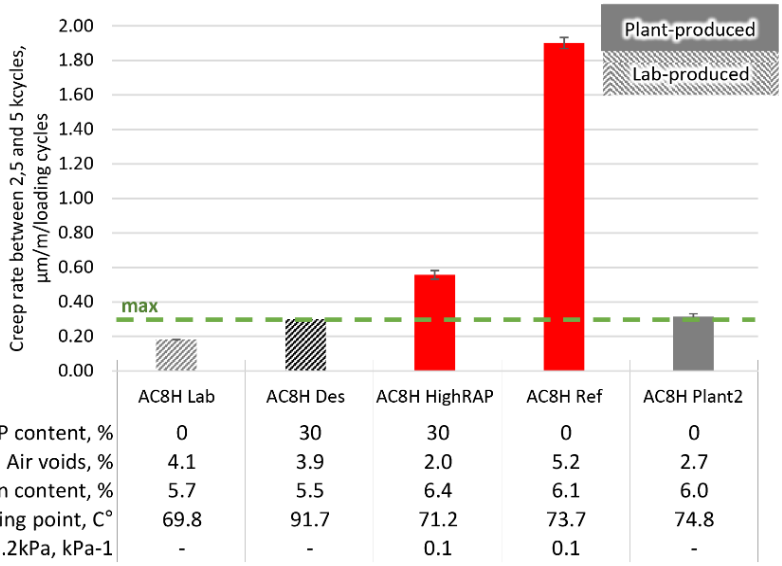


*Fig. 22 Flexibility Index of ACT22S type mixtures. Dash line indicates min required FI, the numbers in columns refer to fracture energy (the error bars represent one standard deviation)*

## 7.2. Rutting Resistance – cyclic compression test

The cyclic compression creep rate between 2,500 and 5,000 cycles is summarized in Fig. 23 through Fig. 25. The figures also contain the maximum permitted creep rate for each mixture type as defined in [26].

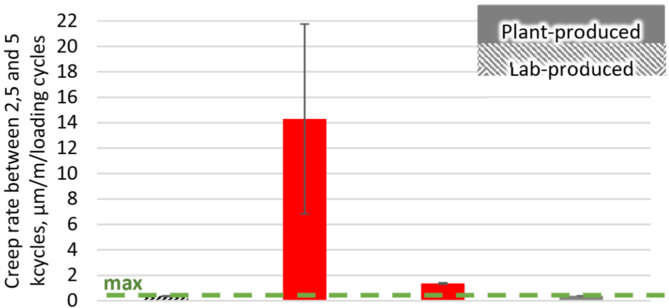
In Fig. 23, the creep rate of the AC8H mixtures is presented. It can be seen that the reference mixture performs worse compared to the HighRAP mixture. Overall, the plant-produced AC8H mixtures and also the other mixture types (reported in the following figures) have a poorer resistance to plastic deformations compared to the respective mixture design and the samples from other jobsites where the same mix type was paved.



| | AC8H Lab | AC8H Des | AC8H HighRAP | AC8H Ref | AC8H Plant2 |
|---|---|---|---|---|---|
| RAP content, % | 0 | 30 | 30 | 0 | 0 |
| Air voids, % | 4.1 | 3.9 | 2.0 | 5.2 | 2.7 |
| Bitumen content, % | 5.7 | 5.5 | 6.4 | 6.1 | 6.0 |
| Softening point, C° | 69.8 | 91.7 | 71.2 | 73.7 | 74.8 |
| MSCR Jnr 3.2kPa, kPa-1 | - | - | 0.1 | 0.1 | - |

Fig. 23 Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for AC8H type mixtures (error bars represent min and max values)

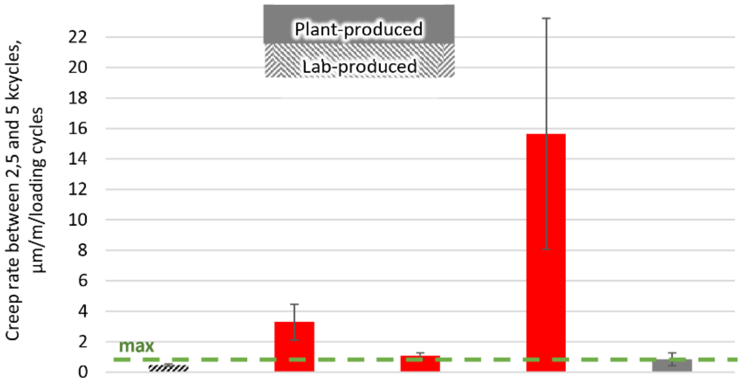
The creep rate of ACB22H mixtures in Fig. 24 shows that the HighRAP mixture has a significantly worse performance compared to the reference mixture. The core reason for this is probably the softer binder. For the reference mixture, the softening point is 73.7 °C while for the HighRAP mixture – 61.7 °C (close to the CC test temperature of 60 °C). The Jnr value in the MSCR test also indicate a lower rutting resistance. As discussed earlier, the reason for this is the high content of RAP.



| | ACB22H Des | ACB22H HighRAP | ACB22H Ref | ACB22H Plant2 |
|---|---|---|---|---|
| RAP content, % | 60 | 60 | 30 | 30 |
| Air voids, % | 4.5 | 4.4 | 4.8 | 3.9 |
| Bitumen content, % | 3.7 | 4.2 | 4.5 | 4.2 |
| Softening point, C° | 64.8 | 61.7 | 73.7 | 69.4 |
| MSCR Jnr 3.2kPa, kPa-1 | - | 0.4 | 0.1 | - |

*Fig. 24 Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for ACB22H type mixtures (error bars represent min and max values)*

The cyclic compression results of the ACT22S mixtures in Fig. 25 show that the reference mixture has the poorest performance in this test compared to any other mixtures that were tested. This result is unexpected, given that the binder in this sample has a higher softening point value and lower Jnr value compared to the HighRAP mixtures. The air void level and the binder content between this and the ACT22S HighRAP 65% mixtures are similar and thus these are unlikely causes of the differences. To verify these results, the ACT22S Ref sample was prepared again, but the test resulted in a similar performance. At this point, no further explanation for the poor performance of this sample can be offered.



| | ACT22S Des | ACT22S HighRAP 65% | ACT22S HighRAP 75% | ACT22S Ref | ACT22S Plant2 |
|---|---|---|---|---|---|
| RAP content, % | 80 | 65 | 75 | 65 | 50 |
| Air voids, % | 5.0 | 2.6 | 3.9 | 2.4 | 4.3 |
| Bitumen content, % | 3.7 | 4.4 | 3.9 | 4.5 | 3.8 |
| Softening point, C° | 58.0 | 53.7 | 64.2 | 57.1 | 60.1 |
| MSCR Jnr 3.2kPa, kPa-1 | - | 1.5 | 0.3 | 0.8 | - |

*Fig. 25 Creep rate between 2,500 and 5,000 cycles, µm/m/loading cycles for ACT22S type mixtures (error bars represent min and max values)*

## 7.3. Rutting Resistance – French Rut Tester

French Rut Tester (FRT) results of the AC8H mixtures in Fig. 26 show that the HighRAP mixture has a slightly lower rut depth compared to the reference mixture. This ranking agrees with the cyclic compression results reported earlier (Fig. 23). The requirement for rut depth in the Swiss specifications (SN EN 13108-1 NA) for this mixture type is less than 10 % rut depth up to 30,000 cycles. Even though for one of the reference samples this limit is slightly exceeded, on average both mixtures fulfill the requirement.

The FRT results of ACB22H mixtures in Fig. 26 show that the HighRAP mixture has a slightly higher rut depth compared to the reference mixture. This ranking agrees with the cyclic compression results but the relative difference in the FRT is considerably smaller than it is in the cyclic compression results. Overall, both mixtures have a smaller rut depth compared to the AC8H samples and both fulfill the Swiss standard requirements.

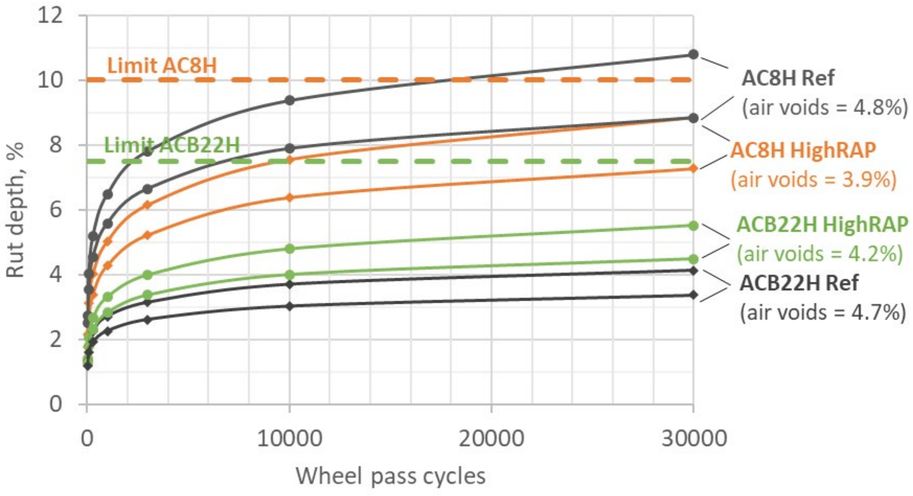


*Fig. 26 Rutting progression with FRT of AC8H and ACB22H mixtures*

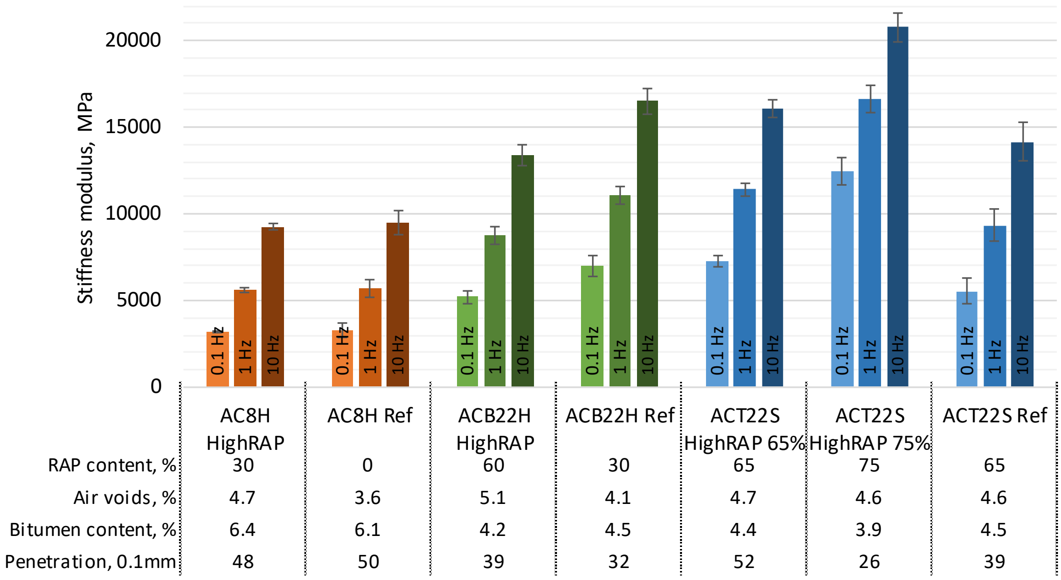
## 7.4. Stiffness

The stiffness results at 10 °C for all three mixture types are summarized in Fig. 28. It can be seen that for the AC8H HighRAP mixture, the stiffness at all frequencies is nearly the same as that of the reference mixture.

Among the ACB22H mixtures, the HighRAP mixture is 23 to 35 % less stiff compared to the reference (depending on the test frequency) which is likely related to the softer binder present in the HighRAP mixture.

Among the ACT22S mixtures, the HighRAP mixtures are stiffer than the reference. For the ACT22S 75% RAP mixture, this was to be expected because of the lower penetration. However, the higher stiffness of the ACT22S 65% compared to the reference is surprising, considering that this mixture has similar gradation (Fig. 19) and nearly equal binder and air void content while the binder penetration is by 13 0.1mm higher (meaning the binder is softer) compared to the reference mixture.

From the pavement design perspective, higher stiffness is a desirable property because it limits strains in the pavement. However, one must make sure that other performance requirements are fulfilled because a stiff pavement can be more cracking adverse.



| | AC8H HighRAP | AC8H Ref | ACB22H HighRAP | ACB22H Ref | ACT22S HighRAP 65% | ACT22S HighRAP 75% | ACT22S Ref |
|---|---|---|---|---|---|---|---|
| RAP content, % | 30 | 0 | 60 | 30 | 65 | 75 | 65 |
| Air voids, % | 4.7 | 3.6 | 5.1 | 4.1 | 4.7 | 4.6 | 4.6 |
| Bitumen content, % | 6.4 | 6.1 | 4.2 | 4.5 | 4.4 | 3.9 | 4.5 |
| Penetration, 0.1mm | 48 | 50 | 39 | 32 | 52 | 26 | 39 |

*Fig. 27 Stiffness modulus results for the mixtures paved in test section (the error bars represent one standard deviation)*

## 7.5. Fatigue Resistance

In Fig. 29 through Fig. 31, the vertical axis shows the number of cycles to a macro crack while the horizontal axis shows the strain at 100 cycles. A typical way to interpret fatigue results is to calculate the initial strain to reach one million cycles ($\varepsilon_6$) so this result is shown in the figures as well. It can be seen that in all cases the coefficient of determination ($R^2$) is above 0.9, which in the German SP-Asphalt 09 standard is defined as an acceptable repeatability. However, it is important to note that less than the required nine samples were tested.

The results in Fig. 29 show that both AC8H mixtures have nearly identical resistance to fatigue despite the fact that the HighRAP mixture contains 30 % more RAP. The performance of these wearing course mixtures is better compared to the base and binder mixtures (reported next), probably due to the higher binder content.

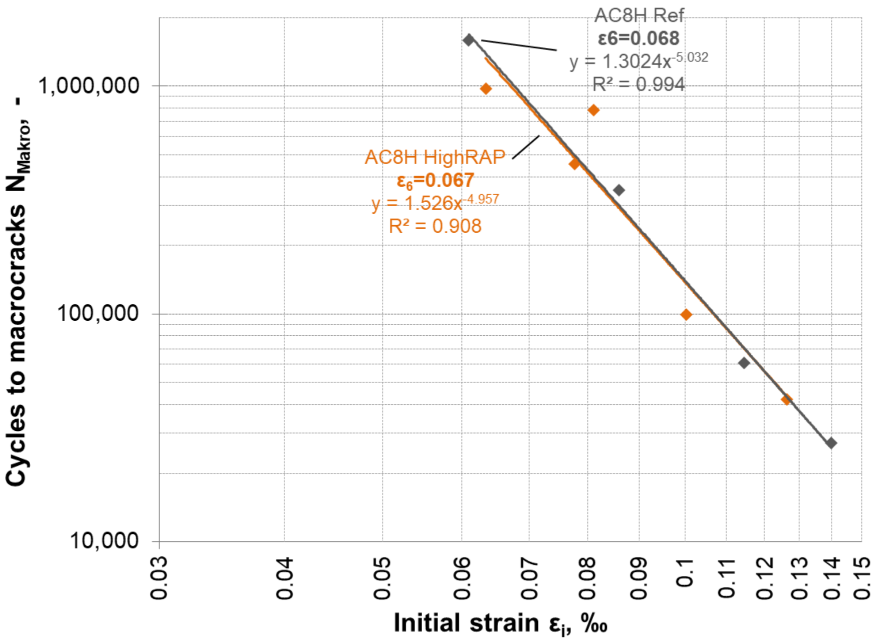


*Fig. 28 Fatigue test results of AC8H mixtures*

The results in Fig. 30 show that the fatigue resistance of the ACB22H reference mixture is slightly better than that of the HighRAP mixture. Part of the reason for this is likely the smaller air void content of the reference mixture (3.7 % versus 5.0 %). Even though the samples were compacted using a gyratory compactor to the same target air voids, the measured air voids after cutting the samples are different in this case. Other research papers have shown that RAP can affect mixture fatigue test results both in a positive [32] and in a negative way [33].

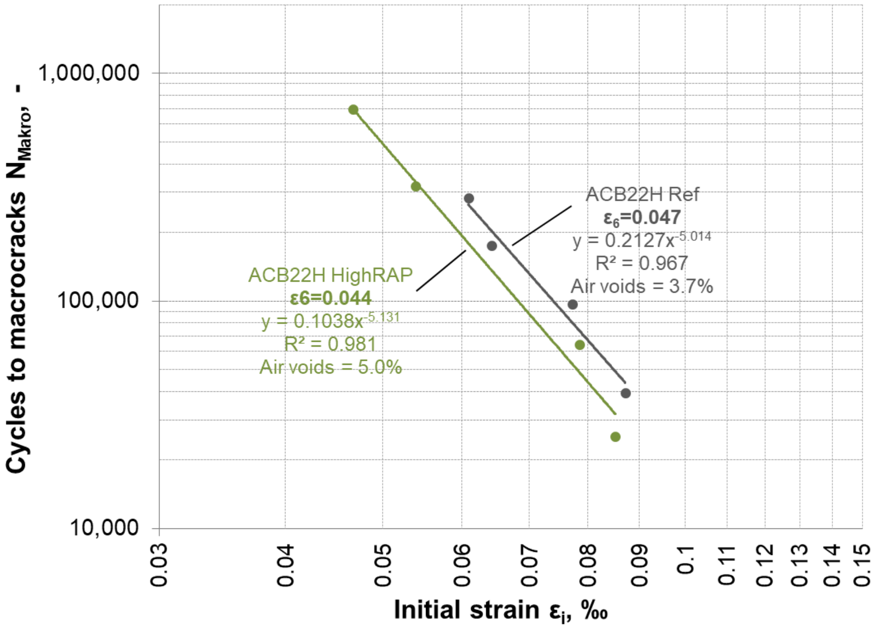


*Fig. 29 Fatigue test results of ACB22H mixtures*

The results in Fig. 31 show that the fatigue resistance of the ACT22S reference mixture and the HighRAP mixture with 65 % RAP content is nearly identical. The HighRAP mixture with 75 % RAP content, however, has a significantly lower resistance to fatigue. This is likely the result of a combination of a lower binder content (3.9% compared to 4.5% for the reference) and higher binder viscosity (penetration 26 0.1 mm compared to 39 0.1mm for the reference).

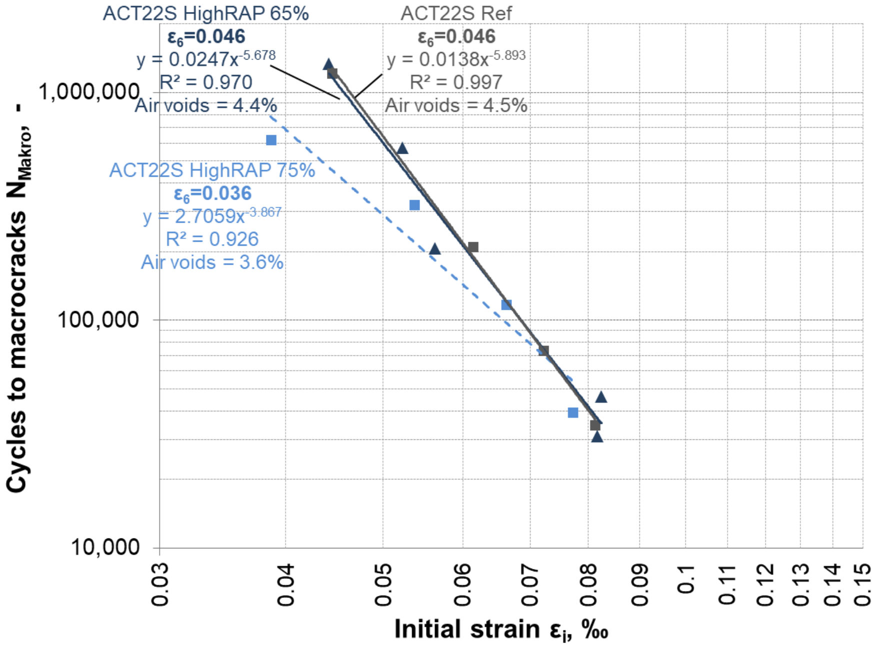


*Fig. 30 Fatigue test results of ACT22S mixtures*

It is worth noting that the results of both ACB22H mixtures are similar to those of ACT22S mixtures (except for the ACT22S with 75% RAP), all having $\varepsilon_6$ value in a narrow range between 0.044 and 0.047. Considering that the gradation and the binder content of all these mixtures is similar, this result shows that the test method likely was not sensitive to the presence of polymer-modified binder (ACB22H contains PmB unlike ACT22S).

### 7.6. Model Mobile Load Simulator results

The Model Mobile Load Simulator (MMLS3) results for the ACB22H mixtures are summarized in Fig. 32. This is the only mixture that was tested using the MMLS3 since the above reported tests revealed potentially inferior performance of the HighRAP mixture.

The evolution of maximum deflection amplitude at the middle of the slab, directly above the notch is shown in the figure. Snapshots of the principal tension strain obtained with the digital image correlation system are also illustrated, showing the progression of the cracks at one side of the specimen.

It can be seen in the figure that initially both slabs experience the same stiffness, manifested by the same deflection amplitude. After about 10,000 cycles, the HighRAP mixture experiences a significant increase in deflection amplitude compared to the reference mixture. A higher deflection amplitude is caused by the progression of the crack due to the continuous wheel loading. This initiation of macro crack progression is evident also in the DIC snapshots. Compared to the fatigue test results of cylindrical specimens, the difference in performance is more pronounced in the MMLS3 results.

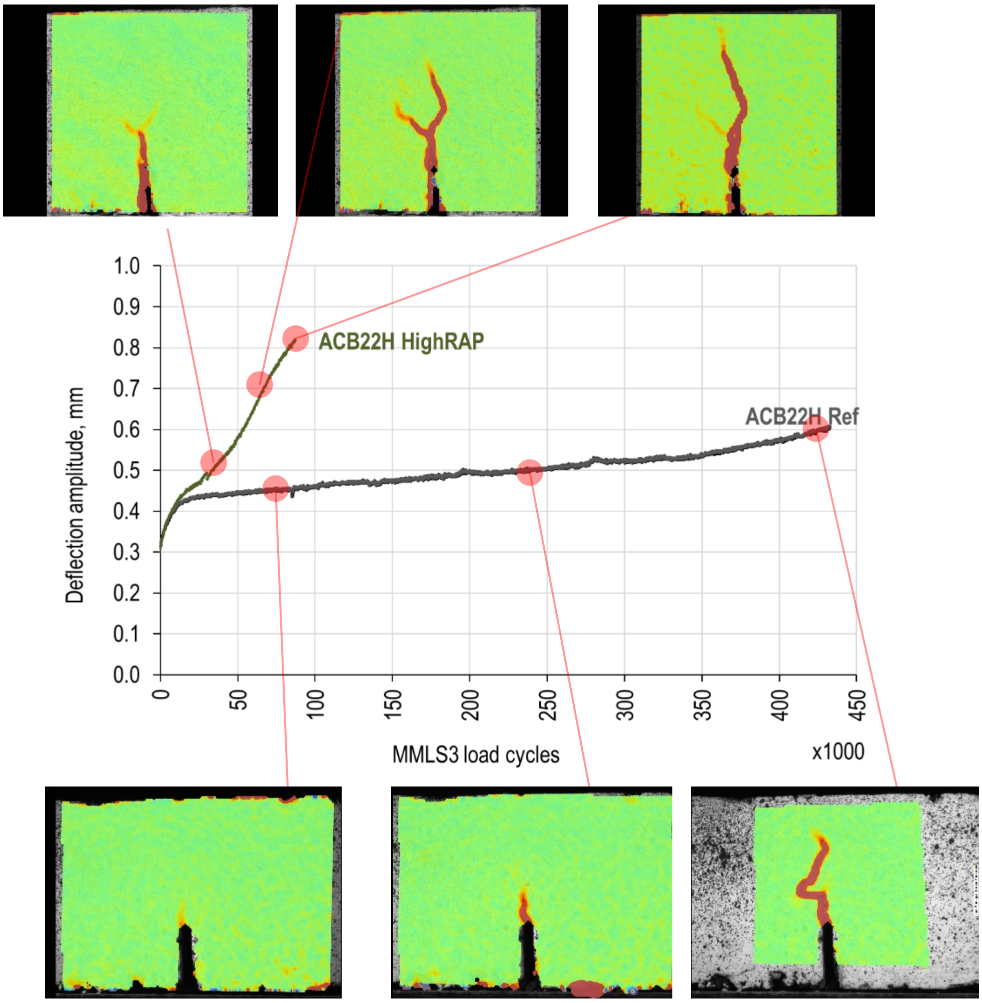
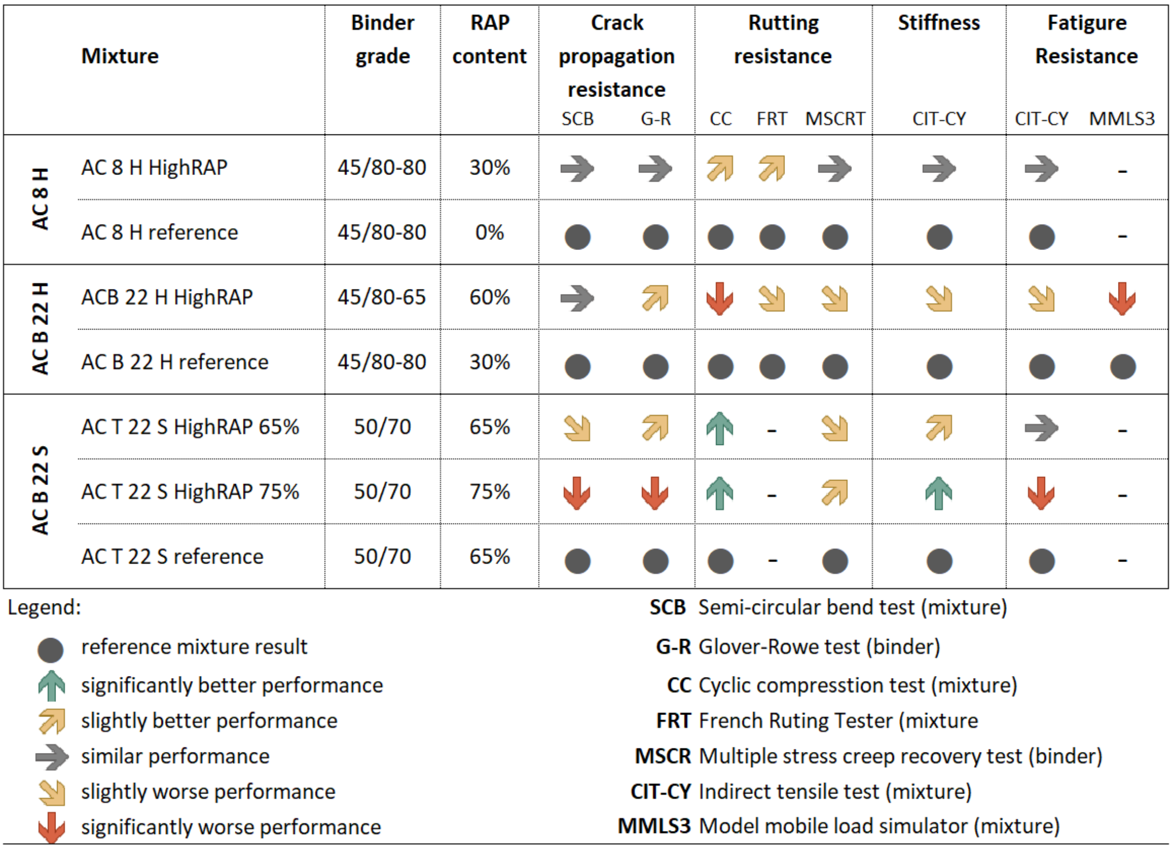


*Fig. 31 Model mobile load simulator results of ACB22H mixtures*

## 8. SUMMARY

The test section mixtures, recovered binder, and road cores were tested for various performance-based properties that are summarized in Fig. 33. The figure shows a relative comparison of the HighRAP design mixtures to the respective reference mixtures (indicated with a circle) on an arbitrary five-level scale.



| | Mixture | Binder grade | RAP content | Crack propagation resistance | | Rutting resistance | | | Stiffness | Fatigue Resistance | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | SCB | G-R | CC | FRT | MSCRT | CIT-CY | CIT-CY | MMLS3 |
| AC 8 H | AC 8 H HighRAP | 45/80-80 | 30% | → | → | ↗ | ↗ | → | → | → | - |
| | AC 8 H reference | 45/80-80 | 0% | ● | ● | ● | ● | ● | ● | ● | - |
| AC B 22 H | ACB 22 H HighRAP | 45/80-65 | 60% | → | ↗ | ↓ | ↘ | ↘ | ↘ | ↘ | ↓ |
| | AC B 22 H reference | 45/80-80 | 30% | ● | ● | ● | ● | ● | ● | ● | ● |
| AC B 22 S | AC T 22 S HighRAP 65% | 50/70 | 65% | ↘ | ↗ | ↑ | - | ↘ | ↗ | → | - |
| | AC T 22 S HighRAP 75% | 50/70 | 75% | ↓ | ↓ | ↑ | - | ↗ | ↑ | ↓ | - |
| | AC T 22 S reference | 50/70 | 65% | ● | ● | ● | - | ● | ● | ● | - |

Legend:

| | | | |
|---|---|---|---|
| ● | reference mixture result | **SCB** | Semi-circular bend test (mixture) |
| ↑ | significantly better performance | **G-R** | Glover-Rowe test (binder) |
| ↗ | slightly better performance | **CC** | Cyclic compresstion test (mixture) |
| → | similar performance | **FRT** | French Ruting Tester (mixture |
| ↘ | slightly worse performance | **MSCR** | Multiple stress creep recovery test (binder) |
| ↓ | significantly worse performance | **CIT-CY** | Indirect tensile test (mixture) |
| | | **MMLS3** | Model mobile load simulator (mixture) |

*Fig. 32 Summary of the performance of the test section mixtures*

Overall, the AC8H mixture with 30% RAP (target grade 45/80-80) performed similarly to reference mixture that had 0% RAP. The ACB22H mixture with 60 % RAP performed worse than the reference mixture holding 30 % RAP (target grade 45/80-80) due to the high dilution of polymer content. However, we consider that adding of 40-50 % RAP along with high polymer content virgin binder would allow ensuring good elastic response and correspondence to the requirements of PmB 45/80-65 grade requirements.

The ACT22S mixture with 65 % had a similar performance to the reference mixture while the 75 % RAP mixture performed considerably worse, likely due to RAP properties that did not correspond to the properties of RAP that was used in the mixture design.

It has to be mentioned that for the base and binder course mixtures, up to 15 % more reclaimed material was used in the mixtures in the form of "reclaimed aggregates". That is – coarse RAP aggregates that were stripped of most binder and used as a replacement of virgin aggregates.

# 9. CONCLUSIONS AND RECOMMENDATIONS

Three mixture types containing 30-75 % Reclaimed Asphalt Pavement (RAP) content were designed using performance-based methods and paved in a test section on a high traffic intensity street along with reference mixtures. The wearing and binder coarse mixtures contained polymer-modified binder. The mixtures, the recovered binder, and road cores were tested for various performance-based and conventional properties.

## 9.1. Conclusions

From the research results, we draw the following conclusions:

- At 30 % RAP content, it is considered possible to fulfill the of 45/80-80 polymer-modified binder grade requirements if a virgin binder with high polymer content is used. At 50 % RAP, it is considered possible to achieve the 45/80-65 polymer-modified binder grade requirements.
- It was possible to produce polymer-modified wearing course mixture with 30% RAP content having similar performance to the reference mixture holding 0 % RAP. Mixture volumetric requirements can be fulfilled as well.
- As a consequence of diluted polymer content, the properties of the ACB22H mixture containing 60% RAP in most performance-tests were slightly worse than those of the reference mixture containing 30 % RAP. Nevertheless, the requirements toward the crack propagation and rutting resistance using the French Rut Tester were fulfilled. To improve the elastic response, either higher polymer content in the virgin binder or reduction of the RAP content are recommended.
- The design of ACT22S mixture with 80 % RAP content was possible in the laboratory but due to the unsuitable properties of the RAP at the time of production, it was only possible to produce a mixture with 65 % RAP that was similar to the reference mixture.
- The SCB Flexibility Index was found a useful method for use in performance-based mixture design since it was sensitive to binder content and binder properties.
- The cyclic compression test in some instances had a high variability and it did not correlate well with the French Rut Tester results.
- The fatigue test was not sensitive toward the use of polymer-modified binder.

## 9.2. Recommendations regarding mix design

The following framework for designing mixtures containing elevated RAP content for high-traffic roads is proposed:

1. Optimize recycling agent content based on penetration test results to reach the target grade.
2. Determine the recycling agent aging resistance using RTFO plus two PAV cycles by testing mass loss and penetration (or using another binder test) before and after aging.

3. Use a plastic deformation and a cracking test to determine the design binder content. The SCB proved in this research a good method for crack resistance testing while the locally used rutting test can be adapted for testing plastic deformations.
4. Validate the designed mixture using any additional necessary binder and mixture tests before approving the final designs. These can be the tests that are locally used for mix approval.

### 9.3. Recommendations regarding RAP use in high traffic intensity pavements

Based on the research results, we propose the following recommendations regarding RAP use in high traffic intensity pavements:

- If the RAP properties permit, allow the use of at least to 30 % RAP in polymer-modified mixtures on pavements intended for very high traffic intensity (in this research target binder grade 45/80-80), including wearing course mixtures.
- If the RAP properties permit, allow the use of at least 50 % RAP in polymer-modified binder intended for pavements with high traffic intensity (in this research target binder grade 45/80-65).
- Ensure the correspondence to conventional binder properties regardless of the RAP content.
- Consider using the MSCR test for quality control of binder properties in polymer-modified mixtures.
- Use a performance-based mixture design procedure to provide a higher degree of certainty in the expected mixture performance. Implement this approach starting with a trial period during which it performance-test should be used as an addition (rather than a replacement) to conventional tests.
- The use of high RAP content in mixtures should only be permitted if high homogeneity of RAP can be ensured.

## CREDIT AUTHOR STATEMENT

Martins Zaumanis: conceptualization, methodology, validation, formal analysis, investigation, data curation, writing – original draft, visualization, project administration, funding acquisition; Lily Poulikakos: writing – review & editing, funding acquisition; Martin Arraigada: formal analysis, investigation, writing – review & editing; Bernhard Kunz: methodology, resources, funding acquisition; Urs Schellenberg: methodology, resources, funding acquisition; Christoph Gassmann: methodology, resources, funding acquisition.

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