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Warm Mix Asphalt Optimization with regards to RA addition (WMA-RAP)

Optimierung von Warmasphalt unter Berücksichtigung von RAP-Zugabe (WMA-RAP)

Optimisation des performances et combinaison avec agrégats d'enrobés

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Research project TRU_20_01G_01 at the request of Working Group Trassee und Umwelt (TRU)
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List of abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society of Testing Materials
BERAG	BERAG Belagslieferwerk Rubigen AG
BFH	Berner Fachhochschule
BK	Monitoring commission of the project (Begleitkommission)
BTSV	Binder-Fast-Characterisation-Test
CIT-CY	Cyclic indirect tensile test on cylindrical specimens
CO2	Carbon dioxide
DSR	Dynamic shear rheometer
E.g.	For example
EME	Enrobé à Module Élevé
Empa	Eidgenössische Materialprüfungs- und Forschungsanstalt
EN	European Normen
FT wax	Fischer-Tropsch wax
HMA	Hot mix asphalt
ITS	Indirect tensile strength
ITSR	Indirect tensile strength ratio
NOx	Nitrogen oxides
RAP	Reclaimed asphalt pavement
R&B	Ring and Ball
SBT	Shear bond test
SCB	Semi-circular bending test
TSRST	Thermal stress restrained specimen test
USA	United States of America
VOC	Volatile organic compounds
VSS	Schweizerische Verband der Strassen- und Verkehrsfachleute
WLF-method	Williams–Landel–Ferry method
WMA	Warm mix asphalt
WP	Work package

Summary

Introduction and Objectives

The research project focuses on optimizing Warm Mix Asphalt (WMA) incorporating Reclaimed Asphalt Pavement (RAP), with a focus on developing environmentally sustainable pavement materials without compromising structural or mechanical performance. RAP usage reduces the need for virgin aggregates and bitumen and contributes to lower emissions during asphalt production — making it a key strategy in promoting resource-efficient infrastructure. The project aims to identify WMA-RAP mixtures that deliver mechanical and durability properties comparable to or better than those of conventional Hot Mix Asphalt (HMA). Specific goals include evaluation of various WMA technologies (additives), performance assessment of laboratory and field (plant) produced WMA-RAP mixtures, and recommending updates to Swiss asphalt mixture standards based on the investigations.

Research Methodology

The methodology adopted in this project was comprehensive and structured, integrating extensive laboratory analysis with the validations of field produced mixtures. The research was organized into five distinct work packages (WPs) as shown in Figure 1, each addressing a critical phase of the study. WP1 involved a thorough literature review and hypothesis development, where global and national studies on WMA and RAP were reviewed. WP2 focused on the selection of suitable chemical and organic additives through binder and mastic testing, identifying those most appropriate for WMA production. In WP3, laboratory testing was conducted on asphalt mixtures containing varying RAP contents (30% and 60%), combined with different WMA additives to evaluate mechanical and durability performance. WP4 included the construction of a test track comprising both WMA and HMA sections followed by field produced mixture evaluation in the laboratory. WP5 integrated the project's findings into a set of practical recommendations for Swiss asphalt mixture standards. A consistent reference mixture, AC B 16 S, was used for all tests except for the field produced mixtures (i.e. 50% RAP), with all materials sourced from Swiss suppliers to ensure the applicability and relevance of the results to national road construction practices.

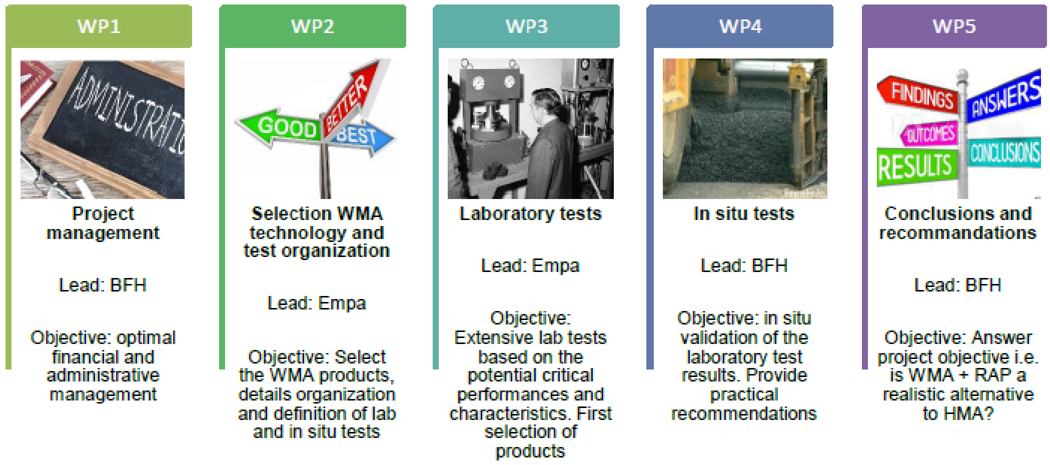


Figure 1: Project overview (Figure 1 in report)

Literature Review and State of the Art

Warm Mix Asphalt technologies are globally recognized for their ability to reduce production and laying temperatures by 20–40°C compared to traditional HMA. This reduction has multiple benefits including lower greenhouse gas emissions, decreased energy consumption, and improved working conditions. However, previous research also indicates potential downsides such as reduced moisture resistance and susceptibility to rutting. The literature identifies three main WMA technology classes: foaming (e.g., water injection into bitumen), chemical additives (e.g., surfactants), and organic additives (e.g., waxes). The project examined a range of these technologies and their potential synergy with RAP. The PLANET project in Switzerland, concluded in 2017, already hinted at the effectiveness of WMA, particularly when RAP was introduced (Arn, 2017).

Experimental Plan

The different stages of the project are presented in Figure 2.

After an update of knowledge and the study of recent representative literature, the selection of WMA technologies for the laboratory investigation (WP2) was carried out using binder and mastic testing.

The mechanical performance analysis was divided into a laboratory and a field (in-situ) investigation. The investigation was conducted based on the potential critical performances and characterizations, resulting in the final selection of the WMA products for the full-scale test sections. WP3 focused on practical aspects of the installation of the warm mix pavements as well as their performance in terms of interlayer adhesion. In a further step, the mixtures for the field test sections were collected from the plant and investigated in the laboratory. The results obtained from the laboratory and in situ tests were finally used to provide practical recommendations.

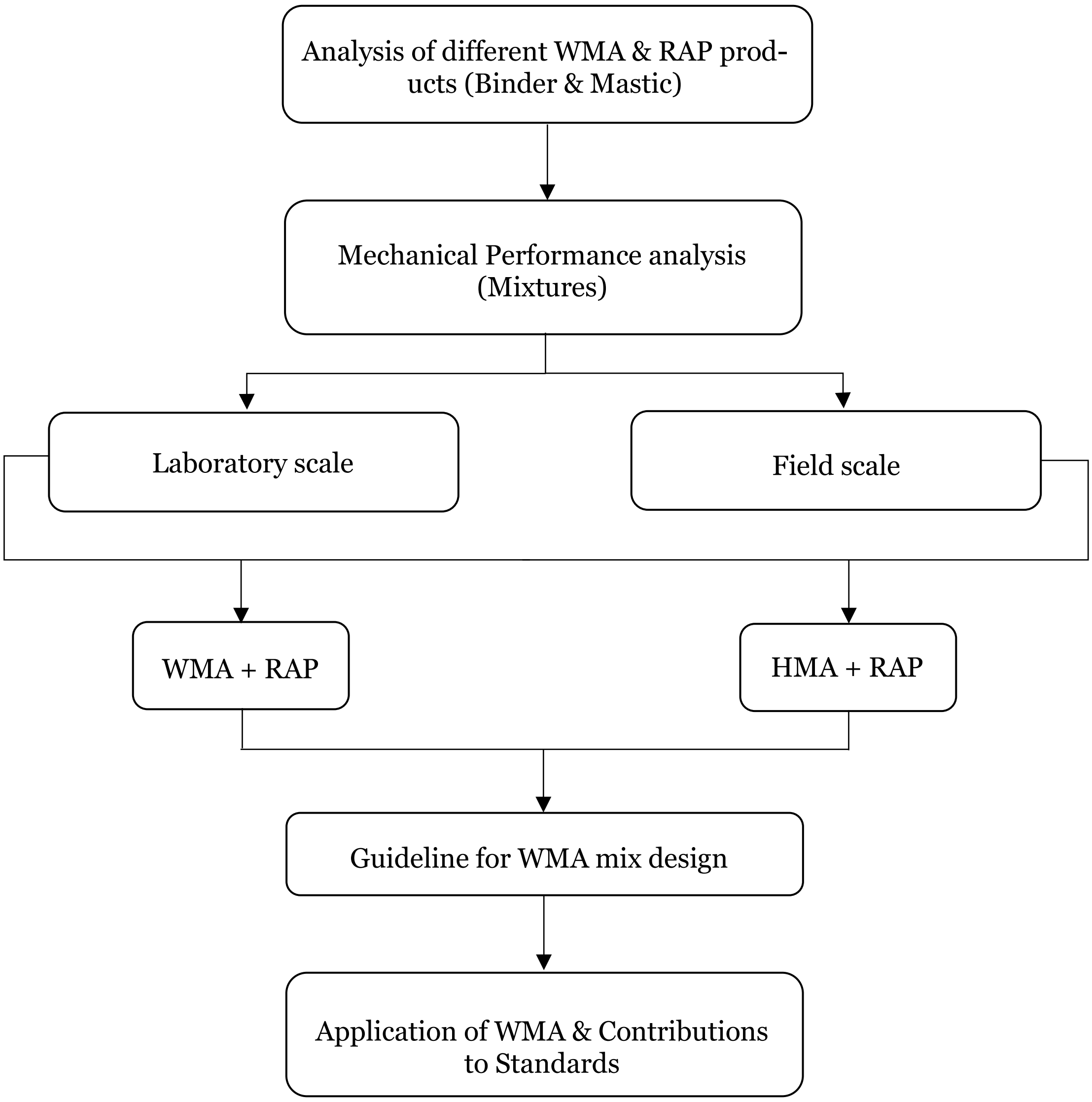


Figure 2: Details of project overview (Figure 2 in report)

Material Selection and Mixture Design

The asphalt materials including virgin aggregates and RAP were sourced from Weibel AG, a Swiss producer, while the binders included a 70/100 grade for 30% RAP and a softer 330/430 grade for 60% RAP to compensate for the stiffness of aged binder.

A total of seven WMA additives were evaluated: four chemical (Chem1 to Chem4), one organic (wax) in combination with Chem1 (Kombi) and foam mixture (only field produced). The selection of WMA additive was based on literature and previous experience, as well as on the commercial availability of the products in Switzerland.

From the beginning (project application) and based on research results (PLANET) and practical experience in Switzerland the following was decided (see also Table 1):

- The focus was placed on chemical additives, since a great variety of these products exists.
- Foaming methods should only be included in situ, while based on earlier experience, zeolites were completely excluded.
- Waxes were excluded for WAM mixtures and only used in the binder testing and in combination with a chemical additive.
- Regarding the limitations of the extensive laboratory testing, the final selection of 2 chemical additives out of 4 commonly used products was based on the initial binder and mastic testing, while the wax for the Kombi-product (wax+chemical additive) was chosen as the commonly used product worldwide.

In a first step, 4 chemical additives were evaluated on the binder and mastic level (see Table 1).

WMA Additives		
Type of products	**Product Code**	**Description**
Foaming technology	Foam	Plant produced foam asphalt
Chemical additives	Chem1	Surfactant
	Chem2	Natural plant based
	Chem3	Surfactant
	Chem4	Natural oil-based additive
Organic additive	Wax	FT paraffin wax
Combination of chemical and organic additive	Kombi	Chem1 + Wax

Table 1: WMA product selection (Table 1 in report)

The performance of these additives was first tested at the binder and mastic level using rheological tests, including the BTSV and DSR, to assess stiffness and temperature susceptibility.

Table 2 shows an overview of all mixtures and blends used in this project. The recycling content is given at the end (30 %, 50 % or 60 %). In the figures, the mixtures from the lab are labelled with L- and from the field with F-.

All laboratory mixtures were produced according to the procedures defined by the European Standard EN 13108-1. The hot mixture production temperature was set at 160 °C and warm mixtures were prepared at a temperature of 130 °C. The field test track mixtures were produced in the plant and samples were collected for the laboratory investigations.

Blends and mixtures				
Lab Code	**Binder blend**	**Mastic blend**	**Lab mixture**	**Field mixture**
HMA 30%	X		X	
HMA 50%				X
HMA 60%	X	X	X	
WMA-Chem1 30%			X	
WMA- Chem1 60%	X	X	X	X
WMA- Chem2 30%			X	
WMA- Chem2 60%	X	X	X	
WMA- Chem3 60%	X	X		
WMA- Chem4 60%	X	X		
WMA- Wax 60%	X	X		
WMA- Kombi 30%			X	
WMA- Kombi 60%		X	X	X
WMA- Foam 60%				X

Table 2: Overview of blends and mixtures with different additives and recycling contents (Table 2 in report)

Binder and Mastic Testing

Binder testing played a vital role in evaluating the effectiveness of selected WMA additives. Rheological properties were assessed using a Dynamic Shear Rheometer (DSR) and the Binder-Fast-Characterization-Test (BTSV). The binder blends as well mastics (binder + filler) included virgin binders 70/100 and 330/430, as well as RAP extracted binder, combined with different additives Chem1, Chem2, Chem3, Chem4 and Kombi (Chem1 + Wax). The study revealed that while chemical additives had minimal influence on binder stiffness, wax-modified binders showed significantly increased stiffness and elevated BTSV temperatures. Regarding low temperature behavior, no significant differences between the Fraass test results of HMA and WMA mixes were observed.

Mastic blends, simulating the filler-asphalt matrix, were tested to evaluate the interaction of the binder with the mineral component. The addition of mineral filler significantly increased the stiffness of the mastics. Interestingly, the ranking of the mastic blends in terms of BTSV temperature and phase angle remained unchanged except for Chem3, which was depicted by a uniform parallel shift of the BTSV results from the binder to the mastic blends (Figure 3). This was interpreted as minimal interaction between the binder (including the WMA additive) and the mineral matrix. In this case, the mastic results added only minimal additional information.

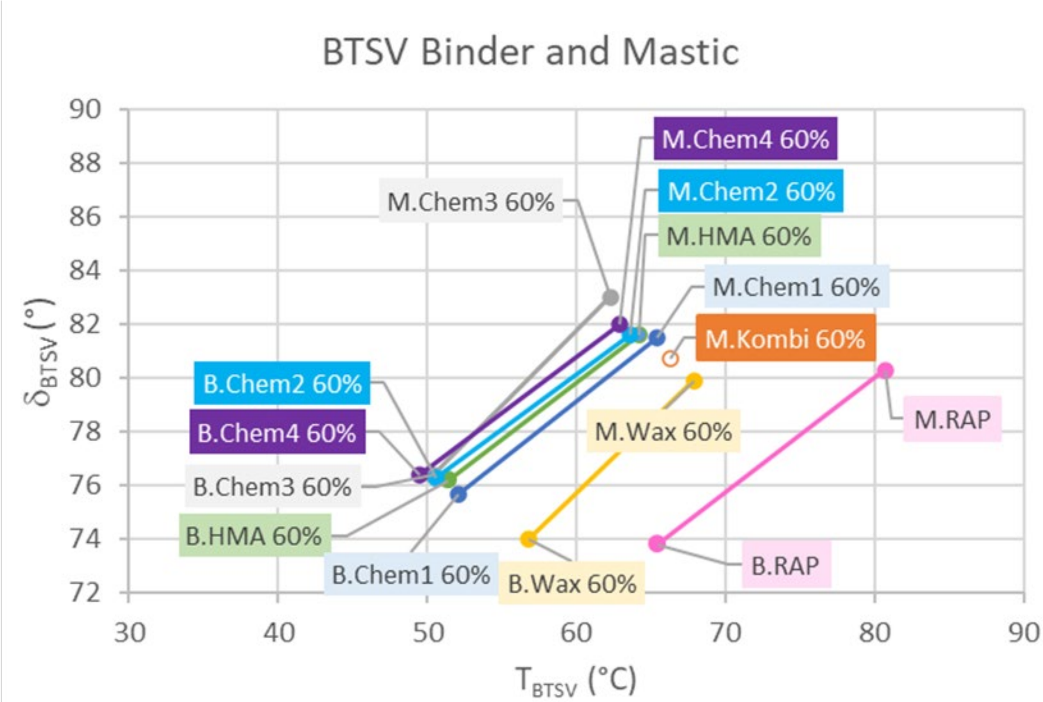


Figure 3: Comparison of BTSV results of binder (B.xxx) and mastic blends (M.xxx) (Figure 15 in report)

Field Test Track

The test track was constructed based on the results of the mixtures analysis (WP-3). For the binder layer it was decided to construct besides the reference (HMA), a section with WMA-Chem1, a section with WMA-Kombi (wax +Chem1) and a WMA-Foam section. It should be noted that all sections except the HMA containing only 50 % RAP, which was not in line with the original plan incorporated 60 % RAP. The binder layers were put on a base layer consisting of WMA AC T 22 S with a thickness of 80 mm and a penetration grade binder 50/70. The base layer itself had been put on a foundation layer AC F 32 with a thickness of 140 mm.

Figure 4 shows the schematic representation of the field test track, while Table 3 provides more details.

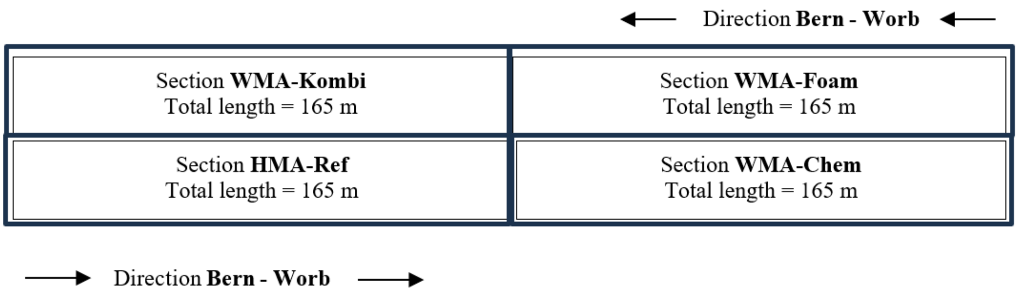


Figure 4: Schematic of the field test

Test track					
Test Section	**Direction**	**Construction Date**	**Material**		**Type**
			Base Layer	**Binder Layer**	
1	Bern-Worb	03/02/2024	WMA ACT22S	WMA ACB16S	WMA-Kombi
2	Worb-Bern	04/06/2024	WMA ACT22S	WMA ACB16S	WMA-Foam
3	Bern-Worb	09/07/2024	WMA ACT22S	WMA ACB16S	HMA-Ref
1	Worb-Bern	28/08/2024	WMA ACT22S	WMA ACB16S	WMA-Chem

Table 3: Details of field test track (Table 10 in report)

Results

The following section shows the test results of the laboratory mixtures in comparison to the field mixtures.

Air void content (Marshall)

Figure 5 illustrates the air voids (%) distribution for laboratory and field asphalt mixture. The results indicate that air void content varies between approximately 3.2 % and 5.2 %. Among the specimens, L-WMA-Kombi 30% exhibits the highest air voids percentage, exceeding 5.0 %, followed closely by L-WMA-Kombi 60%. In contrast, the lowest air void content is observed in L-HMA 30% and F-HMA 50%, both falling slightly above 3.0 %. The inclusion of WMA additives, particularly chemical and foam-based modifiers, appears to influence the air void content, with some mixtures demonstrating increased porosity compared to traditional HMA. These findings suggest that the selection of WMA technology and replacement levels can significantly impact the volumetric properties of asphalt mixtures, potentially affecting their compaction characteristics and long-term performance. Overall, the difference air voids between the laboratory and field mixtures were not significant.

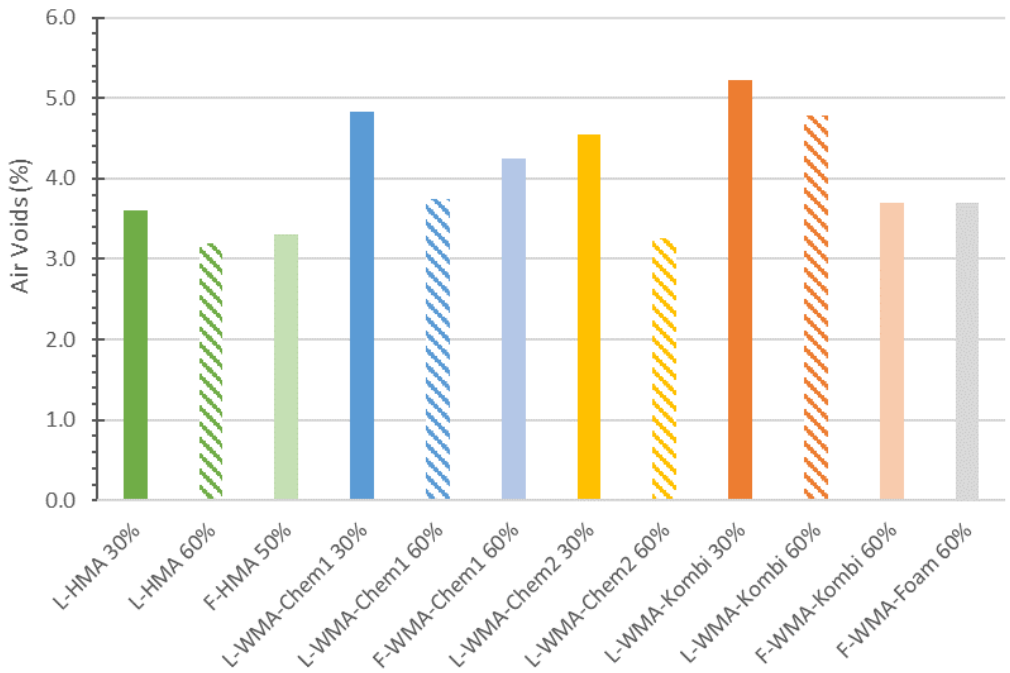


Figure 5: Marshall air voids distribution (Lab. vs field mixtures) (Figure 46 in report)

Compactability

Figure 6 presents a comparative analysis of laboratory and field-produced asphalt mixtures, with all samples compacted under identical laboratory conditions to isolate the effect of production method on compactability (K) and initial void content V (1). The plant-produced mixtures generally exhibited lower initial void contents than the laboratory-produced ones, suggesting that the production method can influence the material's compactability and early densification behaviour. L-WMA-Kombi 60% has still the best compactability among all field and lab mixes. The field mixes have similar compactability, except F-WMA-Chem 1 60%, which has relatively lower compactability. Laboratory mixes generally show higher compactability (K-values) than their field counterparts.

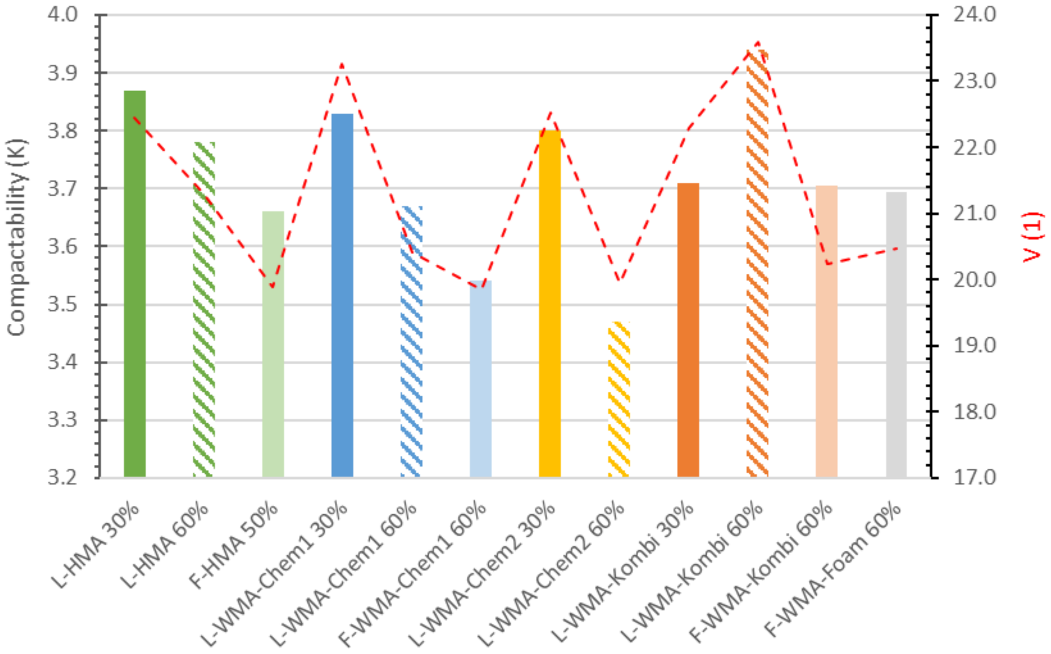


Figure 6: Mixtures compactability (K) and void content V (1) (Lab. vs field mixtures) (Figure 50 in report)

Indirect tensile strength ratio (ITSR)

Figure 7 shows the Indirect Tensile Strength Ratio (ITSR) as an indicator of water sensitivity. ITSR is the ratio of the indirect tensile strength in the wet state to the tensile strength in the dry state and indicates how well a mixture can resist potential moisture damage. A high ITSR value (close to 100 %) means less sensitivity to water. ITSR values below 80 %, on the other hand, indicate a potentially high sensitivity to water. Some mixtures exceed 90 % and therefore have a low water sensitivity value. Others show slightly lower ITSR values, although all values are above the Swiss standard limit of 80%. Field-produced mixtures (F-WMA) tend to show higher ITSR values than most laboratory mixtures, which could be due to real compaction and short-term ageing effects. The proportion of RAP also appears to have an influence on the indirect tensile strength ITSR ratio, whereby a higher proportion of RAP (50 % to 60 %) can lead to higher, but also lower water sensitivity values.

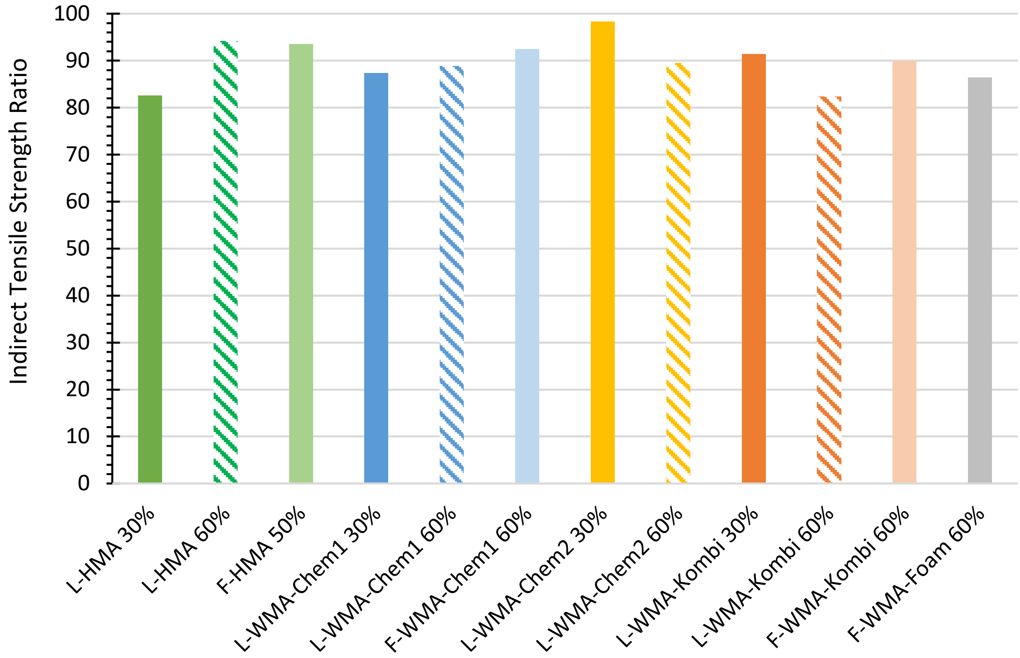


Figure 7: Indirect tensile strength ratio (Lab. vs field mixtures) (Figure 53 in report)

Rutting

Figure 8 shows the rutting test results after 30000 cycles for all laboratory and field mixtures. All field mixtures, except F-WMA-Foam 60% could be tested with 30'000 cycles, while only 4 laboratory mixtures could be tested to this target number, as the rut depth exceeded the measuring limit of the device.

Only L-WMA-Kombi 60% with a rut depth of 8.2% fulfils the requirement according to the Swiss standard of 10 %. The only HMA mixture that withstood 30'000 cycles was L-HMA 30%, but with a rut depth of 12.8 % could not achieve the standard requirement. All field mixtures except WMA-Foam fulfil the standard requirements according to the Swiss standard (≤10%). For the field mixture F-WMA-Foam 60% a rut depth was determined to be 9.3 % already after 3000 cycles.

A comparison between field and laboratory mixtures clearly reveals a better resistance against permanent deformation for the field mixtures. The reason for this behaviour could not be determined, especially since the air void content of all lab mixtures was close to the aspired value of 4.5 vol-%.

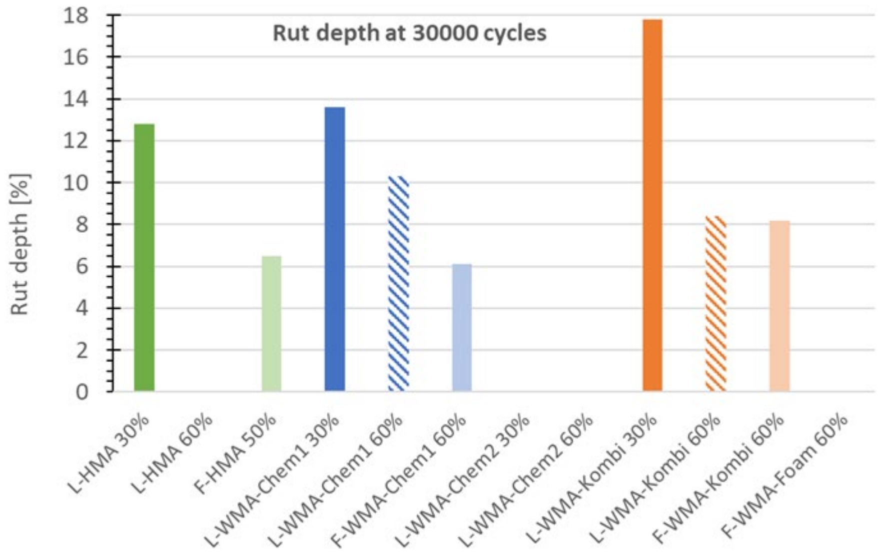


Figure 8: Rut depth of lab and field mixtures at 30'000 cycles (Figure 55 in report)

Semicircular bending test (SCB)

The test results of Semicircular bending test (SCB) of the laboratory and field mixtures are shown in Figure 9. The laboratory mixtures L-HMA 30 % and L-HMA 60 % show high fracture toughness. L-WMA-Chem 1 (30 % RAP) and (60 % RAP) show a slightly lower fracture toughness, which indicates a negative effect of the additive Chem1. L-WMA-Chem2 and L-WMA-Kombi, on the other hand, show the highest fracture toughness values, which indicates the suitability of these additives. The field mixture F-HMA 50 % has a high fracture toughness. F-WMA-Kombi 60 % even has one of the highest toughness values, which confirms that the combination of wax and Chem1 improves the fracture toughness even under field conditions. F-WMA-Foam 60 % and F-WMA-Chem1 60 % have an average fracture toughness, which confirms the finding that different chemical additives have different efficacies.

A higher proportion of RAP (60 %) does not always have a negative effect on fracture toughness: some WMA mixtures (e.g. Kombi and Chem2) even show higher values with an increased proportion of RAP than with a proportion of 30 %. F-WMA-Chem1 shows a significant decrease in fracture toughness with 60% RAP, which could indicate that Chem1 may not function as effectively with the addition of RAP. In contrast, the F-HMA 50% field mixtures show a high fracture toughness, which confirms that the addition of RAP does not cause any problems for HMA. Overall, HMA and WMA laboratory mixtures generally show a slightly higher fracture toughness than the WMA field mixtures, which could be due to the controlled manufacturing conditions in the laboratory.

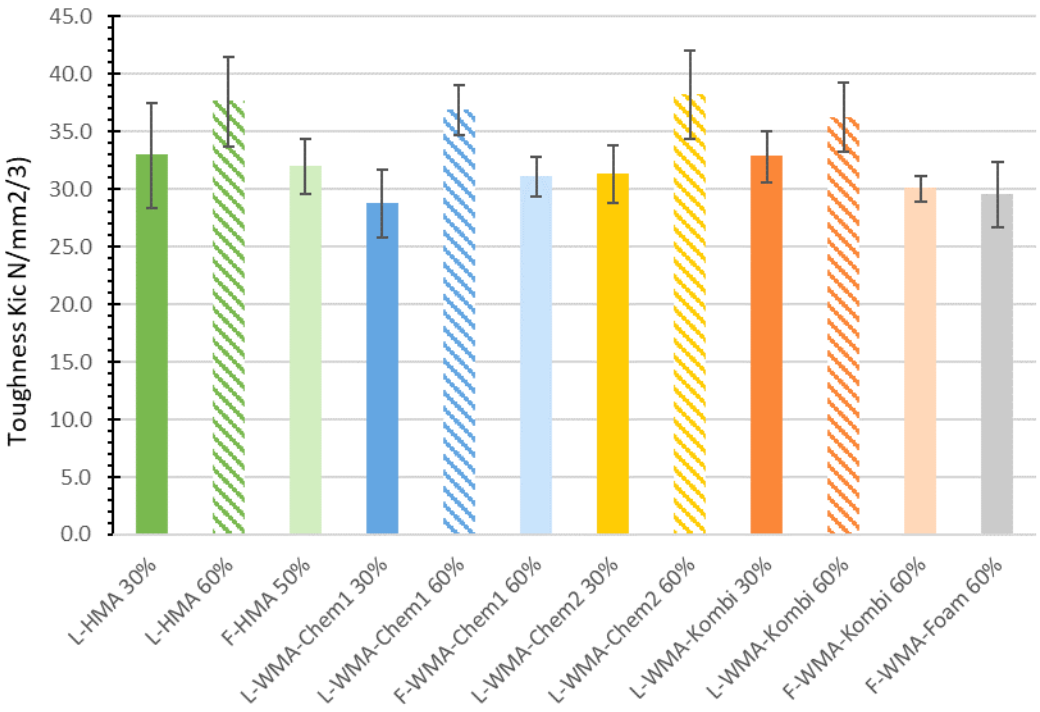


Figure 9: SCB test results of laboratory and field mixtures (Lab. vs field mixtures) (Figure 51 in report)

TRST

Figure 10 shows the failure temperatures of the mixtures from the field in comparison to the laboratory mixtures. The field mixtures with Chem1 and the Kombi show a slightly lower failure temperature than the laboratory mixtures, but for the hot mix reference this is the opposite and results in the highest failure temperature. The failure temperature of the foam asphalt (-34 °C) is higher compared to the mixtures with a chemical additive, but similar to the hot mix reference of the field. In summary, the field mixtures with a chemical additive showed a slightly better or equal low temperature performance compared to the field HMA, but all results were good with failure temperatures below -32°C.

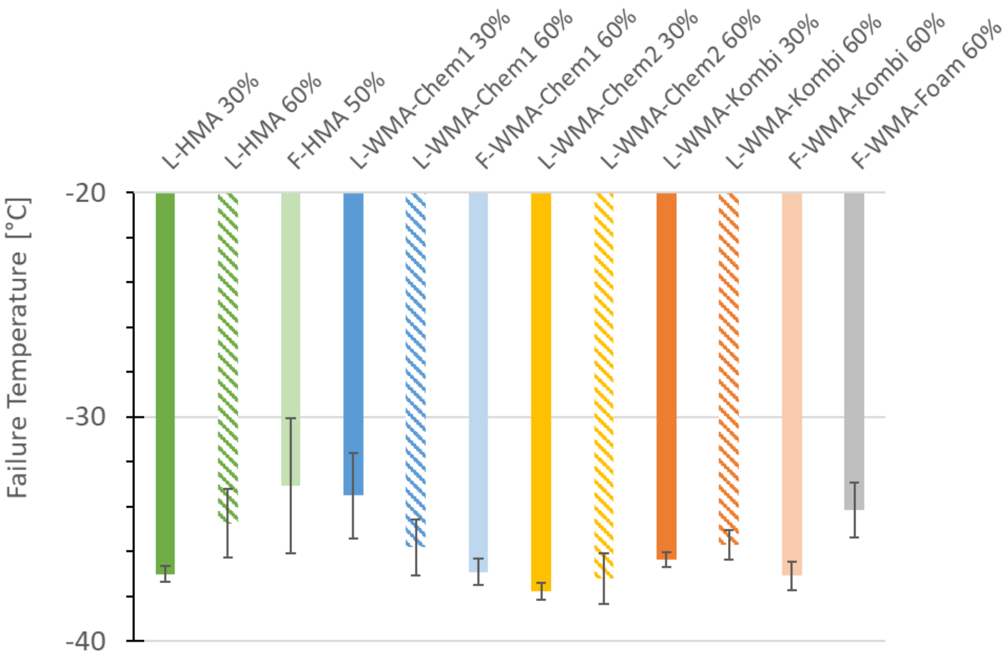


Figure 10: TSRST failure temperature (Figure 62 in report)

Layer adhesion of field extracted cores

The Leutner layer adhesion test results between the binder and base layer for the field cores (within or outside the wheel path) are presented in Figure 11. The Leutner test results show very high shear forces well above the Swiss standard requirement of 12 kN for the bond between base and binder layers. F-HMA-50% shows the highest values of more than 30 kN, while F-Chem1-60% has values only around 26 KN. Regarding the measurement precision and the fact that only one core was tested no difference between the values within and outside the wheel path can be found. Only for F-Foam-60% an increase in adhesion strength in the wheel path according to trafficking and curing seems possible (with a value similar to F-HMA-50%).

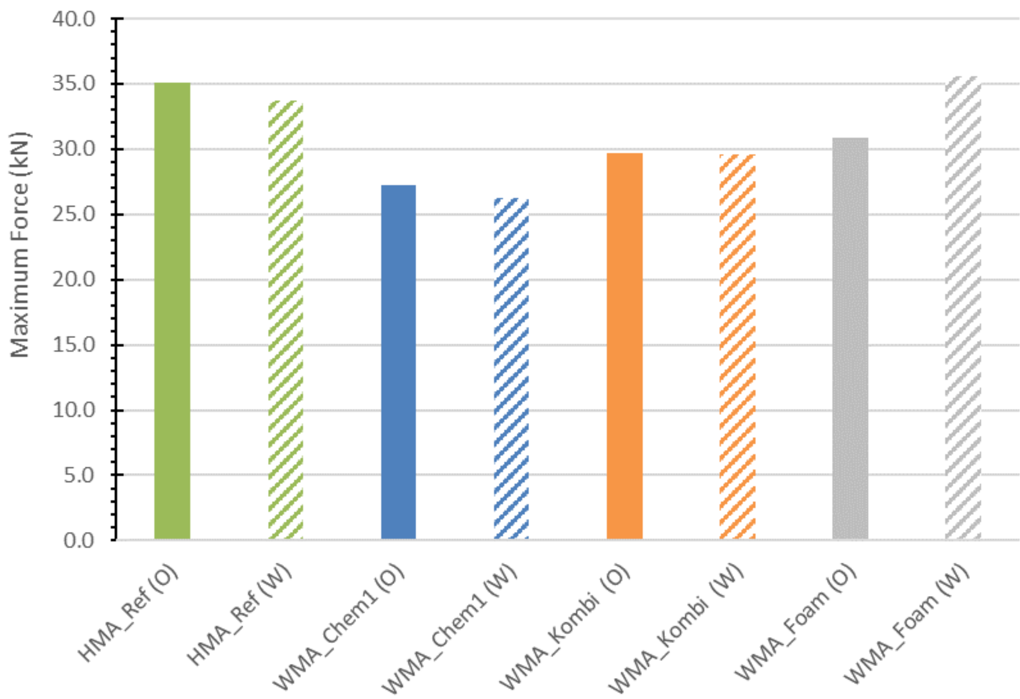


Figure 11: Leutner test results of extracted field cores (Layer adhesion) (Figure 64 in report)

Discussion

The selection of WMA additive according to the project proposal was mainly based on previous experience and the use of the products in Switzerland. Therefore, the focus was on chemical additives, while zeolites were excluded, and the use of waxes was only indented in combination with a chemical additive.

Regarding the limitations of the extensive laboratory testing, the final selection of 2 chemical additives out of 4 commonly used products was based on the initial binder and mastic testing, while the wax for the Kombi product (wax + chemical additive) was chosen as the commonly used product worldwide. Since binder and mastic evaluation could not result in clear differences between the 4 chemical additives, the second additive was chosen based on the Fraass breaking point as low temperature characteristic.

The addition of WMA additives was found to result in a higher Marshall air void content compared to HMA. Marshall stability results indicated that WMA could achieve strength comparable to HMA except for L-Chem2 30%, especially in field applications, even with high RAP content of 60 %. In terms of maniability, higher RAP content generally resulted in comparable maniability values except for L-Chem2 60%. Field mixtures demonstrated less favourable workability for F-Chem1 at 60% RAP compared to HMA. A clear trend in compactability was observed: laboratory mixtures with 30% RAP generally showed better compactability than the mixtures with 60% RAP content. Laboratory mixes generally show higher compactability (K-values) than their field counterparts.

In the field mixes, there was generally no significant difference in compactability between the WMA and HMA mixes. However, the mix containing Chem1 exhibited slightly lower compaction. In this study, the effect of WMA additives on compactability was not consistent. As for HMA, the tensile strength of WMA in dry conditions consistently shows higher tensile strength (ITS) compared to wet conditions, indicating that moisture negatively affects the strength of asphalt mixtures. HMA (RAP 30 %) shows the highest ITS in dry conditions, while WMA and field-produced mixtures (F-WMA) tend to exhibit slightly lower ITS values. Some L-WMA and F-WMA mixtures maintain competitive ITS values even in wet conditions, suggesting that specific additives or treatment processes help retain strength under moisture exposure. All ITSR results were very good, exceeding 80 %, both for lab and field mixtures. This suggests that lower production temperatures in combination with additives or foam bitumen do not negatively affect water sensitivity, even in the case of high RAP addition. However, in the literature the influence of WMA additives on the water sensitivity of WMA is not uniform, depending on the test method for the evaluation and void content of the mixture. Especially open porous mixtures with additives based on wax, zeolithes or foam bitumen resulted in poor performance (Guo, 2020). For WMA with chemical additives no detrimental effect was observed compared to HMA, probably because these additives are chemically often similar to conventional anti-stripping agents (Oliveira et al., 2012). The addition of RAP resulted in controversial results too.

Fracture resistance (SCB) tests highlight that there is no significant difference between HMA and WMA. Surprisingly, the higher RAP content of 60% had a positive impact on the fracture toughness values in general, while no difference was found between field mixtures and lab mixtures.

The rut depth was unexpectedly high for all laboratory mixtures, regardless of the type of WMA process and the RAP content. This is very unusual, even in the case of HMA. In contrast, the rut depths for the field mixtures, except for F-Foam, were below the value of 10% required by the Swiss standard after 30,000 cycles. However, increased rutting sensitivity was described in some literature as well (Guo et al., 2020), specifically when a high RAP content was used. In general, wax-based WMA additives improved the rutting behaviour, whereas foam asphalt showed inferior rutting performance. But the crucial parameter seems to be the correct dosage of the low viscosity additive, which make the binder and the mixture deformable if the additive amount is too high. The mixing energy is mentioned as another criterion to be considered. In the asphalt plant fast, high energy twin shaft mixers are used, whereas laboratories are mostly equipped with "bakery type" single shaft mixers, which are slow and are not able to produce the same quality of asphalt mixtures. This is especially important when a high percentage of RAP is added, where the old RAP binder needs to be blended with the small amount of virgin binder and additives.

Based on this, it is questionable to conclude that high temperature properties and permanent deformation might be problematic for WMA, although Marshall stability was rather low as well. The stiffness modulus at -10 °C and 1 Hz shows a similar trend for all the mixtures: L-30% RAP > L-60% RAP > field mixtures. The only exception is the field HMA with 50 % RAP, which is on the same level as the corresponding L-30%

WMA. There are some differences between HMA and WMA, but no clear trend can be found. The master curves show that the differences in stiffness modulus are larger at high temperatures and that ranking at high and low temperatures can be different. The low temperature properties of WMA are in most cases equivalent to HMA and some cases even better, but all very good ranging from –33 to -38 °C. In the case of field mixtures, the HMA has a higher failure temperature then WMA with additives, but similar to WMA with foam asphalt. There is no consistent conclusion about the effect of WMA additives on low temperature cracking resistance of WMA-RAP in the literature, when RAP content was below 40% (Guo et al., 2020). Some studies observed better or equivalent cracking performance for WAM compared to HMA with RAP, while others are the opposite. However, when more than 40% RAP was added, the cracking resistance decreased.

Overall, in the present research project, all WMA mixtures perform very similar to HMA. There is no WMA process, which is significantly better. However, some differences were observed, for example between the additive Chem1 and Chem2. In one test, additive Chem1 shows better results, but this was the opposite in another test. For foam asphalt, although only the results from the field tests with 60 % of RAP were available, it was mostly comparable with the other WMA mixtures.

Conclusions and Recommendations

The main conclusion of this research is obvious. All warm mix asphalt mixtures performed very similar to the reference hot mix asphalt. There are some minor differences in the test results, but they are generally not consistent. The following conclusions are drawn based on the project specific results and analysis:

- There was no WMA process which was superior to others. However, as the additive selection was based on prior experience, it is not granted that all WMA additives on the market are suitable.
- In some tests the 60 % RAP mixtures show a stiffer behavior (softening point ring and ball), in other tests it is the opposite (stiffness modulus at -10 °C, Fraass breaking point) and sometimes it is random (Marshall stability, TSRST failure temperature). Nevertheless, the difference in stiffness cannot be attributed to a higher RAP content, as the stiffness is adjusted by the type of the added binder.
- It is surprising that the mixtures with 30% RAP and bitumen 70/100 show similar performance like the ones with 60% RAP and a very soft added bitumen 330/400, because no fine tuning was made to fit the commercial binders (e.g. mixing two virgin binders to a target value).
- The rutting results were inconclusive and should be supplemented with additional tests to better characterize high-temperature performance. In any case, special attention should be given to monitoring permanent deformations on the test tracks in the coming years.
- HMA mixtures, both laboratory and field-produced, demonstrate consistently high Marshall stability, confirming their strong performance even with up to 60 % RAP.
- Maniability and compactability of WMA were not affected negatively by the lower production and compaction temperature.
- The long-term behaviour of WMA was not investigated in this study but should be addressed in a follow-up project. In this context special attention should be paid to

the rutting behaviour. Further, the interlayer bond between the binder and the surface layer needs to be determined. A US study observed that WMA mixtures begin their service lives with lower stiffness and tend to age in place more rapidly, but ultimately their stiffness and rutting resistance are comparable to HMA (NCHRP, 2015).

- Higher RAP contents (up to 60 %) can be successfully incorporated into both HMA and WMA mixtures without significantly compromising mechanical performance. The study should be extended to additional mixture types and even higher RAP contents.
- The results of this research suggested that the WMA technologies, particularly those incorporating chemical additives such as Chem1 and Kombi, present a promising sustainable alternative to traditional HMA, without compromising the key performance of their mechanical properties.

Résumé

Introduction et Objectifs

Ce projet de recherche vise à optimiser les mélanges d'enrobés tièdes (Warm Mix Asphalt, WMA) intégrant des enrobés recyclés (Reclaimed Asphalt Pavement, RAP), dans le but de développer des matériaux de chaussée durables sur le plan environnemental, sans compromettre leurs performances structurelles ou mécaniques. L'utilisation de RAP permet de réduire la consommation d'agrégats et de bitume vierges, tout en diminuant les émissions lors de la production d'enrobés, constituant ainsi une stratégie clé pour promouvoir une infrastructure efficiente en ressources. Le projet a pour objectif d'identifier des mélanges WMA-RAP offrant des propriétés mécaniques et de durabilité comparables, voire supérieures, à celles des enrobés à chaud conventionnels (Hot Mix Asphalt, HMA). Les objectifs spécifiques incluent l'évaluation de diverses technologies WMA (additifs), l'analyse des performances de mélanges WMA-RAP produits en laboratoire et en usine, ainsi que la proposition de mises à jour des normes suisses relatives aux mélanges d'enrobés, sur la base des investigations menées.

Méthodologie de Recherche

La méthodologie adoptée dans ce projet était complète et structurée, intégrant une analyse approfondie en laboratoire avec des validations des mélanges produits sur le terrain. La recherche a été organisée en cinq lots de travail distincts (WP) comme illustré à la Figure 1, chacun traitant une phase critique de l'étude.

Le WP1 consistait en une revue de littérature approfondie et le développement d'hypothèses, où des études mondiales et nationales sur le WMA et le RAP ont été examinées. Le WP2 s'est concentré sur la sélection d'additifs chimiques et organiques adaptés via des tests sur liants et mastics, identifiant ceux les plus appropriés pour la production de WMA.

Dans le WP3, des essais en laboratoire ont été réalisés sur des mélanges bitumineux contenant différentes teneurs en RAP (30 % et 60 %), combinées à divers additifs WMA, afin d'évaluer la performance mécanique et la durabilité. Le WP4 a inclus la construction d'une piste d'essai composée de sections WMA et HMA, suivie de l'évaluation des mélanges produits sur le terrain en laboratoire.

Le WP5 a intégré les résultats du projet dans un ensemble de recommandations pratiques pour les normes suisses des mélanges bitumineux. Un mélange de référence constant, AC B 16 S, a été utilisé pour tous les tests sauf pour les mélanges produits sur le terrain (i.e. 50 % RAP), avec tous les matériaux provenant de fournisseurs suisses afin de garantir la pertinence et l'applicabilité des résultats aux pratiques nationales de construction routière.

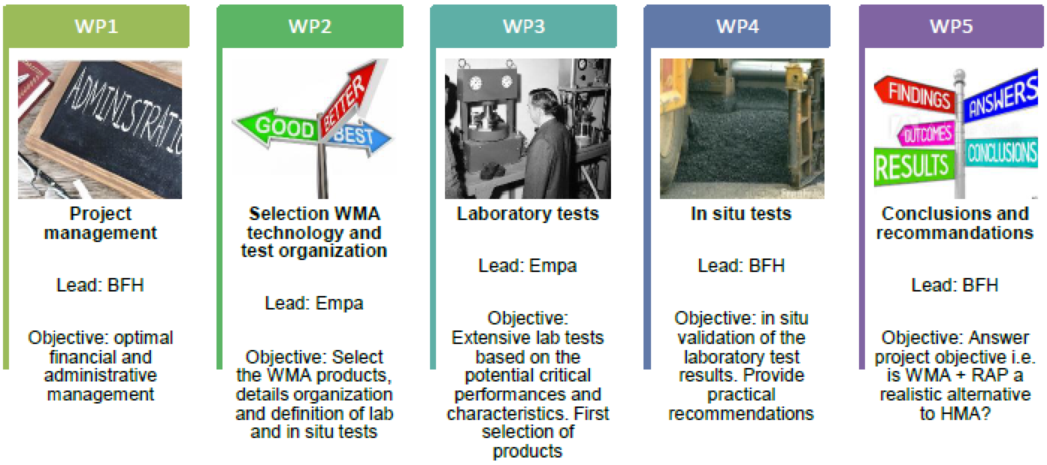


Figure 1: Vue d'ensemble du projet (Figure 1 du rapport)

Revue de la Littérature et État de l'Art

Les technologies d'enrobés tièdes (WMA) sont reconnues mondialement pour leur capacité à réduire les températures de production et de mise en œuvre de 20 à 40 °C par rapport aux enrobés à chaud traditionnels (HMA). Cette réduction présente de multiples avantages, notamment une diminution des émissions de gaz à effet de serre, une consommation d'énergie réduite et une amélioration des conditions de travail. Cependant, des recherches antérieures indiquent également des inconvénients potentiels tels qu'une résistance à l'humidité réduite et une susceptibilité au fluage. La littérature identifie trois principales classes de technologies WMA : le moussage (par exemple, l'injection d'eau dans le bitume), les additifs chimiques (par exemple, les tensioactifs) et les additifs organiques (par exemple, les cires). Le projet a examiné une gamme de ces technologies et leur synergie potentielle avec le RAP. Le projet PLANET en Suisse, conclu en 2017, avait déjà suggéré l'efficacité des WMA, en particulier lorsqu'ils intègrent du RAP (Arn, 2017).

Plan Expérimental

Les différentes étapes du projet sont présentées dans la Figure 2. Après une mise à jour des connaissances et l'étude de la littérature récente, la sélection des technologies WMA pour l'investigation en laboratoire (WP2) a été réalisée à l'aide de tests sur liants et mastics. L'analyse des performances mécaniques a été divisée en une investigation en laboratoire et une investigation sur le terrain (in situ). L'investigation a été menée en fonction des performances critiques potentielles et des caractérisations, aboutissant à la sélection finale des produits WMA pour les sections d'essai à grande échelle. Le WP3 s'est concentré sur les aspects pratiques de l'installation des chaussées en enrobé tiède ainsi que sur leurs performances en termes d'adhérence inter-couches. Dans une étape ultérieure, les mélanges pour les sections d'essai sur le terrain ont été collectés à l'usine et analysés en laboratoire. Les résultats obtenus des tests en laboratoire et in situ ont finalement été utilisés pour formuler des recommandations pratiques.

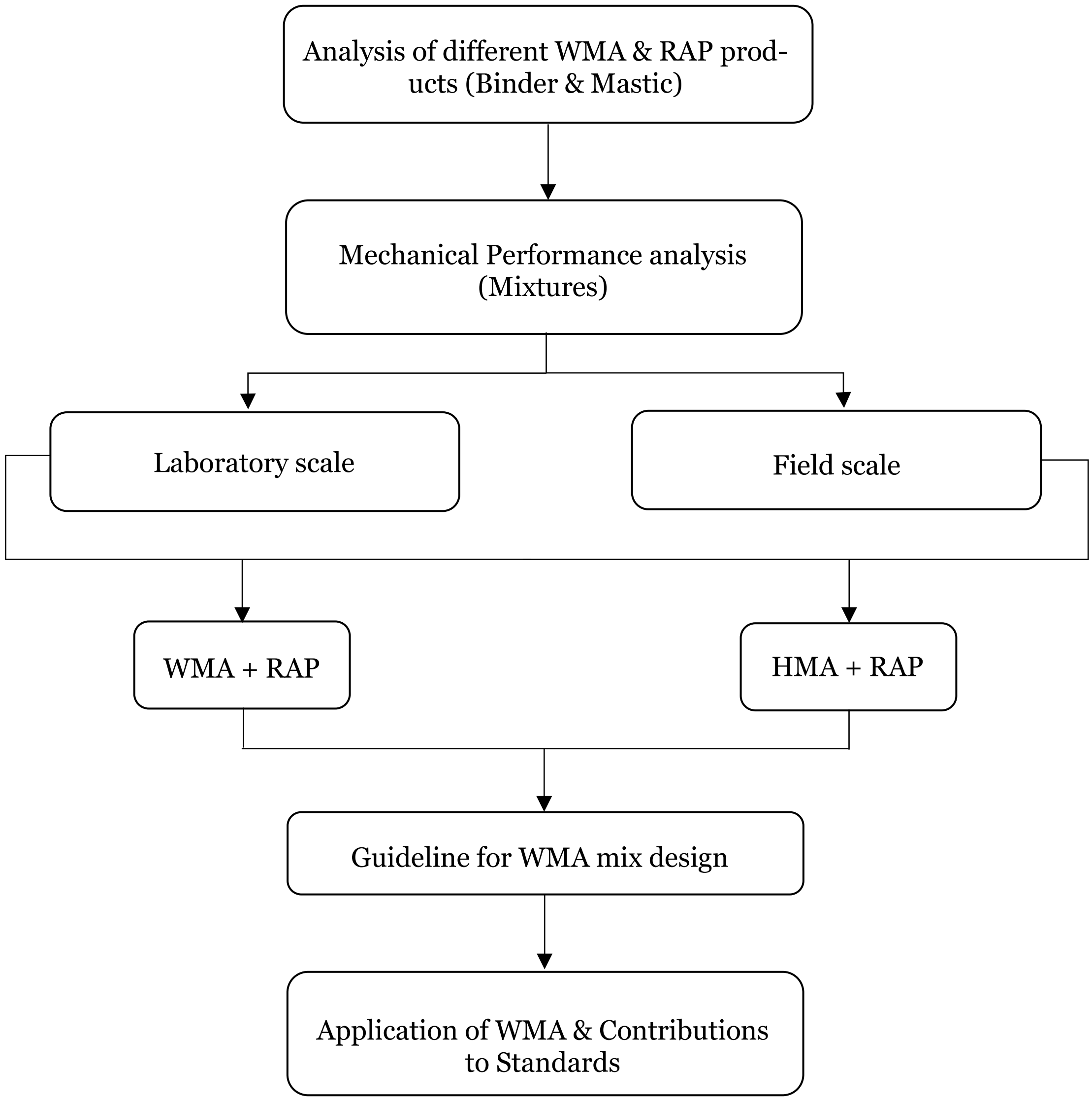


Figure 2: Détails de la vue d'ensemble du projet (Figure 2 du rapport)

Sélection des Matériaux et Formulation des Mélanges

Les matériaux d'enrobé, y compris les agrégats vierges et le RAP, ont été fournis par WeibelAG, un producteur suisse, tandis que les liants comprenaient un grade 70/100 pour 30 % de RAP et un grade plus souple 330/430 pour 60 % de RAP afin de compenser la rigidité du liant vieilli.

Un total de sept additifs WMA ont été évalués : quatre chimiques (Chem1 à Chem4), un organique (cire) en combinaison avec Chem1 (Kombi) et un mélange moussé (produit uniquement en usine). La sélection des additifs WMA s'est basée sur la littérature, l'expérience antérieure ainsi que sur la disponibilité commerciale des produits en Suisse. Dès le début (demande de projet) et sur la base des résultats de recherche (PLANET) et de l'expérience pratique en Suisse, les décisions suivantes ont été prises (voir également le Tableau 1):

- L'accent a été mis sur les additifs chimiques, en raison de la grande variété de ces produits.
- Les méthodes de moussage ne devaient être incluses qu'in situ, tandis que, sur la base d'expériences antérieures, les zéolites ont été complètement exclues.
- Les cires ont été exclues pour les mélanges WAM et utilisées uniquement dans les tests sur liants et en combinaison avec un additif chimique.
- En raison des limitations des tests en laboratoire extensifs, la sélection finale de 2 additifs chimiques parmi 4 produits couramment utilisés s'est basée sur les tests initiaux sur liants et mastics, tandis que la cire pour le produit Kombi (cire + additif chimique) a été choisie comme produit couramment utilisé dans le monde.

Dans une première étape, 4 additifs chimiques ont été évalués au niveau des liants et des mastics (voir Tableau 1).

Les performances de ces additifs ont d'abord été testées au niveau des liants et des mastics à l'aide de tests rhéologiques, y compris le BTSV et le DSR, pour évaluer la rigidité et la susceptibilité à la température.

Le Tableau 2 présente un aperçu de tous les mélanges et combinaisons utilisés dans ce projet. Le contenu en RAP est indiqué à la fin (30 %, 50 % ou 60 %). Dans les figures, les mélanges de laboratoire sont étiquetés avec L- et ceux du terrain avec F-.

Additifs WMA

Type de produit	Code produit	Description
Technologie de moussage	Foam	Enrobé mousse produit en usine
Chemical additives	Chem1	Tensioactif
	Chem2	Dérivé naturel à base de plante
	Chem3	Tensioactif
	Chem4	Additif naturel à base d'huile
Additif organique	Wax	Cire paraffine FT
Combinaison d'additif chimique et organique	Kombi	Chem1 + Cire

Tableau 1: Sélection des produits WMA (Tableau 1 dans le rapport)

Tous les mélanges de laboratoire ont été produits selon les procédures définies par la norme européenne EN 13108-1. La température de production des mélanges à chaud a été fixée à 160 °C et celle des mélanges tièdes à 130 °C. Les mélanges de la piste d'essai sur le terrain ont été produits en usine et des échantillons ont été collectés pour les investigations en laboratoire.

Mélanges et compositions				
Code laboratoire	**Mélange liant**	**Mélange mastic**	**Mélange laboratoire**	**Mélange terrain**
HMA 30%	X		X	
HMA 50%				X
HMA 60%	X	X	X	
WMA-Chem1 30%			X	
WMA-Chem1 60%	X	X	X	X
WMA-Chem2 30%			X	
WMA-Chem2 60%	X	X	X	
WMA-Chem3 60%	X	X		
WMA-Chem4 60%	X	X		
WMA-Wax 60%	X	X		
WMA-Kombi 30%			X	
WMA-Kombi 60%		X	X	X
WMA-Foam 60%				X

Tableau 2: Aperçu des mélanges et compositions avec différents additifs et taux de recyclage (Tableau 2 dans le rapport)

Tests sur Liants et Mastics

Les tests sur liants ont joué un rôle essentiel dans l'évaluation de l'efficacité des additifs WMA sélectionnés. Les propriétés rhéologiques ont été évaluées à l'aide d'un rhéomètre à cisaillement dynamique (DSR) et du test de caractérisation rapide des liants (BTSV). Les mélanges de liants ainsi que les mastics (liant + filler) comprenaient des liants vierges 70/100 et 330/430, ainsi que des liants extraits de RAP, combinés avec différents additifs Chem1, Chem2, Chem3, Chem4 et Kombi (Chem1 + cire). L'étude a révélé que, bien que les additifs chimiques exercent une influence minimale sur la rigidité des liants, les liants modifiés par la cire présentaient une rigidité significativement accrue et des températures BTSV plus élevées. Concernant le comportement à basse température, aucune différence significative entre les résultats du test Fraass des mélanges HMA et WMA n'a été observée. Les mélanges de mastics, simulant la matrice filler-bitume, ont été testés pour évaluer l'interaction du liant avec la composante minérale. L'ajout de filler minéral a significativement augmenté la rigidité des mastics. Il est intéressant de noter que le classement des mélanges de mastics en termes de température BTSV et d'angle de phase est resté inchangé, sauf pour Chem3, qui a montré un décalage parallèle uniforme des résultats BTSV du liant aux mélanges de mastics (Figure 3). Cela a été interprété comme une interaction minimale entre le liant (y compris l'additif WMA) et la matrice minérale. Dans ce cas, les résultats des mastics ont apporté peu d'informations supplémentaires.

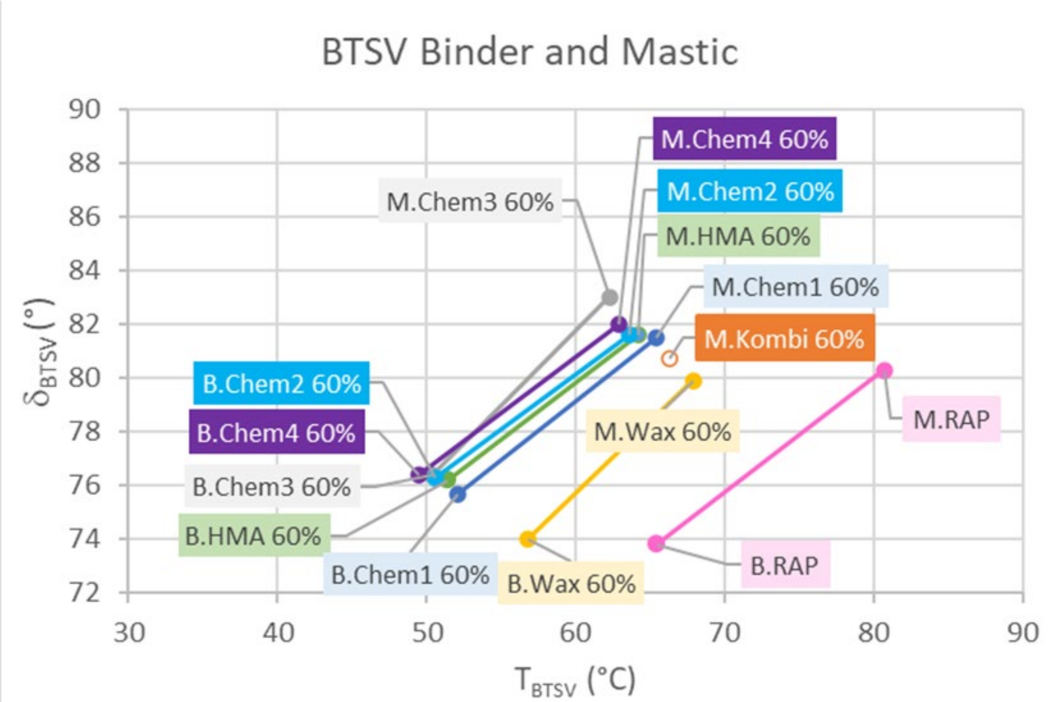


Figure 3: Comparaison des résultats BTSV des liants (B.xxx) et des mélanges de mastic (M.xxx) (Figure 15 du rapport)

Piste d'essai sur le terrain

La piste d'essai a été construite sur la base des résultats de l'analyse des mélanges (WP-3). Pour la couche de liant, il a été décidé de construire, en plus de la section de référence (HMA), une section avec WMA-Chem1, une section avec WMA-Kombi (cire + Chem1) et une section avec WMA-Foam. Il convient de noter que toutes les sections, à l'exception du HMA contenant uniquement 50 % de RAP comme prévu initialement, ont incorporé 60 % de RAP. Les couches de liant ont été posées sur une couche de base constituée de WMA AC T 22 S, d'une épaisseur de 80 mm, utilisant un liant de grade de pénétration 50/70. La couche de base elle-même repose sur une couche de fondation AC F 32 de 140 mm d'épaisseur.
La Figure 4 présente le schéma de la piste d'essai, tandis que le Tableau 3 en donne les détails.

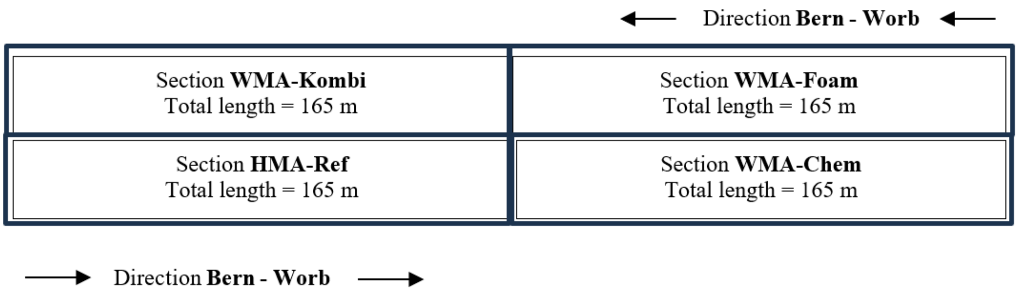


Figure 4: Schéma de la piste d'essai sur le terrain

Piste d'essai					
Essai Section	**Direction**	**Date de construction**	**Matériau**		**Type**
			Couche de base	**Couche de liant**	
1	Bern-Worb	03/02/2024	WMA ACT22S	WMA ACB16S	WMA-Kombi
2	Worb-Bern	04/06/2024	WMA ACT22S	WMA ACB16S	WMA-Foam
3	Bern-Worb	09/07/2024	WMA ACT22S	WMA ACB16S	HMA-Ref
1	Worb-Bern	28/08/2024	WMA ACT22S	WMA ACB16S	WMA-Chem

Table 3: Détails de la piste d'essai sur site (Tableau 10 dans le rapport)

Résultats

La section suivante compare les résultats des essais entre les mélanges issus du laboratoire et ceux issus du terrain.

Teneur en vides d'air (Marshall)

La Figure 5 illustre la répartition de la teneur en vides d'air (%) pour les mélanges d'enrobés en laboratoire et sur le terrain. Les résultats indiquent que la teneur en vides varie entre environ 3,2 % et 5,2 %.

Parmi les éprouvettes, L-WMA-Kombi 30 % présente la teneur en vides la plus élevée, dépassant 5,0 %, suivie de près par L-WMA-Kombi 60 %. En revanche, la plus faible teneur en vides est observée pour L-HMA 30 % et F-HMA 50 %, toutes deux légèrement au-dessus de 3,0 %.

L'utilisation d'additifs WMA, en particulier chimiques ou à base de mousse, semble influencer la porosité, certaines formules montrant une porosité accrue par rapport au HMA traditionnel. Ces résultats suggèrent que le choix de la technologie WMA et le taux de substitution influencent significativement les propriétés volumiques des mélanges, affectant ainsi leur compacité et leurs performances à long terme.

Globalement, les différences de teneur en vides entre les mélanges de laboratoire et ceux de terrain ne sont pas significatives.

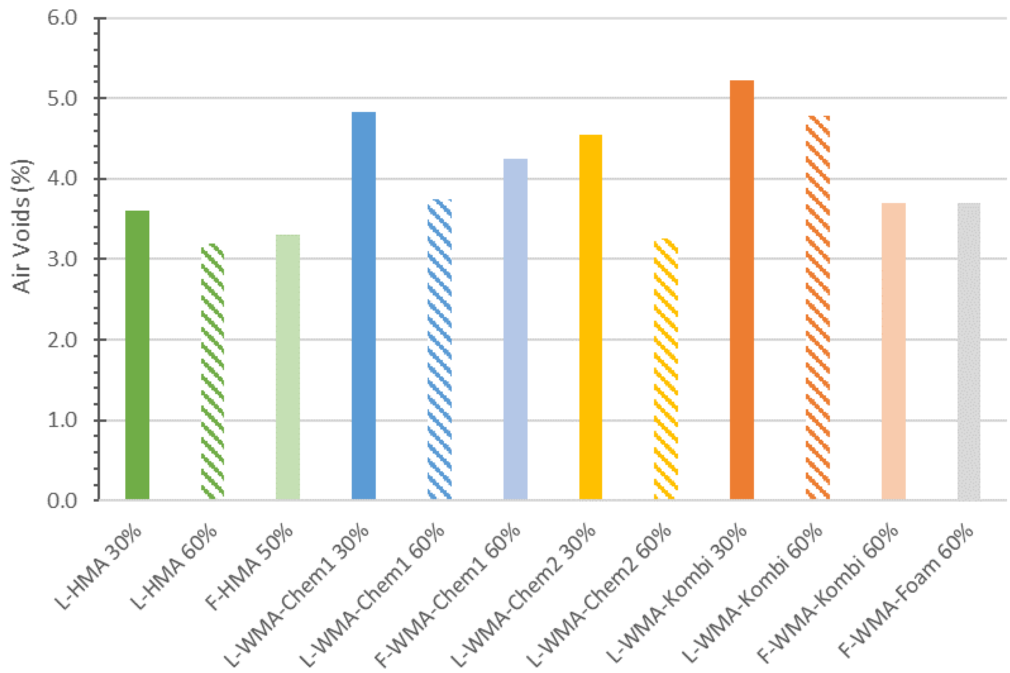


Figure 5: Répartition des vides Marshall (Mélanges laboratoire vs mélanges terrain) (Figure 46 du rapport)

Compactabilité

La Figure 6 présente une comparaison entre les mélanges bitumineux produits en laboratoire et ceux produits en centrale, tous compactés dans les mêmes conditions en laboratoire, afin d'isoler l'influence de la méthode de production sur la compacité (K) et la teneur initiale en vides V(1).

Les mélanges issus de la centrale présentent généralement une teneur en vides initiale plus faible que ceux produits en laboratoire, ce qui suggère que la méthode de production a un impact sur la compacité et le comportement initial de densification du matériau.

Le mélange L-WMA-Kombi 60 % présente la meilleure compacité parmi l'ensemble des mélanges, qu'ils soient de laboratoire ou de terrain. Les mélanges produits sur le terrain présentent des niveaux de compacité proches, à l'exception du F-WMA-Chem1 60 %, qui affiche une compacité relativement plus faible.

De manière générale, les mélanges de laboratoire atteignent des valeurs de compacité (K) plus élevées que leurs équivalents fabriqués en centrale.

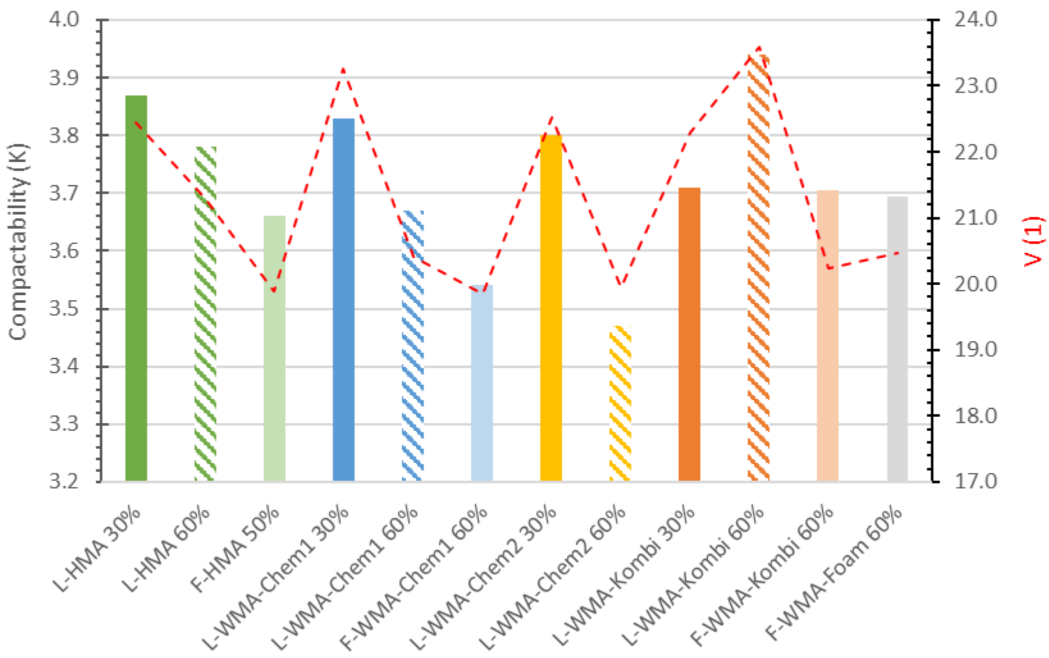


Figure 6: Compacité des mélanges (K) et teneur en vides V(1) (Mélanges laboratoire vs mélanges terrain) (Figure 50 du rapport)

Rapport de résistance à la traction indirecte (ITSR)

La Figure 7 présente les résultats du TSR (Tensile Strength Ratio), qui évalue la sensibilité des mélanges à l'humidité. Le TSR correspond au rapport entre la résistance à la traction en condition humide et en condition sèche. Une valeur élevée (proche de 100 %) indique une bonne résistance à l'humidité. Certains mélanges affichent des TSR supérieurs à 90 %, ce qui témoigne d'une forte résistance, tandis que d'autres présentent des valeurs plus faibles, indiquant une sensibilité accrue à l'humidité.

Les mélanges produits sur le terrain (F-WMA) montrent généralement des TSR plus élevés que ceux issus du laboratoire, probablement en raison d'une compaction plus efficace et d'un vieillissement à court terme lors de la mise en œuvre. Dans l'ensemble, l'exposition à l'humidité réduit la résistance mécanique des enrobés : les résistances mesurées en condition sèche restent systématiquement plus élevées.

La teneur en RAP affecte également la résistance : des proportions élevées (50 % à 60 %) influencent à la fois la résistance à la traction (ITS) et le TSR. Certains mélanges de terrain présentent de meilleures performances, probablement grâce à l'effet des additifs ou du vieillissement. En général, des valeurs de TSR supérieures à 85-90 % traduisent une bonne résistance à l'humidité, tandis que des valeurs inférieures à 80 % peuvent signaler une susceptibilité notable.

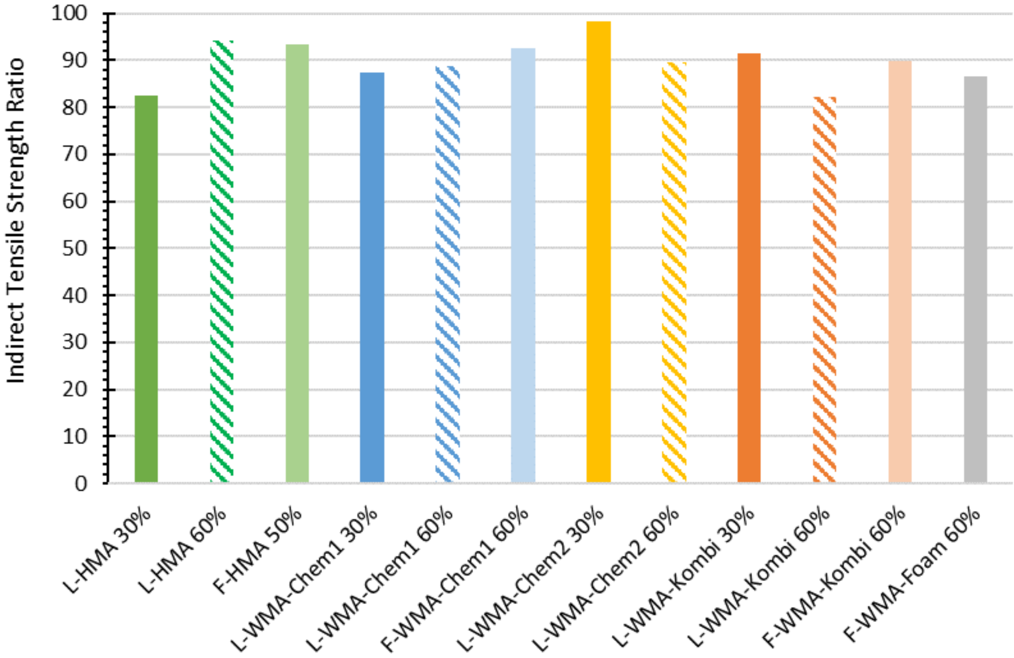


Figure 7: Taux de résistance à la traction indirecte (Mélanges laboratoire vs mélanges terrain) (Figure 53 du rapport)

Orniérage

La Figure 8 présente les résultats des essais d'orniérage menés jusqu'à 30 000 cycles sur différents mélanges bitumineux, issus soit du laboratoire, soit du terrain. Tous les mélanges de terrain ont pu être testés jusqu'à 30 000 cycles, à l'exception du F-WMA-Foam 60 %. En revanche, seuls quatre mélanges de laboratoire ont atteint ce seuil, les autres ayant généré des ornières dépassant la capacité de mesure de l'appareil.

Parmi les mélanges de laboratoire, seul L-WMA-Kombi 60 % respecte la norme suisse (ornière ≤10 %), avec une profondeur de 8,2 %. Le mélange L-HMA 30 % a résisté aux 30 000 cycles, mais avec une profondeur de 12,8 %, il ne respecte pas la norme.
Tous les mélanges de terrain sont également conformes à la norme suisse (ornière ≤10 %), à l'exception de F-WMA-Foam 60 %, qui a atteint une profondeur de 9,3 % après seulement 3 000 cycles et n'a pas pu être testé jusqu'à 30 000 cycles.

De manière générale, les mélanges de terrain montrent une meilleure résistance à la déformation permanente que ceux préparés en laboratoire. Ce constat reste partiellement inexpliqué, d'autant plus que les teneurs en vides des mélanges de laboratoire étaient proches de la valeur cible de 4,5 vol-%.

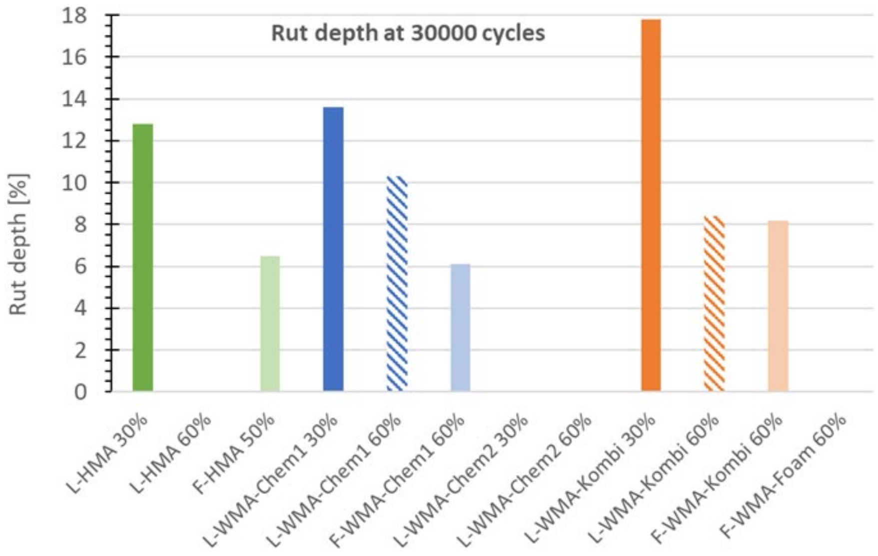


Figure 8: Profondeur d'orniérage des mélanges laboratoire et terrain à 30 000 cycles (Figure 55 du rapport)

Essai de flexion semi-circulaire (SCB)

La Figure 9 présente les résultats des essais SCB, qui évaluent la ténacité des mélanges issus du laboratoire et du terrain (leur résistance à la fissuration).

Les mélanges de laboratoire L-HMA 30 % et 60 % affichent une ténacité élevée, confirmant la robustesse structurelle du HMA. Le mélange L-WMA-Chem1 (30 % et 60 % de RAP) présente une ténacité légèrement plus faible, suggérant un effet négatif de l'additif Chem1 sur la ténacité par rapport au HMA. En revanche, L-WMA-Chem2 et L-WMA-Kombi obtiennent les meilleures performances, ce qui indique que ces additifs renforcent la résistance à la fissuration.

Côté terrain, le mélange F-HMA 50 % montre également une bonne ténacité, confirmant la robustesse du HMA in situ. F-WMA-Kombi 60 % se distingue par une des meilleures performances, attribuables à la combinaison cire + Chem1. En revanche, F-WMA-Foam 60 % et F-WMA-Chem1 60 % présentent une ténacité modérée, traduisant une efficacité plus variable selon les additifs chimiques.

L'effet d'un taux élevé en RAP (60 %) n'entraîne pas systématiquement une baisse de ténacité, comme en témoignent les bons résultats obtenus avec Kombi et Chem2. Cependant, une nette baisse est observée avec F-WMA-Chem1, suggérant une moins bonne compatibilité avec le RAP.

Globalement, les mélanges de laboratoire présentent une ténacité légèrement supérieure à ceux du terrain, probablement en raison de meilleures conditions de fabrication (mélange, compactage, durcissement).

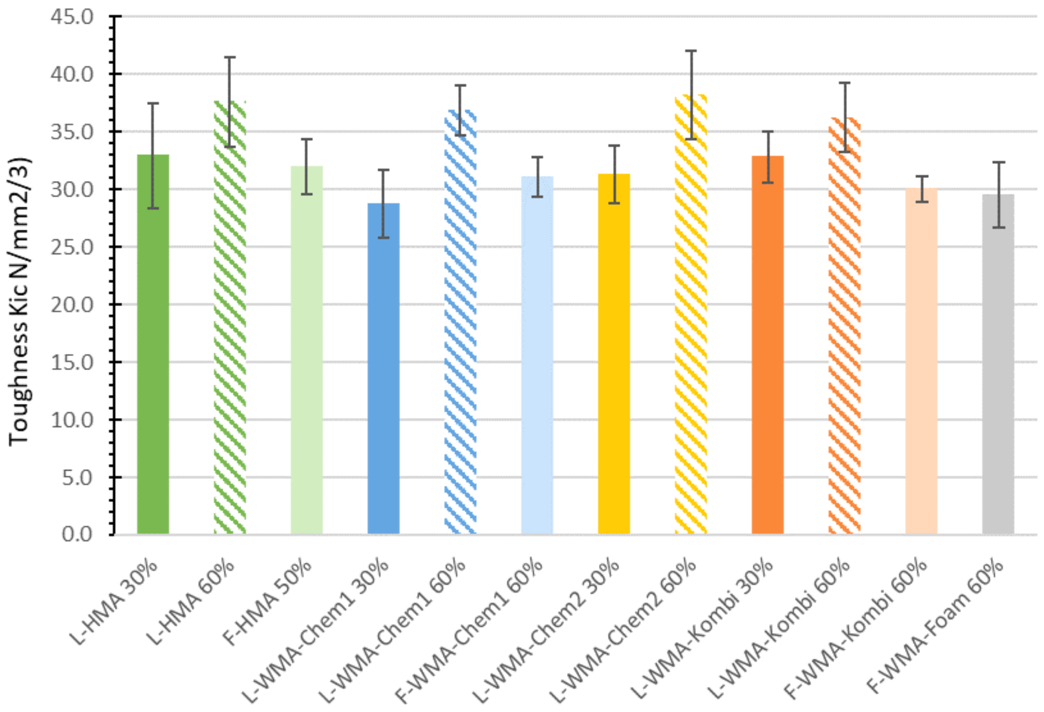


Figure 9: Résultats des essais SCB des mélanges laboratoire et terrain (Figure 51 du rapport)

TSRST

La Figure 10 compare les températures de rupture (résistance au froid) des mélanges produits sur le terrain à celles des mélanges de laboratoire.

Les mélanges de terrain contenant les additifs Chem1 et Kombi présentent une température de rupture légèrement inférieure à leurs homologues de laboratoire, ce qui indiquent une résistance au froid légèrement meilleure. Le mélange HMA de référence sur le terrain présente la température de rupture la plus élevée (et donc la moins bonne résistance). L'enrobé moussant a une température de rupture de -34 °C, comparable à celle du HMA, mais supérieure à celle des mélanges avec additifs chimiques.

En résumé, tous les mélanges de terrain avec additifs chimiques présentent de bonnes performances à basse température, comparables ou légèrement supérieures à celles du HMA, avec des températures de rupture inférieures à -32 °C, ce qui semble satisfaisant pour des conditions hivernales.

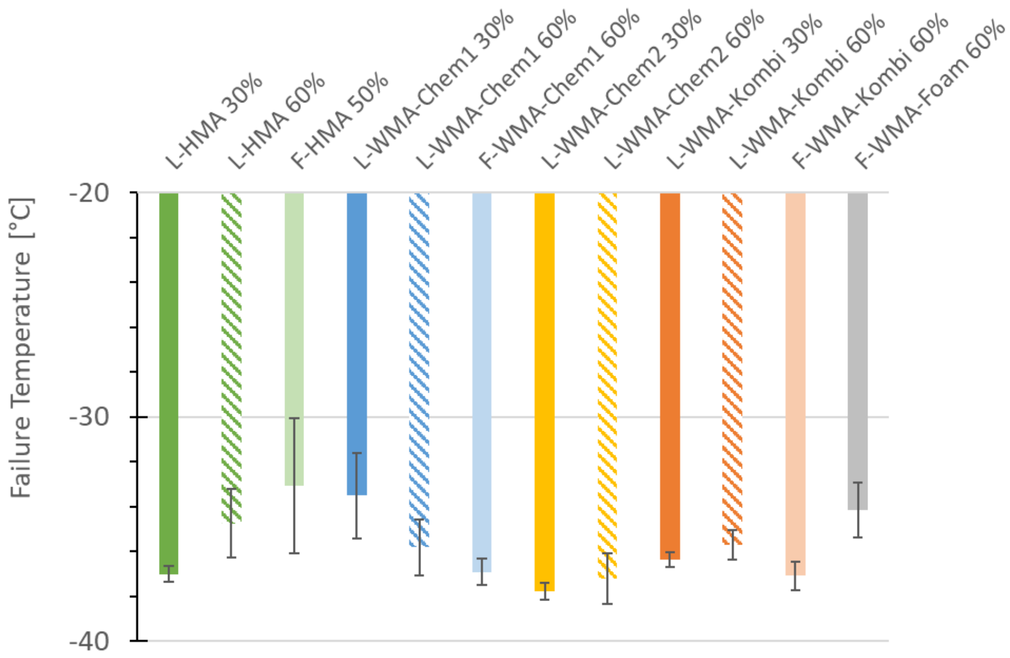


Figure 10: Températures de rupture TSRST (Figure 62 du rapport)

Adhésion inter-couches des carottes extraites sur le terrain

La Figure 11 présente les résultats des essais Leutner d'adhésion entre les couches de liant et de base pour les carottes de terrain (dans ou hors de la trace de roulement).

Les résultats montrent des forces de cisaillement très élevées, bien supérieures à l'exigence suisse de 12 kN. Le F-HMA 50 % atteint plus de 30 kN, tandis que F-Chem1 60 % atteint environ 26 kN. En raison de la précision des mesures et du fait qu'une seule carotte a été testée, aucune différence notable n'a été observée entre les zones dans ou hors de la trace de roulement. Seul F-Foam 60 % montre une augmentation possible de l'adhésion dans la trace, liée au trafic et au durcissement, atteignant des valeurs similaires à F-HMA 50 %.

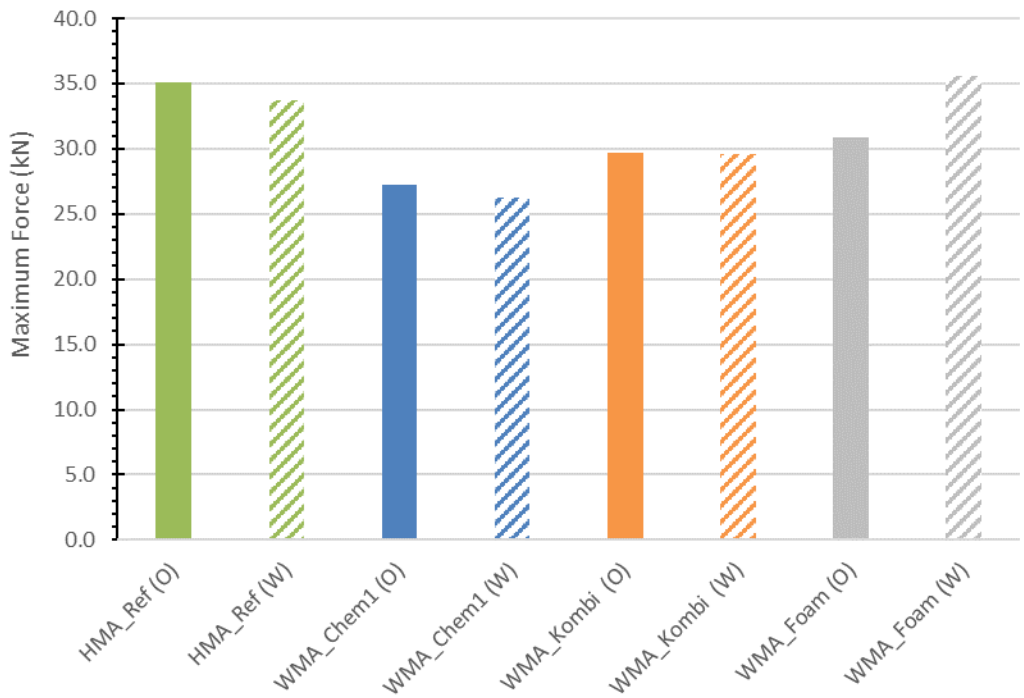


Figure 11: Résultats de l'essai de Leutner sur carottes extraites du chantier (Adhésion entre couches) (Figure 64 du rapport)

Discussion

La sélection des additifs WMA (asphalte tiède) dans ce projet s'est fondée principalement sur l'expérience acquise et l'usage courant de ces produits en Suisse. Ainsi, l'accent a été mis sur les additifs chimiques, tandis que les zéolites ont été exclues et que l'usage de cires était uniquement envisagé en combinaison avec un additif chimique.

Concernant les limites des essais en laboratoire, le choix final de deux additifs chimiques parmi les quatre produits couramment utilisés s'est basé sur les résultats des essais initiaux sur liants et mastics. La cire utilisée dans le produit Kombi (cire + additif chimique) a été choisie car elle est répandue à l'échelle mondiale. Les essais sur liant et mastic n'ayant pas permis de départager clairement les quatre additifs chimiques, le deuxième additif a été retenu sur la base du point de rupture Fraass, caractéristique des propriétés à basse température.

L'ajout d'additifs WMA a conduit à une teneur en vides d'air Marshall plus élevée par rapport à l'HMA (asphalte à chaud). Les résultats de stabilité Marshall ont montré que les mélanges WMA pouvaient atteindre une résistance comparable à celle de l'HMA, sauf pour L-Chem2 30 %, en particulier dans les applications en conditions réelles, même avec un taux élevé de RAP de 60 %. En termes de maniabilité, l'augmentation du RAP n'a pas affecté significativement les valeurs obtenues, sauf pour L-Chem2 60 %. Les mélanges en centrale ont montré une maniabilité moins favorable pour F-Chem1 avec 60 % de RAP par rapport à l'HMA. Une tendance nette en compactabilité a été observée : les mélanges avec 30 % de RAP présentent généralement une meilleure compactabilité que ceux à 60 %. Globalement, les mélanges de laboratoire affichent une compactabilité plus élevée (valeurs K) que ceux produits sur le terrain.

Dans les mélanges sur le terrain, aucune différence significative de compactabilité n'a été constatée entre les formulations WMA et HMA. Toutefois, le mélange contenant l'additif Chem1 présente une compaction légèrement inférieure. Dans cette étude, l'effet des additifs WMA sur la compactabilité n'est pas uniforme. Pour ce qui est de la résistance à la traction, les WMA montrent, en conditions sèches, des valeurs d'ITS systématiquement supérieures à celles en conditions humides, ce qui indique un affaiblissement sous l'effet de l'humidité. L'HMA avec 30 % de RAP montre la résistance à la traction sèche la plus élevée, tandis que les WMA et les mélanges produits en centrale affichent des valeurs légèrement inférieures. Toutefois, certains mélanges L-WMA et F-WMA conservent de bonnes performances même en conditions humides, ce qui laisse penser que certains additifs ou processus de traitement peuvent préserver la résistance en présence d'humidité. Tous les résultats ITSR sont excellents, dépassant 80 %, en laboratoire comme sur le terrain. Cela suggère que les températures de production plus basses combinées à des additifs ou au bitume mousse n'affectent pas négativement la sensibilité à l'eau, même avec un fort taux de RAP.

Cependant, la littérature indique que l'effet des additifs WMA sur la sensibilité à l'eau est variable, en fonction des méthodes d'essai et de la teneur en vides des mélanges. En particulier, les mélanges poreux ouverts contenant des additifs à base de cire, de zéolite ou de mousse de bitume présentent parfois de faibles performances (Guo et al., 2020). En revanche, les WMA avec additifs chimiques n'ont pas montré d'effets négatifs par rapport aux HMA, probablement parce que ces additifs sont chimiquement similaires aux agents anti-stripping classiques (Oliveira et al., 2012). Les résultats concernant l'ajout de RAP sont également contrastés.

Les essais de résistance à la fissuration (SCB) indiquent qu'il n'y a pas de différence notable entre HMA et WMA. Fait surprenant, un taux élevé de RAP (60 %) semble avoir un effet bénéfique sur la ténacité en général, sans différence notable entre mélanges de laboratoire et mélanges de terrain. Les résultats d'orniérage étaient étonnamment élevés pour tous les mélanges de laboratoire, y compris l'HMA, ce qui est inhabituel. Ce phénomène ne dépend ni du taux de RAP ni du type de procédé WMA. Seuls les mélanges produits sur le terrain ont donné des profondeurs d'ornières acceptables. Une sensibilité accrue à l'orniérage a toutefois été rapportée dans certaines publications (Guo et al., 2020), notamment pour les mélanges à fort taux de RAP.

En général, les additifs WMA à base de cire améliorent la résistance à l'orniérage, tandis que les procédés à mousse de bitume montrent des performances moindres. Toutefois, un paramètre crucial est le dosage correct de l'additif à faible viscosité, car un excès rend le liant et le mélange trop souples. L'énergie de malaxage est un autre facteur à considérer : en centrale, on utilise des malaxeurs à double arbre à haute énergie, alors qu'en laboratoire, les malaxeurs sont souvent de type "pâtissier", à arbre unique et à faible puissance, produisant des mélanges de qualité inférieure. Ceci est particulièrement critique avec un taux élevé de RAP, car le liant vieux doit être bien mélangé avec le faible taux de liant neuf et les additifs.

En conclusion, il est discutable d'affirmer que les propriétés à haute température et la résistance à la déformation permanente sont problématiques pour les WMA, bien que la stabilité Marshall soit également relativement faible. Le module de rigidité à -10 °C et 1 Hz montre une tendance similaire pour tous les mélanges : L-30 % RAP > L-60 % RAP > mélanges de terrain, à l'exception du HMA de terrain avec 50 % de RAP, qui est au même niveau que le L-WMA 30 %. Les courbes maîtresses révèlent que les écarts de rigidité sont plus importants à haute température, et que le classement à basse et haute température peut être différent. Les performances à basse température des WMA sont généralement équivalentes, voire meilleures que celles des HMA, avec des températures de rupture comprises entre –33 et –38 °C. Dans les mélanges de terrain, le HMA a une température de rupture plus élevée que les WMA avec additifs, mais similaire à celle du WMA à mousse de bitume. Aucune conclusion définitive ne peut être tirée de la littérature quant à l'influence des additifs WMA sur la fissuration à basse température lorsque le RAP est inférieur à 40 % (Guo et al., 2020). Certaines études rapportent une performance égale ou meilleure, d'autres le contraire. Au-delà de 40 %, une dégradation de la résistance à la fissuration est souvent constatée.

Globalement, dans cette étude, tous les mélanges WMA se comportent de manière très similaire à l'HMA. Aucun procédé WMA ne se démarque nettement. Des différences ont toutefois été observées, notamment entre les additifs Chem1 et Chem2 : dans certains essais, Chem1 donne de meilleurs résultats, dans d'autres, c'est l'inverse. En ce qui concerne l'asphalte mousse, les résultats disponibles (issus uniquement des essais terrain avec 60 % de RAP) sont globalement comparables aux autres WMA.

Conclusions et recommandations

Les conclusions principales de cette recherche sont claires. Tous les mélanges d'asphalte tiède (WMA) ont présenté des performances très proches de celles du mélange de référence à chaud (HMA). Des différences mineures apparaissent dans les résultats de certains essais, mais elles ne sont généralement pas cohérentes. Les conclusions suivantes peuvent être tirées sur la base des résultats spécifiques du projet:

- Aucun procédé WMA ne s'est révélé supérieur aux autres. Toutefois, la sélection des additifs reposant sur l'expérience préalable, il n'est pas garanti que tous les additifs du marché conviennent.
- Dans certains essais, les mélanges à 60 % de RAP montrent un comportement plus rigide (point de ramollissement anneau et bille), tandis que dans d'autres, c'est l'inverse (module à -10 °C, point de rupture Fraass), et parfois les résultats sont aléatoires (stabilité Marshall, température de rupture TSRST). Néanmoins, la rigidité ne peut pas être attribuée uniquement au taux de RAP, car elle dépend aussi du type de liant utilisé.
- Il est surprenant que les mélanges avec 30 % de RAP et bitume 70/100 présentent des performances similaires à ceux avec 60 % de RAP et un bitume très tendre (330/400), alors qu'aucun ajustement fin des liants commerciaux n'a été effectué.
- Les résultats d'orniérage sont peu concluants et devraient être complétés par des essais supplémentaires pour mieux caractériser le comportement à haute température. Un suivi particulier de la déformation permanente sur les sections d'essai est recommandé dans les prochaines années.

- Les mélanges HMA, qu'ils soient produits en laboratoire ou sur le terrain, montrent une stabilité Marshall élevée, confirmant leurs bonnes performances, même avec 60 % de RAP.
- La maniabilité et la compactabilité des WMA ne sont pas affectées négativement par les températures réduites de production et de compactage.
- Le comportement à long terme des WMA n'a pas été étudié ici, mais devrait faire l'objet d'un projet de suivi. Une attention particulière devra être portée à l'orniérage, ainsi qu'à l'adhésion intercouche entre la couche de liaison et la couche de roulement. Une étude américaine a montré que les mélanges WMA démarrent avec une rigidité plus faible et vieillissent plus rapidement, mais leur rigidité finale et leur résistance à l'orniérage deviennent comparables à celles des HMA (NCHRP, 2015).
- Des taux de RAP élevés (jusqu'à 60 %) peuvent être intégrés avec succès dans les mélanges HMA et WMA sans compromettre significativement les performances mécaniques. Il serait pertinent d'étendre l'étude à d'autres types de mélanges et à des taux de RAP encore plus élevés.
- Les résultats de cette recherche suggèrent que les technologies WMA, notamment celles à base d'additifs chimiques comme Chem1 et Kombi, offrent une alternative durable prometteuse aux HMA, sans compromettre les performances mécaniques clés.

Zusammenfassung

Einleitung und Zielsetzung

Das Forschungsprojekt befasst sich mit der Optimierung von Warmasphalt (WMA – Warm Mix Asphalt) unter Einbindung von Recyclingasphalt (RAP – Reclaimed Asphalt Pavement), mit dem Ziel, umweltfreundliche Strassenbaumaterialien zu entwickeln, ohne dabei die strukturelle oder mechanische Leistungsfähigkeit zu beeinträchtigen. Der Einsatz von RAP reduziert den Bedarf an Primärrohstoffen wie Gesteinskörnungen und Bitumen und trägt zur Senkung der Emissionen während der Asphaltproduktion bei – eine zentrale Strategie zur Förderung ressourceneffizienter Infrastrukturen. Ziel des Projekts ist es, WMA-RAP-Mischungen zu bestimmen, die hinsichtlich mechanischer Eigenschaften und Dauerhaftigkeit mit konventionellen Heissmischasphalten (HMA – Hot Mix Asphalt) vergleichbar oder ihnen sogar überlegen sind. Zu den spezifischen Zielen gehören die Bewertung verschiedener WMA-Technologien (Additive), die Leistungsbewertung von im Labor und in der Anlage produzierten WMA-RAP-Mischungen sowie die Ableitung von Empfehlungen zur Aktualisierung der Schweizer Asphaltmischgutnormen auf Grundlage der Untersuchungsergebnisse.

Forschungsmethodik

Die im Rahmen dieses Projekts angewandte Methodik war umfassend und strukturiert. Sie kombinierte umfangreiche Laboruntersuchungen mit der Validierung von in der Anlage produzierten Mischungen. Die Forschung war, wie in Abbildung 1 dargestellt, in fünf unterschiedliche Arbeitspakete (WPs) untergliedert wobei jedes Paket eine zentrale Phase der Studie bildet. WP1 beinhaltete eine umfassende Literaturrecherche und die Entwicklung von Hypothesen, in deren Rahmen globale und nationale Studien zu WMA und RAP analysiert wurden. WP2 konzentrierte sich auf die Auswahl geeigneter chemischer und organischer Additive durch Bindemittel- und Mastixprüfungen, um die Produkte zu identifizieren, die sich am besten für die WMA-Herstellung eignen. In WP3 wurden Laborprüfungen an Asphaltgütern mit unterschiedlichen RAP-Gehalten (30 % und 60 %) in Kombination mit verschiedenen WMA-Additiven durchgeführt, um deren mechanische und dauerhafte Eigenschaften zu bewerten. WP4 beinhaltete den Bau einer Versuchsstrecke mit Abschnitten aus WMA und HMA sowie die anschliessende vergleichende Laboruntersuchung. Im WP5 werden die Projektergebnisse ausgewertet und praxisorientierte Empfehlungen für die Schweizer Asphaltnormen gegeben. Für alle Untersuchungen wurde ein einheitliches Referenzmischgut, AC B 16 S, verwendet – mit Ausnahme der im Werk hergestellten Mischungen (d. h. 50 % RAP) – wobei alle Materialien von Schweizer Lieferanten bezogen wurden, um die Anwendbarkeit und Relevanz der Ergebnisse für den nationalen Strassenbau sicherzustellen.

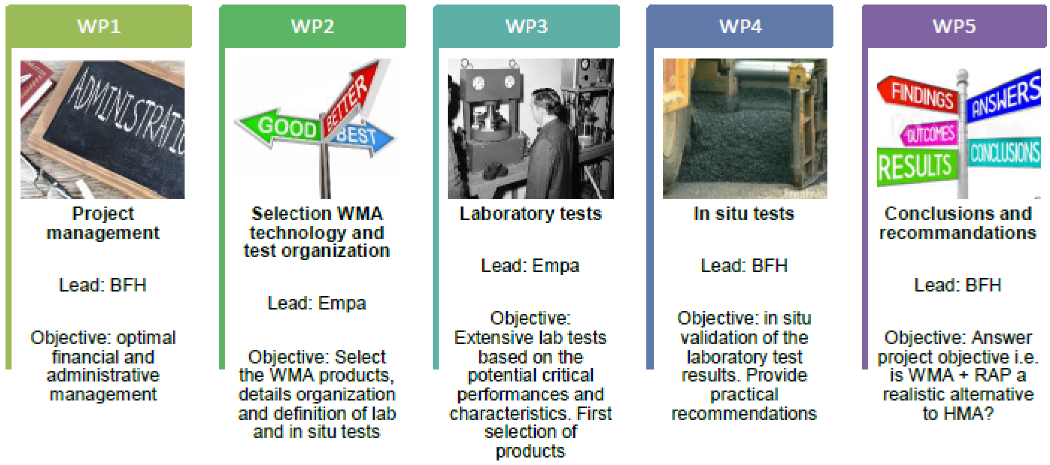


Abbildung 1: Projektübersicht (Abbildung 1 im Bericht)

Literaturübersicht und Stand der Technik

Warmasphalt-Technologien (WMA) sind weltweit für ihre Fähigkeit anerkannt, Produktions- und Einbautemperaturen im Vergleich zu herkömmlichem Heissmischasphalt (HMA) um 20–40 °C zu senken. Diese Reduktion bringt mehrere Vorteile mit sich, darunter geringere Treibhausgasemissionen, einen geringeren Energieverbrauch und verbesserte Arbeitsbedingungen. Frühere Untersuchungen weisen jedoch auch auf potenzielle Nachteile, wie eine reduzierte Feuchtigkeitsbeständigkeit und eine Anfälligkeit für Spurrinnenbildung, hin. Laut Literatur gibt es drei Hauptklassen von WMA-Technologien: das Schaumverfahren (z. B. Wassereinspritzung in Bitumen), chemische Zusätze (z. B. Tenside) und organische Zusätze (z. B. Wachse).

Das Projekt behandelt einige dieser Technologien und deren mögliche Synergien mit recyceltem Asphaltgranulat (RAP). Das PLANET-Projekt (Arn, 2017) in der Schweiz, das 2017 abgeschlossen wurde, deutete bereits auf die Effektivität von WMA hin, insbesondere bei der Zugabe von RAP.

Experimenteller Plan

Die verschiedenen Projektphasen sind in Abbildung 2 dargestellt. Nach einer Aktualisierung des Wissensstands und der Sichtung der repräsentativen Literatur wurde die Auswahl der WMA-Technologien für die Laboruntersuchungen anhand von Bitumen- und Mastix-Untersuchungen vorgenommen. Die Analyse der mechanischen Eigenschaften und der Performance wurde in eine Labor- und eine Felduntersuchung (in situ) unterteilt. Die Untersuchungen basierten auf potenziell kritischen Parametern, was zur endgültigen Auswahl der WMA-Produkte für den grossmassstäblichen Feldeinbau führte. Arbeitspaket 3 konzentrierte sich auf praktische Aspekte der Einbauweise der Warmmischasphalte sowie deren Verhalten hinsichtlich der Schichtenhaftung. In einem weiteren Schritt wurden die Mischgüter für den Feldeinbau aus dem Werk entnommen und im Labor untersucht. Die im Labor-und in-situ gewonnenen Ergebnisse dienten schliesslich zur Ableitung praktischer Empfehlungen.

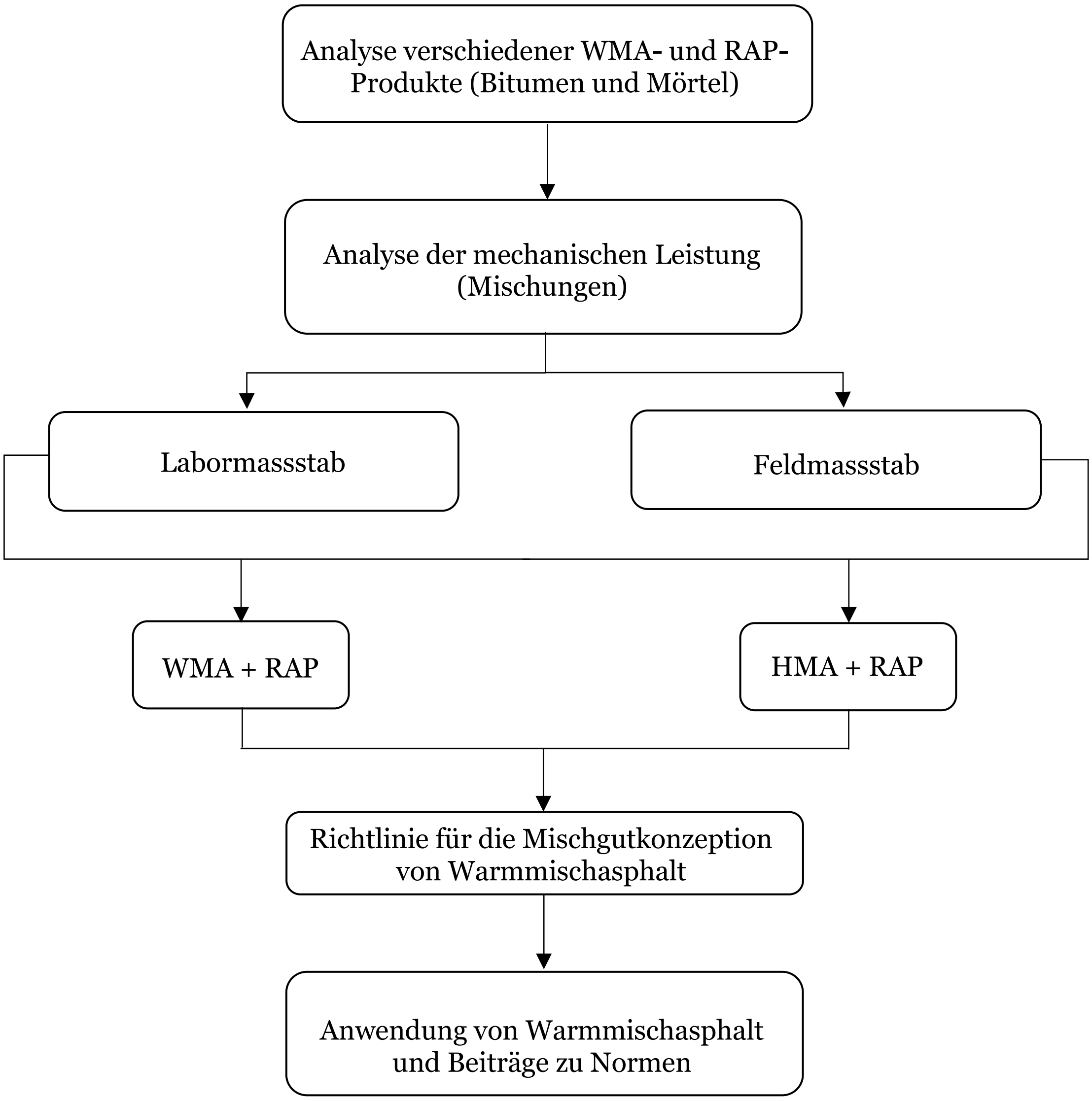


Abbildung 2: Details der Projektübersicht (Abbildung 2 im Bericht)

Materialauswahl und Mischgutdesign

Die Materialien, einschliesslich der Gesteinskörnungen und des recycelten Asphaltgranulats (RAP), wurden von der Weibel AG, einem Schweizer Hersteller, bezogen. Die Bindemittel umfassten ein Bitumen 70/100 für eine Zugabe von 30 % RAP und ein weicheres Bitumen 330/430 für eine Zugabe von 60 % RAP, um die Steifigkeit des gealterten Bindemittels auszugleichen.

Insgesamt wurden sieben WMA-Additive bewertet: vier chemische (Chem1 bis Chem4), ein organisches (Wachs) in Kombination mit dem chemischen Chem1 (genannt: Kombi) sowie ein Schaum (nur in situ verwendet). Die Auswahl der WMA-

Additive basierte auf Literaturauswertungen, bisherigen Erfahrungen und der kommerziellen Verfügbarkeit der Produkte in der Schweiz.

Von Anfang an (Projektantrag) und basierend auf Forschungsergebnissen (PLANET) (Arn, 2017) sowie praktischen Erfahrungen in der Schweiz wurde Folgendes entschieden (siehe auch Tabelle 1):

- Der Fokus lag auf chemischen Additiven, da eine grosse Vielfalt dieser Produkte existiert.
- Schaumverfahren sollten nur in situ berücksichtigt werden, während Zeolithe aufgrund früherer Erfahrungen vollständig ausgeschlossen wurden.
- Wachse wurden für WMA-Mischungen ausgeschlossen und nur im Bindemitteltest sowie in Kombination mit einem chemischen Zusatzstoff verwendet.
- Aufgrund der umfangreichen Laborprüfungen wurden schliesslich 2 chemische Additive aus 4 gängigen Produkten basierend auf den Ergebnissen von Bindemittel- und Mastixprüfungen ausgewählt. Als Wachs für das Kombi-Produkt (Wachs + chemischer Zusatzstoff) wurde das weltweit gebräuchlichste Produkt gewählt.

In einem ersten Schritt wurden 4 chemische Zusatzstoffe auf Bitumen- und Mastix-Ebene evaluiert (siehe Tabelle 1).

WMA-Zusatzstoffe (Additive)

Produkttyp	Produktcode	Beschreibung
Schaumtechnologie	Foam	Im Werk produzierter Schaumasphalt
Chemische Zusatzstoffe	Chem1	Tensid
	Chem2	Pflanzlich, naturbasiert
	Chem3	Tensid
	Chem4	Natürliches, öl-basiertes Additiv
Organischer Zusatzstoff	Wachs	FT Paraffinwachs
Kombination chemisch + organisch	Kombi	Chem1 + Wachs

Tabelle 1: Auswahl der WMA-Produkte (Tabelle 1 im Bericht)

Das Verhalten dieser Zusatzstoffe wurde zunächst auf Bitumen- und Mastix-Ebene mittels rheologischer Prüfungen, einschliesslich BTSV und DSR, untersucht, um so Steifigkeit und Temperaturempfindlichkeit bewerten zu können.

Tabelle 2 gibt einen Überblick über alle in diesem Projekt verwendeten Bindemittel- und Mastixmischungen und Mischgüter. Der Recyclinganteil wird jeweils ebenfalls angegeben (30 %, 50 % oder 60 %). In den Abbildungen sind die Mischungen aus dem Labor mit „L-“ und diejenigen aus dem Feld mit „F-“ bezeichnet.

Alle Labor-Mischungen wurden gemäss den Vorgaben der europäischen Norm EN 13108-1 hergestellt. Die Produktionstemperatur für Heissmischgut lag bei 160 °C, während Warmasphaltmischungen bei 130 °C produziert wurden. Die Mischgüter für die Teststrecke wurden im Werk hergestellt und es wurden Proben für die Laboruntersuchungen entnommen.

Mischungen und Blends				
Labor-Code	**Bitmen-mischung**	**Mastix-mischung**	**Labor-mischung**	**Feldmischung**
HMA 30%	X		X	
HMA 50%				X
HMA 60%	X	X	X	
WMA-Chem1 30%			X	
WMA-Chem1 60%	X	X	X	X
WMA-Chem2 30%			X	
WMA-Chem2 60%	X	X	X	
WMA-Chem3 60%	X	X		
WMA-Chem4 60%	X	X		
WMA-Wachs 60%	X	X		
WMA-Kombi 30%			X	
WMA-Kombi 60%		X	X	X
WMA-Schaum 60%				X

Tabelle 2: Übersicht der Blends und Mischungen mit unterschiedlichen Zusätzen und Recyclinganteilen (Tabelle 2 im Bericht)

Bitumen- und Mastixprüfungen

Bitumenprüfungen spielten eine zentrale Rolle bei der Bewertung der Wirksamkeit der ausgewählten WMA-Zusatzstoffe. Die rheologischen Eigenschaften wurden mit dem Dynamischen Shear Rheometer (DSR) und dem Bitumen-Typisierungs-Schnell-Verfahren (BTSV) beurteilt. Die Bitumen- und Mastixmischungen (Bitumen + Füller) umfassten Bitumen 70/100 und 330/430 sowie das aus dem RAP extrahierte Bitumen, kombiniert mit den Zusätzen Chem1, Chem2, Chem3, Chem4 und Kombi (Chem1 + Wachs). Die Untersuchung zeigte, dass chemische Zusätze nur einen minimalen Einfluss auf die Steifigkeit hatten, wohingegen wachsmodifizierte Bindemittel eine deutlich erhöhte Steifigkeit und höhere BTSV-Temperaturen aufwiesen. Hinsichtlich des Verhaltens bei niedrigen Temperaturen wurden keine signifikanten Unterschiede zwischen den Fraass-Prüfergebnissen der HMA- und der WMA-Mischungen festgestellt.

Mastixmischungen, die die Füller-Bitumen-Matrix simulieren, wurden geprüft, um die Interaktion des Bitumens mit den mineralischen Bestandteilen zu bewerten. Die Zugabe von mineralischem Füller erhöhte die Steifigkeit deutlich. Interessanterweise blieb die Reihenfolge der Mastixmischungen hinsichtlich der BTSV-Temperatur und des Phasenwinkels unverändert, mit Ausnahme von Chem3, was sich durch eine gleichmässige parallele Verschiebung der BTSV-Ergebnisse vom Bitumen zu dem Mastix zeigte (Abbildung 3). Dies wurde als minimale Wechselwirkung zwischen dem Bindemittel (einschliesslich des WMA-Zusatzstoffs) und der mineralischen Matrix interpretiert. In diesem Fall lieferten die Mastixuntersuchungen nur minimale zusätzliche Informationen.

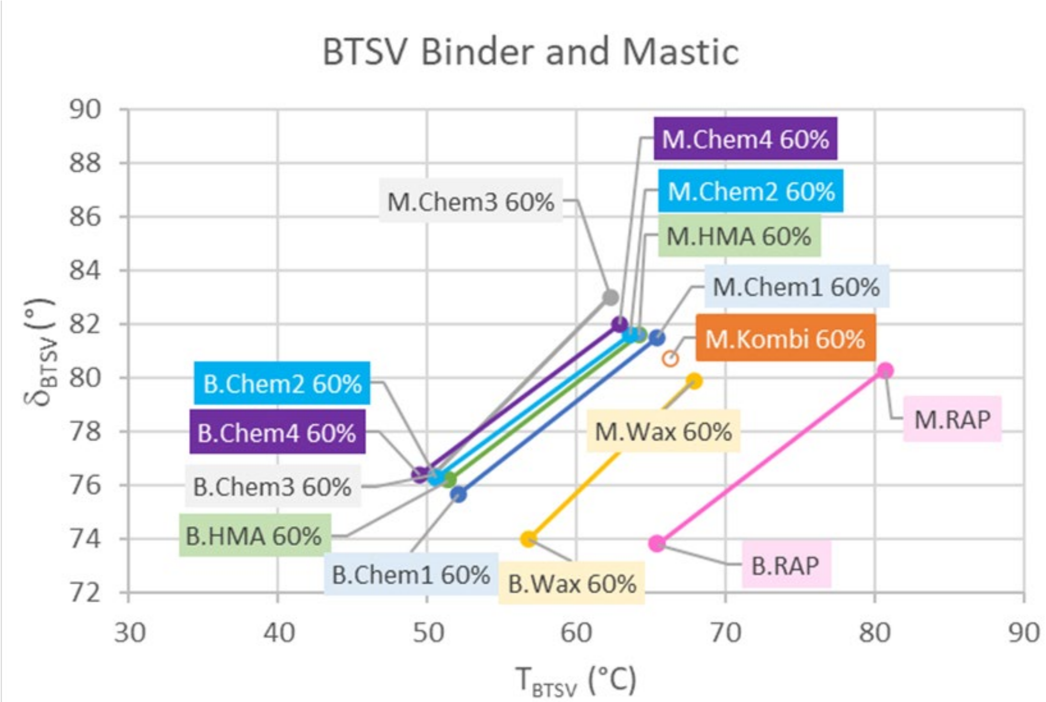


Abbildung 3: Vergleich der BTSV-Ergebnisse von Bitumen- (B.xxx) und Mastixmischungens (M.xxx) (Abbildung 15 im Bericht)

Teststrecke

Die Mischungen für die Teststrecke wurde basierend auf den Ergebnissen der Mischungsanalyse (WP-3) ausgewählt. Für die im Forschungsprojekt wesentliche Binderschicht wurde neben der Referenz (HMA), ein Abschnitt mit WMA-Chem1, ein Abschnitt mit WMA-Kombi (Wachs + Chem1) sowie ein Abschnitt mit WMA-Schaum erstellt. Alle Abschnitte mit Ausnahme des HMA, welcher nur 50 % RAP enthielt (abweichend vom ursprünglichen Plan) enthielten eine RAP-Anteil von 60 %. Die Binderschichten wurden auf eine Tragschicht aus WMA AC T 22 S der Dicke 80 mm (Bitumen 50/70) aufgebracht. Die Tragschicht lag selbst auf einer Fundationsschicht AC F 32 der Dicke von 140 mm.

Abbildung 4 zeigt die schematische Darstellung der Teststrecke, während Tabelle 3 weitere Details liefert.

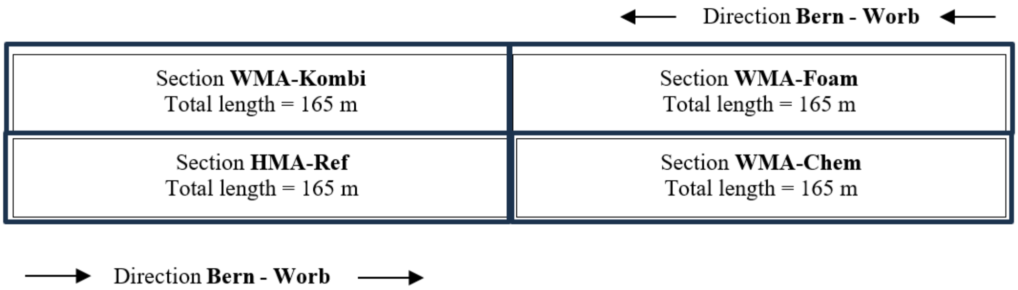


Abbildung 4: Schematische Darstellung der Teststrecke

Details der Teststrecke

Prüfabschnitt	Fahrtrichtung	Einbau-Datum	Material		Typ
			Trag-schicht	Binder-schicht	
1	Bern-Worb	03/02/2024	WMA ACT22S	WMA ACB16S	WMA-Kombi
2	Worb-Bern	04/06/2024	WMA ACT22S	WMA ACB16S	WMA-Foam
3	Bern-Worb	09/07/2024	WMA ACT22S	WMA ACB16S	HMA-Ref
1	Worb-Bern	28/08/2024	WMA ACT22S	WMA ACB16S	WMA-Chem

Tabelle 3: Details derTeststrecke (Tabelle 10 im Bericht)

Ergebnisse

Im Folgenden werden die Ergebnisse an den Labor- und Feldmischungen im Vergleich dargestellt.

Hohlraumgehalt (Marshall)

Abbildung 5 zeigt den Hohlraumgehalt (%) der Labor- und Feldmischungen. Der Hohlraumgehalt variiert zwischen 3,2 % und 5,2 %. Unter den Proben weist L-WMA-Kombi 30 % den höchsten Hohlraumgehalt von über 5,0 % auf, gefolgt von L-WMA-Kombi 60 %. Die niedrigsten Hohlraumgehalte wurden bei L-HMA 30 % und F-HMA 50 % gemessen, beide liegen knapp über 3,0 %. Die Zugabe von WMA-Zusätzen, insbesondere chemische und schaumgebundenen Additive, scheinen den Hohlraumgehalt zu beeinflussen, wobei einige WMA-Mischungen eine erhöhte Porosität gegenüber HMA zeigen. Diese Ergebnisse deuten darauf hin, dass die Wahl der WMA-Technologie und des Recyclinganteils die volumetrischen Eigenschaften der Asphaltmischungen beeinflussen kann, was Auswirkungen auf die Verdichtungseigenschaften und das Langzeitverhalten haben könnte. Insgesamt waren die Unterschiede im Hohlraumgehalt zwischen Labor- und Feldmischungen nicht signifikant.

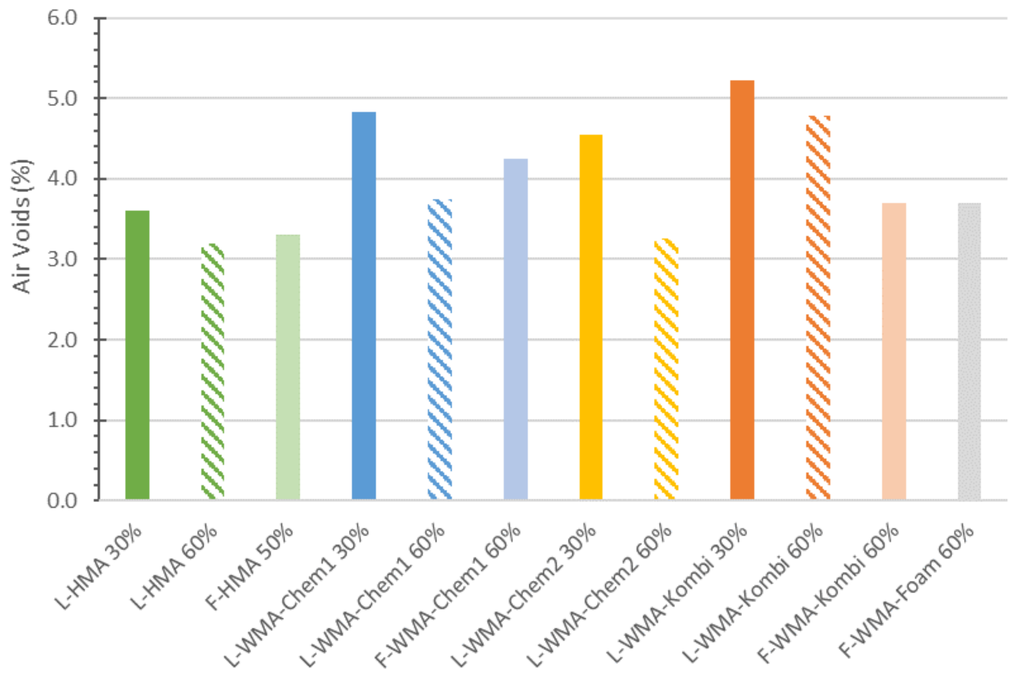


Abbildung 5: Marshall-Hohlraumgehalt (Labor- vs. Feldmischungen) (Abbildung 46 im Bericht)

Verdichtbarkeit

Abbildung 6 zeigt den Vergleich zwischen Labor- und Feldmischungen, wobei alle Proben unter identischen Laborbedingungen verdichtet wurden, um den Einfluss des Produktionsverfahrens auf die Verdichtbarkeit (K) und den Anfangsluftporengehalt V(1) auszuschliessen. Die auf der Anlage produzierten Mischungen (Feldmischungen) zeigten generell niedrigere Hohlraumgehalte als die im Labor hergestellten, was darauf hindeutet, dass das Produktionsverfahren die Verdichtbarkeit und das Verdichtungsverhalten beeinflussen kann. L-WMA-Kombi 60 % weist die beste Verdichtbarkeit aller Mischungen auf. Alle Feldmischungen zeigen ähnliche Verdichtbarkeitswerte, mit Ausnahme von F-WMA-Chem1 60 %, das recht geringe Werte aufweist. Die Labor-Mischungen zeigen insgesamt höhere K-Werte als die Feldmischungen.

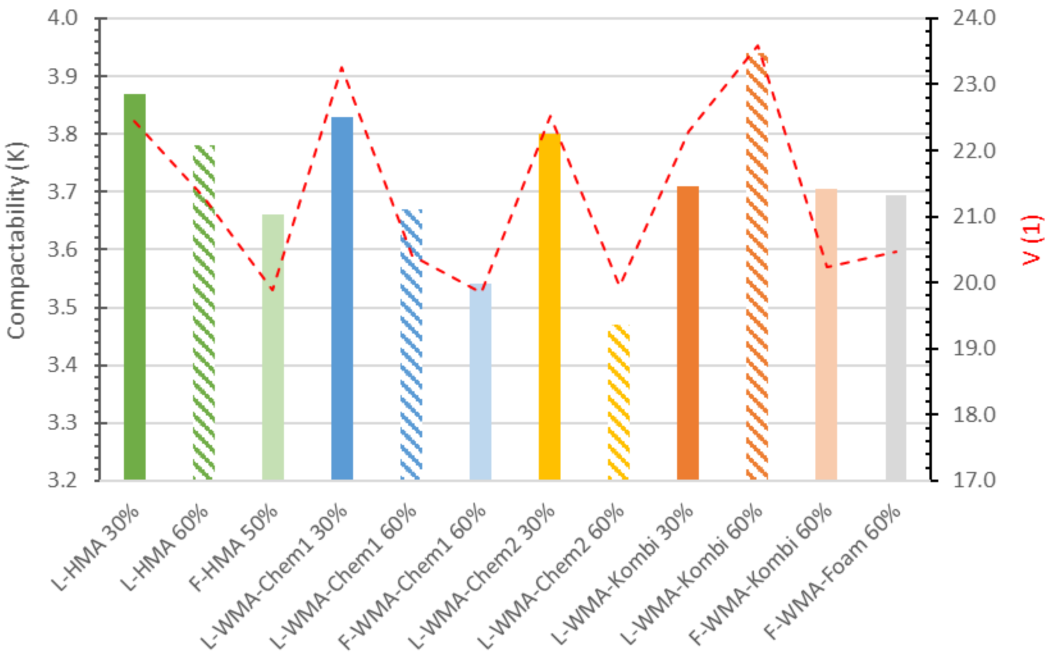


Abbildung 6: Verdichtbarkeit der Mischungen (K) und Hohlraumgehalt V(1) (Labor- vs. Feldmischungen) (Abbildung 50 im Bericht)

Verhältnis der Indirekten Zugfestigkeiten (ITSR)

Abbildung 7 zeigt das Verhältnis der Indirekten Zugfestigkeiten (ITSR) als Indikator für die Wasserempfindlichkeit. ITSR ist das Verhältnis der indirekten Zugfestigkeit im nassen Zustand zur Zugfestigkeit im trockenen Zustand und gibt an, wie gut ein Mischgut potentiellen Feuchtigkeitsschäden widerstehen kann. Ein hoher ITSR-Wert (nahe 100 %) bedeutet eine geringere Wasserempfindlichkeit. ITSR-Werte unter 80 % weisen dagegen auf eine potenziell hohe Wasserempfindlichkeit hin. Einige Mischungen überschreiten 90 % und weisen somit einen geringe Wasserempfindlichkeitswert auf. Andere zeigen etwas niedrigere ITSR-Werte, wobei alle Werte über dem Grenzwert der Schweizer Norm von 80% liegen. Feldmischungen (F-WMA) zeigen tendenziell höhere ITSR-Werte als die meisten Labormischungen, was auf reale Verdichtungs- und Kurzzeitalterungseffekte zurückzuführen sein könnte. Der RAP-Anteil scheint ebenfalls einen Einfluss auf das Verhältnis der indirekten Zugfestigkeit ITSR zu haben, wobei ein höherer RAP-Anteil (50 % bis 60 %) zu höheren, aber auch niedrigeren Werten führen kann.

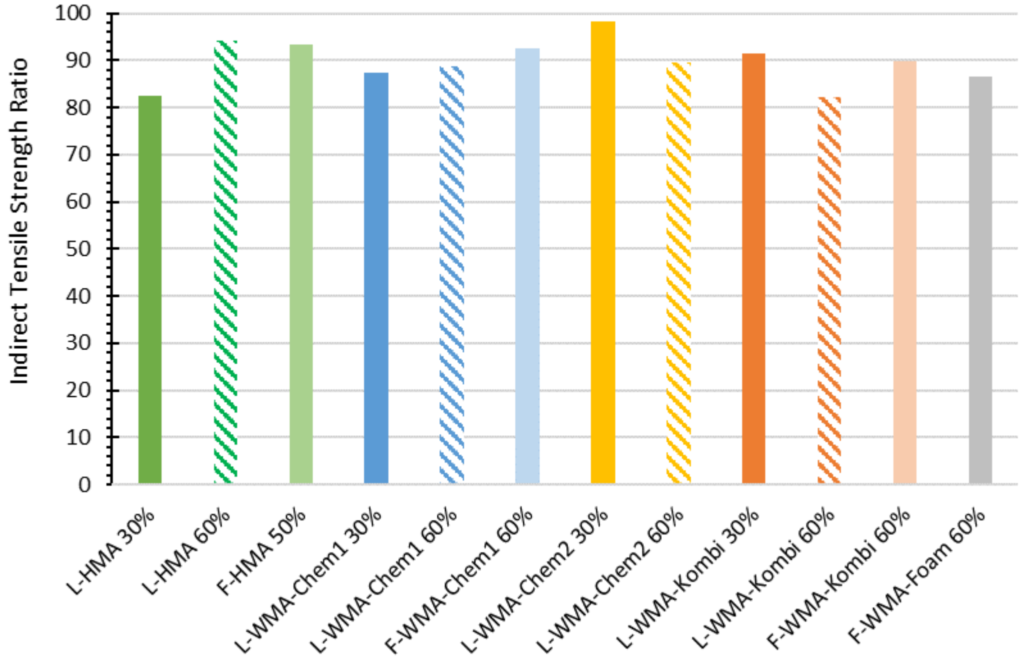


Abbildung 7: Verhältnis der Indirekten Zugfestigkeiten (Labor- vs. Feldmischungen) (Abbildung 53 im Bericht)

Spurbildungsprüfung

Abbildung 8 zeigt die Ergebnisse der Spurbildungsprüfung nach 30.000 Zyklen für alle Labor- und Feldmischungen. Alle Feldmischungen, mit Ausnahme von F-WMA-Schaum 60 %, konnten mit der angestrebten Anzahl von 30.000 Zyklen getestet werden, während nur vier Labormischungen diese Anzahl von Zyklen erreichten. Bei den anderen Labormischungen überschritt die Spurtiefe bereits vor Erreichen dieser Anzahl an Zyklen (bereits nach 3000 oder 10000 Zyklen) die Messgrenze des Prüfgeräts.

Nur L-WMA-Kombi 60 % mit einer Spurtiefe von 8,2 % erfüllt die Anforderungen der Schweizer Norm von maximal 10 %. Die einzige HMA-Mischung, die 30.000 Zyklen erreichte, war L-HMA 30 %, die mit einer Spurtiefe von 12,8 % aber die Normanforderung nicht erfüllte. Alle Feldmischungen ausser WMA-Schaum erfüllen die Anforderungen der Schweizer Norm (≤ 10 %). Für die Feldmischung F-WMA-Schaum 60 % wurde bereits nach 3.000 Zyklen eine Spurtiefe von 9,3 % gemessen.

Der Vergleich zwischen Feld- und Labor-Mischungen zeigt eindeutig für die Feldmischungen eine bessere Beständigkeit gegen bleibende Verformung. Die Ursache hierfür konnte nicht geklärt werden, insbesondere da der Hohlraumgehalt aller Labor-Mischungen nahe dem angestrebten Wert von 4,5 Vol.-% lag.

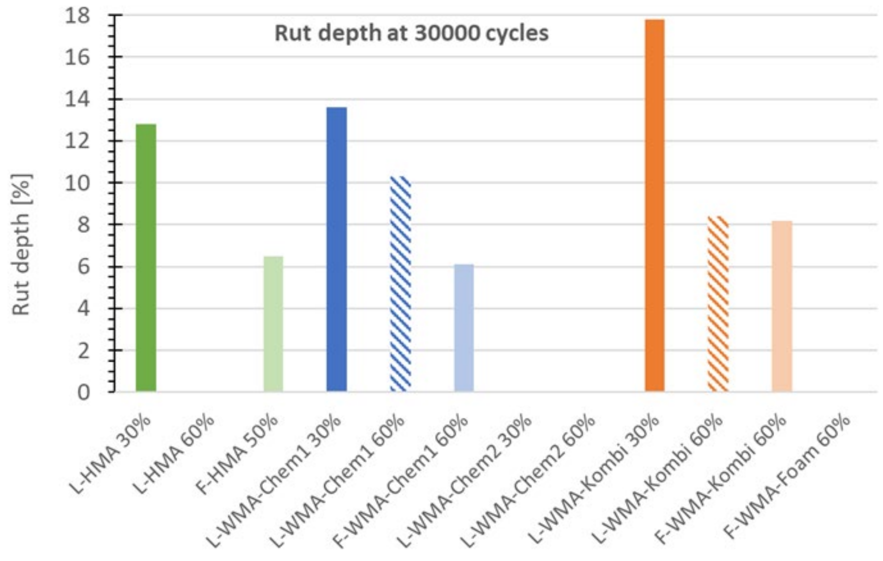


Abbildung 8: Spurrinnentiefe der Labor- und Feldmischungen nach 30.000 Zyklen (Abbildung 55 im Bericht)

Halbzylinder-Biegeversuch (SCB)

Die Versuchsergebnisse des Halbzylinder-Biegeversuchs (SCB) der Labor- und Feldmischungen sind in Abbildung 9 dargestellt. Die Labor-Mischungen L-HMA 30 % und L-HMA 60 % besitzen eine hohe Bruchzähigkeit. L-WMA-Chem 1 (30 % RAP) und (60 % RAP) weisen eine etwas geringere Bruchzähigkeit auf, was auf eine negative Auswirkung des Additives Chem1 hindeutet. L-WMA-Chem2 und L-WMA-Kombi dagegen zeigen die höchsten Bruchzähigkeitswerte, was auf die Eignung dieser Zusatzstoffe hinweist. Die Feldmischung F-HMA 50 % besitzt ebenfalls eine hohe Bruchzähigkeit. F-WMA-Kombi 60 % hat sogar einen der höchsten Zähigkeitswerte, was bestätigt, dass die Kombination aus Wachs und Chem1 die Bruchzähigkeit selbst unter Feldbedingungen verbessert. F-WMA-Schaum 60 % und F-WMA-Chem1 60 % weisen eine mittlere Bruchzähigkeit auf, was darauf die Feststellung bestätigt, dass verschiedene chemische Zusatzstoffe unterschiedliche Wirksamkeit haben.

Ein höherer RAP-Anteil (60 %) wirkt sich nicht immer negativ auf die Bruchzähigkeit aus: einige WMA-Mischungen (z.B. Kombi und Chem2) weisen mit einem erhöhten RAP-Anteil sogar höhere Werte als mit einem Anteil von 30% auf. F-WMA-Chem1 zeigt mit 60%-RAP eine deutliche Abnahme der Bruchzähigkeit, was darauf hindeuten könnte, dass Chem1 eine RAP-Beimischung möglicherweise nicht so effektiv funktioniert. Die Feldmischungen F-HMA 50 % zeigen dagegen eine hohe Bruchzähigkeit, was bestätigt, dass die Beimengung von RAP für HMA keine Probleme bereitet. Insgesamt zeigen HMA- und WMA-Laborproben im Allgemeinen eine etwas höhere Bruchzähigkeit als die im Feld hergestellten WMA-Mischungen, was auf die kontrollierten Herstellungsbedingungen im Labor zurückzuführen sein könnte.

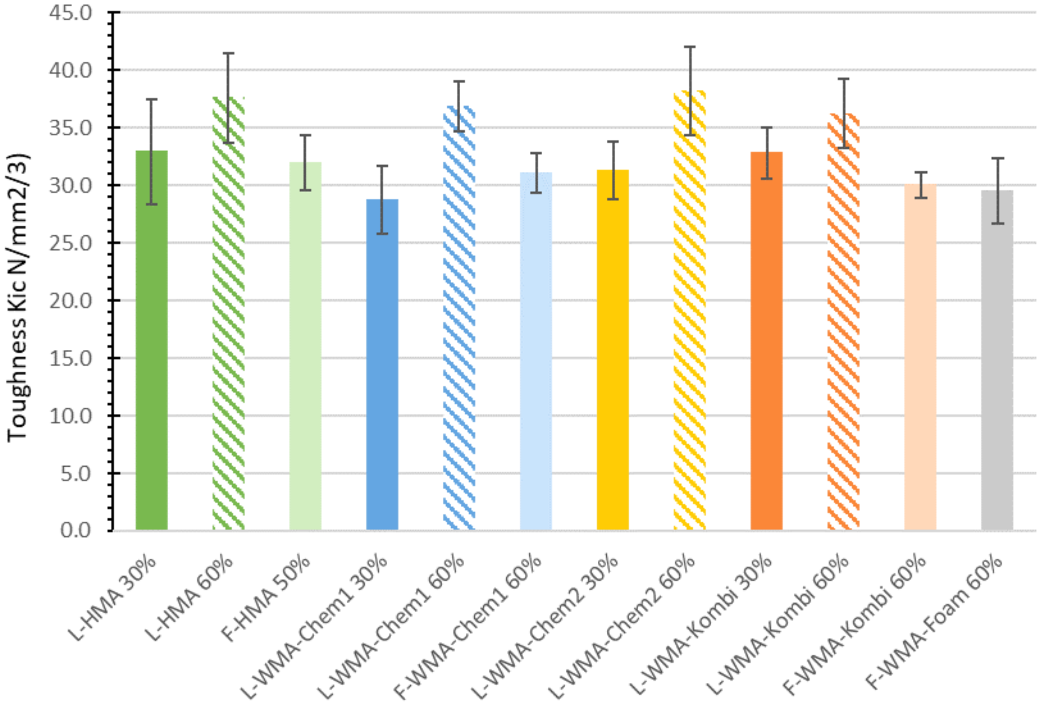


Abbildung 9: SCB-Versuchsergebnisse von Labor- und Feldmischungen (Labor vs. Feldmischungen) (Abbildung 51 des Berichts)

Abkühlversuch TRST

Abbildung 10 zeigt die Ausfall-Temperaturen der Feldmischungen im Vergleich mit den Labormischungen. F-Chem1 und F-Kombi weisen eine etwas niedrigere Ausfall-Temperatur als die Labormischungen auf, beim Heissasphalt-Referenzmischgut ist es jedoch umgekehrt, hier besitzt das Feldmischgut die höchste Ausfall-Temperatur. Die Ausfall-Temperatur des Schaumasphalts (-34 °C) ist höher als die der Mischungen mit chemischen Zusatzstoffen, aber ähnlich zur Heissasphalt-Referenz im Feld. Zusammenfassend zeigten die Feldmischungen mit chemischen Zusatzstoffen eine etwas bessere oder gleichwertige Kältebeständigkeit im Vergleich zur HMA-Feldmischung, wobei alle Ausfall-Temperaturen unter -32 °C lagen und die Ergebnisse aller untersuchten Mischgüter als gut bezeichnet werden können.

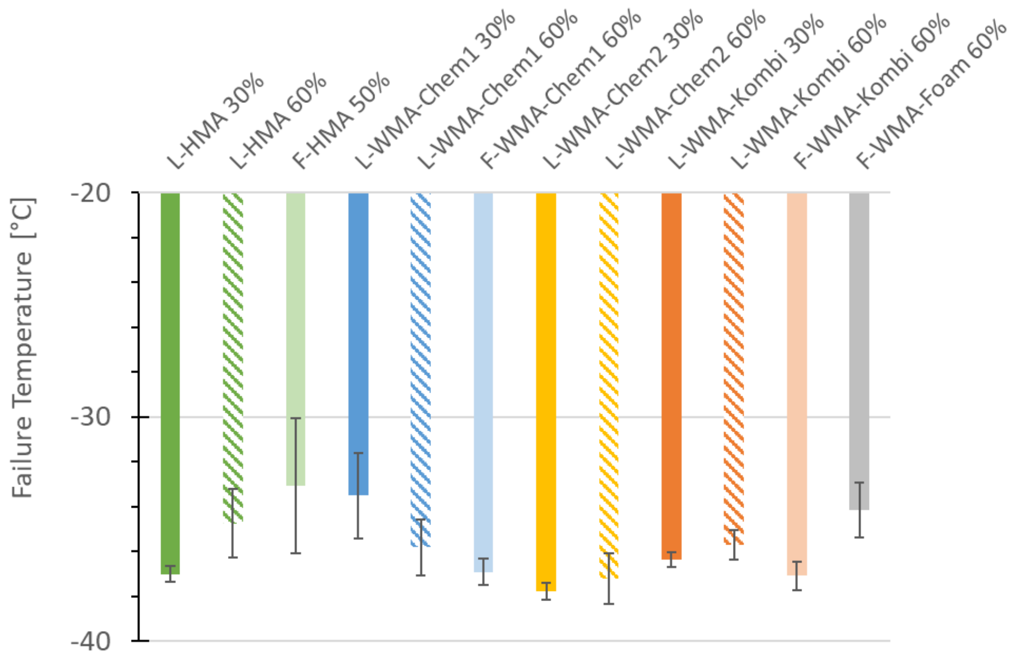


Abbildung 10: TSRST-Ausfall-Temperatur (Abbildung 62 des Berichts)

Schichthaftung der aus der Teststrecke entnommenen Bohrkerne

Die Ergebnisse des Schichtenverbundprüfung nach Leutner zwischen Binder- und Tragschicht (innerhalb und ausserhalb der Fahrspur) sind in Abbildung 11 dargestellt. Die Ergebnisse zeigen sehr hohe Scherkräfte, die deutlich über dem von der Schweizer Norm zwischen Binder- und Tragschicht vorgeschriebenen Wert von 12 kN liegen. F-HMA-50 % zeigt die höchsten Werte von über 30 kN, während F-Chem1-60 % Werte um etwa 26 kN aufweist. Aufgrund der Messgenauigkeit und der Tatsache, dass nur ein Bohrkern geprüft wurde, konnten keine Unterschiede zwischen den Werten innerhalb und ausserhalb der Fahrspur festgestellt werden. Nur bei F-Foam-60 % scheint es durch Verkehr und Verfestigung (Curing) zu einer Erhöhung der Haftfestigkeit in der Fahrspur zu kommen (mit einem Wert vergleichbar mit F-HMA-50 %).

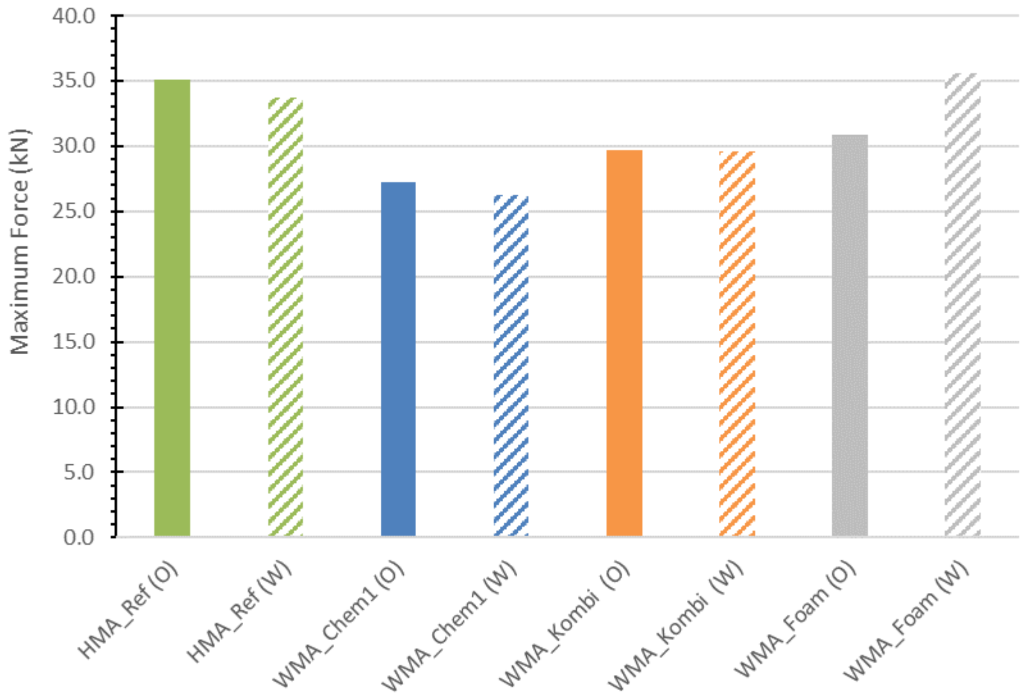


Abbildung 11: Leutner-Test-Ergebnisse von entnommenen Feldkernen (Schichthaftung) (Abbildung 64 des Berichts)

Diskussion

Die Auswahl des WMA-Zusatzstoffs gemäss dem Projektvorschlag basierte hauptsächlich auf früheren Erfahrungen und der Verwendung in der Schweiz gebräuchlichen Produkte. Daher lag der Fokus auf chemischen Zusatzstoffen, während Zeolithe ausgeschlossen wurden und der Einsatz von Wachsen nur in Kombination mit chemischen Zusatzstoffen vorgesehen war.

Unter Berücksichtigung des erheblichen Prüfumfangs wurden für die Laboruntersuchungen 2 chemischen Zusatzstoffe aus 4 gebräuchlichen Produkten basierend auf ersten Bitumen- und Mastixprüfungen bestimmt, während für das Wachs im Kombi-Produkt (Wachs + chemischer Zusatzstoff) das weltweit gebräuchliche Produkt ausgewählt wurde. Da die Bewertung von Bitumen und Mastix keine eindeutigen Unterschiede zwischen den 4 chemischen Zusatzstoffen ergab, wurde der zweite Zusatzstoff anhand des Brechpunktes nach Fraass ausgewählt.

Die Zugabe von WMA-Zusatzstoffen führte zu einem höheren Hohlraumgehalt (Marshall) im Vergleich zu HMA. Die Ergebnisse der Marshall-Stabilität (mit Ausnahme von L-Chem2 30 %) zeigten, dass selbst mit hohem RAP-Gehalt von 60 % und insbesondere in situ WMA vergleichbare Festigkeiten wie HMA erreicht werden.

Hinsichtlich der Verarbeitbarkeit ergab sich, dass ein höherer RAP-Gehalt im Allgemeinen - ausser im Fall von L-Chem2 60 % - sich nicht nachteilig auf diese auswirkt. Feldmischungen zeigten eine geringere Verarbeitbarkeit für F-Chem1 bei 60 % RAP im Vergleich zu HMA.

Bei der Verdichtbarkeit zeigte sich ein klarer Trend: Labor-Mischungen mit 30 % RAP zeigten dabei eine bessere Verdichtbarkeit als Mischungen mit 60 % RAP. Labor-Mischungen zeigen allgemein höhere Verdichtbarkeitswerte (K-Werte) als vergleichbare Feldmischungen. Bei den Feldmischungen gab es keinen signifikanten Unterschied in der Verdichtbarkeit zwischen WMA- und HMA-Mischungen. Die Mischung mit Chem1 zeigte jedoch eine leicht geringere Verdichtbarkeit. Insgesamt war aber im Rahmen des Projekts der Einfluss von WMA-Zusätzen auf die Verdichtbarkeit nicht unterschiedlich und nicht eindeutig nachweisbar.

Wie bei HMA ergaben sich für die indirekte Zugfestigkeit (ITS) von WMA im trockenen Zustand höhere Werte als im nassen Zustand, wobei HMA (RAP 30 %) im trockenen Zustand die höchsten Werte aufwies, während L-WMA- und F-WMA tendenziell leicht niedrigere ITS-Werte zeigen.

Für alle Labor- und Feldmischungen lag das Verhältnis der indirekten Zugfestigkeit über dem Grenzwert der Schweizer Norm von 80%. Dies deutet darauf hin, dass niedrigere Produktionstemperaturen in Kombination mit Additiven oder Schaumbitumen die Wasserempfindlichkeit selbst bei einem hohem RAP-Anteil nicht negativ beeinflussen. Feldmischungen (F-WMA) zeigen tendenziell höhere ITSR-Werte als die meisten Labormischungen, was auf reale Verdichtungs- und Kurzzeitalterungseffekte zurückzuführen sein könnte.

In der Literatur präsentiert sich der Einfluss von WMA-Zusatzstoffen auf die Wasserempfindlichkeit jedoch nicht einheitlich, d.h. abhängig von der Prüfmethode und dem Hohlraumgehalt der Mischung. Besonders offenporige Mischungen mit Zusätzen auf Wachs-, Zeolith- oder Schaumbitumenbasis zeigen ein schlechtes Verhalten (Guo et al., 2020). Für WMA mit chemischen Zusatzstoffen wurde im Vergleich zu HMA kein nachteiliger Effekt festgestellt, vermutlich weil diese Zusatzstoffe chemisch oft konventionellen Anti-Stripping-Mitteln ähneln (Oliveira et al., 2012). Die Zugabe von RAP führte laut Literatur ebenfalls zu widersprüchlichen Ergebnissen.

Halbzylinder-Biegeversuche (SCB) zeigen, dass es keinen signifikanten Unterschied zwischen HMA und WMA gibt. Überraschenderweise hatte ein höherer RAP-Gehalt von 60 % im Allgemeinen einen positiven Einfluss auf die Bruchzähigkeit, während zwischen Feld- und Labor-Mischungen kein Unterschied festgestellt wurde.

Die Spurrinnentiefe war für alle Labor-Mischungen, unabhängig vom Typ des WMA-Verfahrens und vom RAP-Anteil, unerwartet hoch. Dies selbst im Fall des HMA, was sehr ungewöhnlich ist. Dagegen ergaben sich für die Feldmischungen mit Ausnahme von F-Schaum Spurrinnentiefen, die unter dem von der Schweizer Norm geforderten Wert von >10% nach 30'000 Zyklen lagen. Allerdings wurde in der Literatur ebenfalls bei hohem RAP-Gehalt eine reduzierte Widerstandsfähigkeit gegen bleibende Verformung beschrieben (Guo et al., 2020). Allgemein verbesserten wachsbasierte WMA-Zusätze das Spurrinnenverhalten, während Schaumasphalt eine reduzierte Widerstandsfähigkeit gegen bleibende Verformung zeigte. Entscheidend gemäss der Literatur die korrekte Dosierung des niedrigviskosen Zusatzstoffs, da dieser das Bindemittel und die Mischung beeinträchtigt, wenn die Zugabemenge zu hoch ist.

Auch die Mischenergie wird als ein wichtiger Faktor angesehen. In Asphaltwerken werden schnelle, hochenergetische Doppelschneckenmischer eingesetzt, während Labore meist mit langsameren "Küchenmaschinentyp"-Einzelschneckenmischern arbeiten, die nicht die gleiche Mischqualität erzeugen können. Dies ist besonders wichtig bei hohem RAP-Anteil, wenn das alte RAP-Bindemittel mit einem geringen Anteil an Frischbindemittel und Zusatzstoffen vermischt werden muss.

Vor diesem Hintergrund ist es fraglich, ob die Hochtemperatureigenschaften und die bleibende Verformung bei WMA als problematisch zu betrachten sind; wobei allerdings für die Marshall-Stabilität ebenfalls eher niedrige Werte festgestellt wurden. Der Steifigkeitsmodul bei -10 °C und 1 Hz zeigt für alle Mischungen einen ähnlichen Trend: L-30 % RAP > L-60 % RAP > Feldmischungen. Die einzige Ausnahme ist die Feldmischung F-HMA mit 50 % RAP, die auf dem gleichen Niveau wie die entsprechende Labormischung L -WMA -30 % liegt. Es gibt Unterschiede zwischen HMA und WMA, jedoch ohne klaren Trend. Die Masterkurven zeigen, dass die Unterschiede im Steifigkeitsmodul bei hohen Temperaturen grösser sind und dass die Rangfolge der Mischungen bei hohen und niedrigen Temperaturen variieren kann.

Die Kälte-Eigenschaften (Ausfall-Temperatur) von WMA mit sehr guten Werten im Bereich von -33 bis -38 °C sind in den meisten Fällen äquivalent zu denen von HMA und in einigen Fällen sogar besser. Betrachtet man die Feldmischungen, so besitzt HMA eine höhere Ausfall-Temperatur als die WMA-Mischungen, aber eine ähnliche wie die Schaumasphaltmischung.

In der Literatur gibt es keine einheitliche Schlussfolgerung zum Effekt von WMA-Zusätzen auf die Kälterissbeständigkeit von WMA-RAP, wenn der RAP-Gehalt unter 40 % lag (Guo et al., 2020). Einige Studien beobachteten ein besseres oder vergleichbares Rissbildungsverhalten von WMA im Vergleich zu HMA mit RAP, andere das Gegenteil. Bei mehr als 40 % RAP scheint gemäss den Angaben in der Literatur jedoch die Rissbeständigkeit ab.

Insgesamt schneiden in diesem Forschungsprojekt alle WMA-Mischungen sehr ähnlich ab wie die HMA-Mischungen. Keiner der untersuchten WMA-Prozesse, erwies sich als signifikant besser. Allerdings wurden einige Unterschiede beobachtet, z.B. zwischen den Zusatzstoffen Chem1 und Chem2: In einem Test zeigte Chem1 bessere Ergebnisse, in einem anderen war das Gegenteil der Fall. Für Schaumasphalt lagen zwar nur die Ergebnisse aus den Feldversuchen mit 60 % RAP-Anteil vor, doch waren diese grösstenteils mit denen der anderen WMA-Mischungen vergleichbar.

Schlussfolgerungen und Empfehlungen

Die wesentliche Schlussfolgerung dieser Forschung ist eindeutig: Alle Warmasphaltmischungen zeigten ähnliche Ergebnisse wie der Referenz-Heissasphalt. Zwar gibt es kleinere Unterschiede in den Testergebnissen, diese sind jedoch meist nicht konsistent. Die folgenden Schlussfolgerungen basieren auf den projektspezifischen Ergebnissen und Analysen:

- Es gab keinen WMA-Prozess, der den anderen überlegen war. Da die Auswahl der Zusatzstoffe jedoch auf früheren Erfahrungen beruhte, ist nicht garantiert, dass alle auf dem Markt erhältlichen WMA-Zusätze geeignet sind.
- In einigen Prüfungen zeigen die 60 % RAP-Mischungen ein steiferes Verhalten (Erweichungspunkt Ring und Kugel), in anderen ist das Gegenteil der Fall (Steifigkeitsmodul bei -10 °C, Brechpunkt nach Fraass). Manchmal scheinen die Ergebnisse auch zufällig zu sein (Marshall-Stabilität, TSRST-Versagens-Temperatur). Dennoch kann der Unterschied in der Steifigkeit nicht auf den höheren RAP-Gehalt zurückgeführt werden, da die Steifigkeit durch die Art des zugesetzten Bindemittels angepasst wird.
- Es ist überraschend, dass Mischungen mit 30 % RAP und Bitumen 70/100 ein ähnliches Verhalten zeigen wie solche mit 60 % RAP und einem zugesetzten sehr weichen Bitumen 330/400, da keine Feinabstimmung vorgenommen wurde, um die kommerziellen Bindemittel anzupassen (z.B. Mischung zweier Frischbindemittel auf einen Zielwert).
- Die Ergebnisse des Spurbildungsprüfung waren nicht eindeutig und sollten durch weitere Prüfungen ergänzt werden, um die Hochtemperatur-Eigenschaften besser bestimmen zu können. In jedem Fall sollte den bleibenden Verformungen auf den Teststrecken in den kommenden Jahren besondere Aufmerksamkeit geschenkt werden.
- HMA-Mischungen, sowohl Labor als Feldmischungen, zeigen eine konstant hohe Marshall-Stabilität und bestätigen ihre starke Leistung selbst bei bis zu 60 % RAP.
- Verarbeitbarkeit und Verdichtbarkeit von WMA-Mischungen wurden durch die niedrigeren Produktions- und Verdichtungstemperaturen nicht negativ beeinflusst.
- Das Langzeitverhalten von WMA wurde in dieser Studie nicht untersucht, sollte aber in einem Folgeprojekt behandelt werden. Dabei sollte besonderes Augenmerk auf das Spurbildungsverhalten gelegt werden. Ausserdem muss die Schichthaftung zwischen Bindemittel- und Deckschicht bestimmt werden. Eine US-Studie beobachtete, dass WMA-Mischungen eine niedrigere Anfangssteifigkeit besitzen und schneller altern, dass jedoch letztlich Steifigkeit und Spurbildungsverhalten mit HMA vergleichbar sind (NCHRP, 2015).
- Höhere RAP-Gehalte (bis zu 60 %) können sowohl in HMA- als auch in WMA-Mischungen erfolgreich eingesetzt werden, ohne die mechanischen Eigenschaften wesentlich zu beeinträchtigen. Die Studie sollte auf weitere Mischtypen und noch höhere RAP-Gehalte ausgeweitet werden.
- Die Ergebnisse dieser Untersuchung deuten darauf hin, dass die WMA-Technologien, insbesondere diejenigen, die chemische Zusätze wie Chem1 und Kombi enthalten, eine vielversprechende nachhaltige Alternative zu herkömmlichen HMA darstellen, ohne die wichtigsten mechanischen Eigenschaften des Asphalts zu beeinträchtigen.

1 Project and objectives

1.1 Objectives

Based on the literature analysis and the experience from the PLANET project (Arn, 2017), this project focuses on warm mix asphalt (WMA) application with the addition of reclaimed asphalt pavement (RAP) with the major objective to demonstrate that WMA with RAP can be a suitable alternative to conventional hot mix asphalt (HMA) with RAP. To achieve this goal and help developing WMA as a mixture that can be widely applied, following sub-objectives have been defined:

- Provide an analysis of different production methods for WMA with RAP and highlight the potential differences between these methods.
- Analyse the performance of WMA mixes both at laboratory and field scale.
- Quantify the mechanical performance of WMA with RAP, comparing it to a reference HMA with RAP.
- Draw conclusions regarding the further application of WMA
- Contribute to standards regarding WMA mixes

1.2 Methodology and hypothesis

A comprehensive methodology has been developed, in order to address each objective and in respect to the allocated project budget and time. An overview of the different project steps and the project methodology is shown in Figure 1. The major work packages (WP) can be summarized as follows:

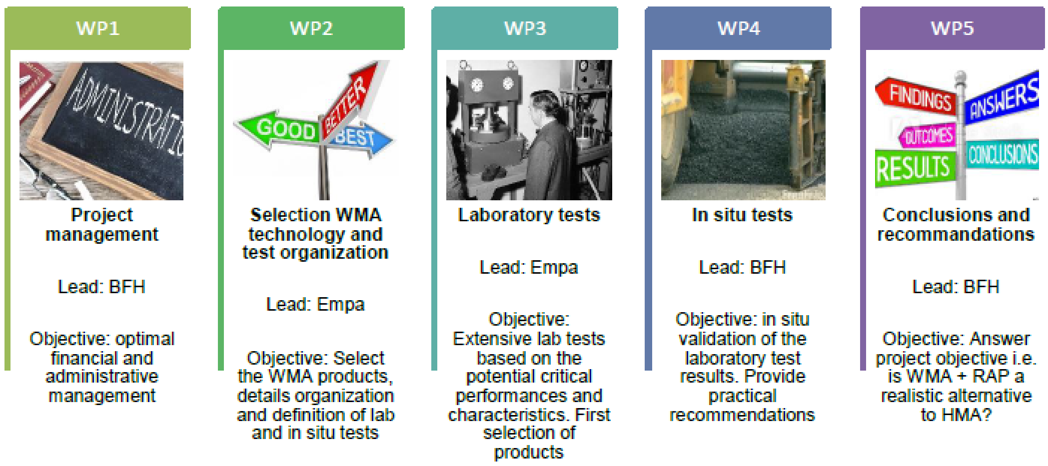


Figure 1: Project overview

The project methodology comprises various aspects such as desk work (WP1, WP2 and WP5) as well as a very important phase of laboratory (WP3) and in situ (WP4) investigations. This methodology requires various competencies and experience, available in the combined expertise of both project partners (BFH and Empa). In addition, a close cooperation with the asphalt producer Weibel AG, one of the leading Swiss companies in the field of WMA is planned.

Considering the project objectives and the available financial resources, some hypotheses have to be made in order to guarantee results that can be finally implemented:

- The project considers an asphalt concrete binder layer AC B 16 S as reference mixture, based on the following reasons:
  - AC B 16 S was already used as a reference in the PLANET project.
  - An AC B recipe according to Swiss standards (suitable for high traffic volume S) can also be used for a base layer AC T.
  - The get more information on their performance it is planned that the AC B 16 mixtures installed on the in-situ test section can be trafficked during one year before being covered with a surface layer.
  - The exact AC B 16 S recipe will be defined based on the raw materials used (aggregates, RAP, binder) and in accordance with the Swiss standards. One option will be to consider a standard plant recipe (from Weibel) while the second option is to develop a proper recipe for the sake of the project. In the frame of the project the same AC B 16 S recipe will be used and adapted to the WMA mixtures (e.g. additives and their dosage) based on literature and suppliers' recommendations.
  - WMA mixtures will be produced and compacted at temperatures between 110°C and 130°C. No sensitivity analysis on WMA temperature is planned, the optimal temperature is being defined by the suppliers and best practice.
- Production in laboratory and further validation / correlation with plant-produced mixtures are planned.
- Aggregates, RAP and binder will be similar within the whole project. Products representative of the Swiss market will be selected.
- No sensitivity analysis of the RAP quality will be provided, since the existing information in the literature is sufficient while further information can be obtained from the ongoing project VSS 2018/329 “Auslotung Grenzbereich RC-Asphaltgranulat-Einsatz in AC EME”.
- The use of rejuvenators will not be addressed within the project.

2 State of the Art

2.1 International research

Warm mix asphalt (WMA) technology is a widely recognized approach, which has been developed in recent years to reduce the temperatures necessary for pavement construction (Capitão et al., 2012; Dong et al., 2017; Yang et al., 2019).

Overall, the temperature reduction of asphalt pursues several goals at once:
- Reduction of emissions (vapours, aerosols, CO2, NOx, VOC); by reducing the production and/ or processing temperatures or processing temperatures.
- Energy savings; through the reduced consumption of fossil fuels.
- Faster traffic release with narrow installation windows.
- Gentle handling of binder and mixing plant; through reduced thermal stress for the materials and aggregates concerned affected materials and aggregates.

An initial compilation and clustering of the measurement results, which were obtained in the course of numerous measurement routes still shows an inconsistent picture (Harnischfeger, 2025).

Although this technology has demonstrated significant economic and environmental advantages (Mazumder et al., 2016), it also has its own set of benefits and drawbacks concerning pavement performance (Behnood, 2020; Kanitpong et al., 2008). One can find numerous literature references related to WMA. In the research paper "A review of the warm mix asphalt (WMA) technologies: Effects on thermo-mechanical and rheological properties" Ali Behnood provides a comprehensive overview on WMA regarding technologies, experience and drawbacks (Behnood, 2020). According to his investigation, the main WMA technologies used worldwide can be classified into three main categories: foaming technologies, chemical additives, and organic or wax additives (Capitão et al., 2012).

By using organic additives (FT wax, amide wax, montane wax), the viscosity of the binder is reduced in the temperature range of asphalt production and paving by the molten additives. As the paved asphalt cools, the phase transition of the additive to microscopically finely dispersed wax particles take place. These generally increase the viscosity and stiffness of the base binder. Organic additives have been part of the collection of experience for many years worldwide and also in Germany. They are available as solids, as a component of fibre pellets or premixed in ready-mixed binders. By reducing the surface tension of the binder, the use of surface-active chemical additives aims to achieve a lighter and more uniform coating at lower temperatures and also utilises a slip film (micelle formation) to facilitate compaction due to polar bound residual moisture from the mineral. Reactive chemical additives facilitate compaction at lower temperatures by changing the properties of the binder. This process begins with modification and is limited in time. Available as liquid additives, chemical additives are currently mainly still on the pilot product list, although there is already a wealth of experience in other countries.

With foaming processes, a distinction is made between foamed bitumen and the use of mineral additives (synthetic zeolite). Foamed bitumen is a process in which 2% to 4% water is atomised into the bitumen jet at the asphalt mixing plant. In the mixer, there is a short-term significant expansion of the binder, which collapses after a defined half-life and facilitates the coating of the minerals at lower temperatures. Foamed bitumen requires a structural change to the mixing plant, but then only the defined addition of water. Foamed asphalts are mainly used in France and the USA, but also in Canada and the Netherlands, while in Germany it is still a subject of research as there is little experience with this process.

When using zeolites, on the other hand, crystalline bound water is introduced into the mixer, which is expelled along a defined outlet curve over a period of six to eight hours as long as the temperature in the mix is above 100 °C. During the water outlet, vapour forms, which leads to the formation of micropores and therefore also to a temporary increase in the binder volume. There is no change in the utilisation properties of the bitumen and the finished layer.

Zeolite has also been the subject of experience from the very beginning and has therefore proven itself many times over - not least because it is regularly used as a processing aid in hot asphalt to overcome difficult paving situations (cold, wind, long delivery routes, manual paving, etc.).

As a mineral additive, zeolite is only available as a solid for direct modification in the mixer (Harnischfeger, 2025).

In addition, there are several new technologies (e.g. Rediset WMX®, Akzo Nobel and EVIX® in the USA) that are neither based on foam nor on viscosity-reducing processes but use several surfactants for temperature reduction.

Figure 2 provides an overview of different technologies and their products (Alizadeh et al., 2024).

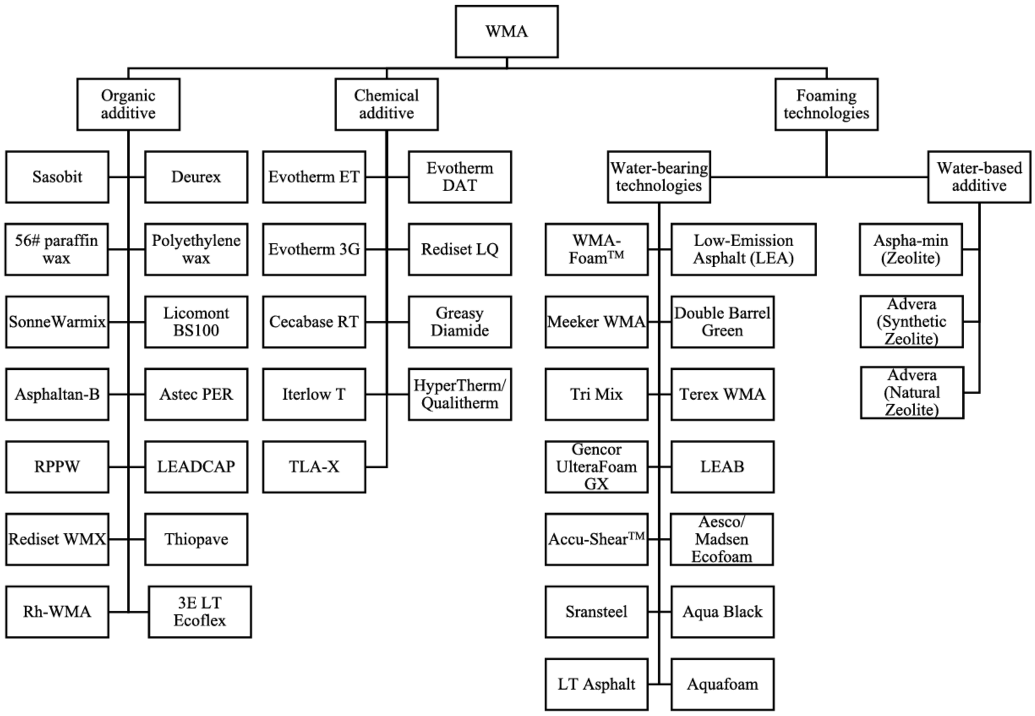


Figure 2: Classification of warm mix asphalt technology (Alizadeh et al., 2024)

With regard to the technical drawbacks, some WMAs have been reported to show less resistance to moisture damage compared to HMA and bonding/coating problems (Garcia Cucalon et al., 2016, Rubio et al., 2012, Yang et al., 2018). In addition, due to the reduced oxidative aging and air void content in WMA, pavements of this mixture type may suffer from distresses such as rutting.

An efficient and cost-effective method for producing pavement materials is to involve the integration of reclaimed asphalt pavement (RAP) into asphalt mixtures (Al-shamayleh et al., 2022; Imaninasab et al., 2022; He and Wong, 2007).

Regarding the use of RAP in WMA, Behnood's survey confirms that with the use an appropriate WMA technology can allow the production of lower temperature asphalt mixtures with high RAP contents (Howard et al., 2013, Tao and Mallick, 2009, Vidal et al., 2013) and that the performance of such recipes depends on the RAP source, RAP content, WMA technology, and WMA additive content. Therefore, the optimum RAP content in WMA depends on the type of WMA technology used in the production of WMA mixtures (Oner and Sengoz, 2015). Overall, the use of RAP materials is able to increase the rutting resistance and improve the high temperature performance of the mixtures due to the aged and stiff binder in the RAP (Behnood, 2019, Guo et al., 2014, Zhao et al., 2013). In other words, WMA mixtures containing RAP materials are more resistant to rutting than the WMA mixtures without RAP. As reported in the investigation by Behnood the low temperature performance of WMA containing RAP has shown an improvement in the resistance to thermal cracking compared to control mixtures (Guo et al., 2017, Guo et al., 2014, Martinho et al., 2017, Xin et al., 2017). There are also studies that reported equal or even better performance at low temperatures in WMA mixtures containing RAP (Mallick et al., 2008, Xiao et al., 2016). Again, the performance of WMA mixtures containing RAP at low temperatures depends on the WMA technology and production temperature. Overall, the use of RAP materials negatively affects the performance of asphalt mixtures at low temperatures. An appropriate WMA technology can offset this effect and can potentially improve the performance of the asphalt mixtures at low temperatures (Behnood, 2020).

Regarding the overall research needs, (Behnood, 2020) states the following:

- Further investigation is required in terms of the performance of WMA mixtures containing RAP at low temperatures.
- Further research is required to investigate the interaction of WMA additives and other modifiers under various loading and environmental conditions.
- Further research is required to investigate the effects of various composite modifiers containing WMA additives and other modifiers such as polymers, crumb rubber, natural bitumen, and PPA (polyphosphoric acid) on the properties of WMA mixtures.

The integration of reclaimed asphalt pavement (RAP) with warm mix asphalt (WMA) offers a practical approach to enhancing environmental performance and economic efficiency within the asphalt sector. By utilizing recycled materials and adopting energy-efficient production techniques, WMA mixtures that contain RAP can markedly diminish the environmental footprint of asphalt pavements. This encompasses a reduction in greenhouse gas emissions, decreased energy usage, and the preservation of natural resources. Figure 3 shows the effects of WMA RAP technology in reducing the global warming impacts (Alizadeh et al., 2024).

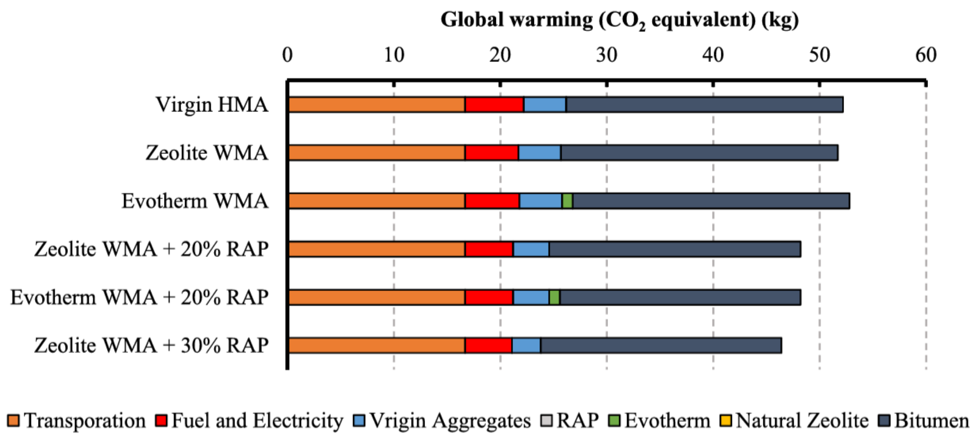


Figure 3: Asphalt mixtures production impact on global warming (Alizadeh et al., 2024)

In recent years, the incorporation of RAP into Warm Mix Asphalt (WMA) has attracted significant interest from researchers, primarily due to its environmental benefits, which include the conservation of natural resources and a reduction in greenhouse gas emissions (Alizadeh et al., 2024). Numerous studies have been conducted to assess the performance of these materials under various conditions. For instance, Guo et al. (2014) performed an extensive laboratory analysis of WMA incorporating RAP, focusing on factors such as rutting, bending, freeze-thaw splitting, Marshall immersion, aging, freeze-thaw cycle splitting, and fatigue. Oner and Sengoz (2015) found that the use of WMA with RAP could lead to lower project costs compared to Hot Mix Asphalt (HMA) and other WMA types. Furthermore, Arshadi et al. (2017) conducted a comparative analysis of plant-produced WMA containing RAP against HMA, specifically examining cracking and rutting through laboratory tests. Whereas most of these studies have focused on WMA that employs RAP independently. Nevertheless, there is a significant gap in studies examining the performance of WMA that incorporates RAP. Furthermore, existing investigations typically compare WMA containing RAP to HMA based on a limited range of laboratory tests conducted on the samples, while field performance data is often insufficient or restricted to specific short-term pavement performance metrics. It is essential to acknowledge that laboratory evaluations of asphalt mixtures do not always accurately forecast their performance in real-world scenarios. It is therefore essential to perform laboratory tests related to performance alongside a comprehensive field study of WMA that incorporates RAP in order to verify that this sustainable pavement mixture design approach fulfils the engineering requirements.

2.2 National research

In Switzerland, the research package PLANET completed in 2017 marked a milestone in the investigation of WMA demonstrated that these mixtures are a valuable alternative to hot mix asphalt, showing at least equivalent performance, but more environmentally friendly and sustainable. Although, not intended, the project already showed the additional value of adding RAP not only in terms of environmental benefits but also in terms of performance aspects.

Nevertheless, at the end of PLANET (Arn, 2017) some critical questions and discussion points remained open and, in this regards, further research needs emerged:

- Binder: Behaviour and viscosity in the warm temperature range.
- Interlayer bonding: Behaviour and function of tack coat in connection with WMA.
- As in the framework of the PLANET project (Arn, 2017), the wax-based WMA methods due to negative cold temperature behaviour were found not to be a good solution, wax additives should only be applied in combination with a chemical additive.
- Concerning the recipe of WMA, it was found that checking and completing the analytical and volumetric procedures for the evaluation of WMA recipes still needs more specific focus.
- The PLANET project (Arn, 2017) did not provide specific and extensive modifications and/or amendments to standardisation and the aspects of laboratory testing (including testing conditions and parameters) on the one hand as well as the production and construction of WMA were described as further needs.

Environmental aspects of pavement have attracted considerable attention from a range of stakeholders in recent years. The implementation of warm mix asphalt (WMA) that incorporates reclaimed asphalt pavement (RAP) has emerged as a recognized environmentally friendly approach to pavement construction, as it helps conserve natural resources and reduce greenhouse gas emissions. However, despite the growing use of these materials, there has been a lack of extensive research involving thorough laboratory and field assessments to evaluate the performance of WMA with RAP in comparison to traditional hot mix asphalt (HMA). Especially, the in-situ sections constructed during the PLANET projects (Arn, 2017) had not been analysed regarding their performance. The new research project, therefore, involves the monitoring of four WMA sections all constructed in Bern employing various techniques, alongside a control HMA section, over a period of a two-year duration. Laboratory analyses will be performed to assess the properties of WMA mixtures qualified for the construction of the test track. The characteristics of lab-compacted mixtures will be examined, focusing on cracking resistance, rutting performance, moisture susceptibility, stiffness and compactability to compare WMA with HMA that includes RAP.

3 Experimental plan

The different stages (work packages WP) of the project are presented in Figure 4.

After an update of knowledge and the study of recent representative literature (WP 1), the selection of WMA technologies for the laboratory investigation (WP2) was carried out using binder and mastic testing (WP 2).

The mechanical performance analysis was divided into a laboratory and a field (in-situ) investigation. The investigation was conducted based on the potential critical performances and characterizations, resulting in the final selection of the WMA products for the full-scale test sections (WP 3). WP3 focused on practical aspects of the installation of the warm mix pavements as well as their performance in terms of interlayer adhesion. In (WP 4), the mixtures for the field test sections were collected from the plant and investigated in the laboratory. The results obtained from the laboratory and in situ tests were finally used to provide practical recommendations (WP 5).

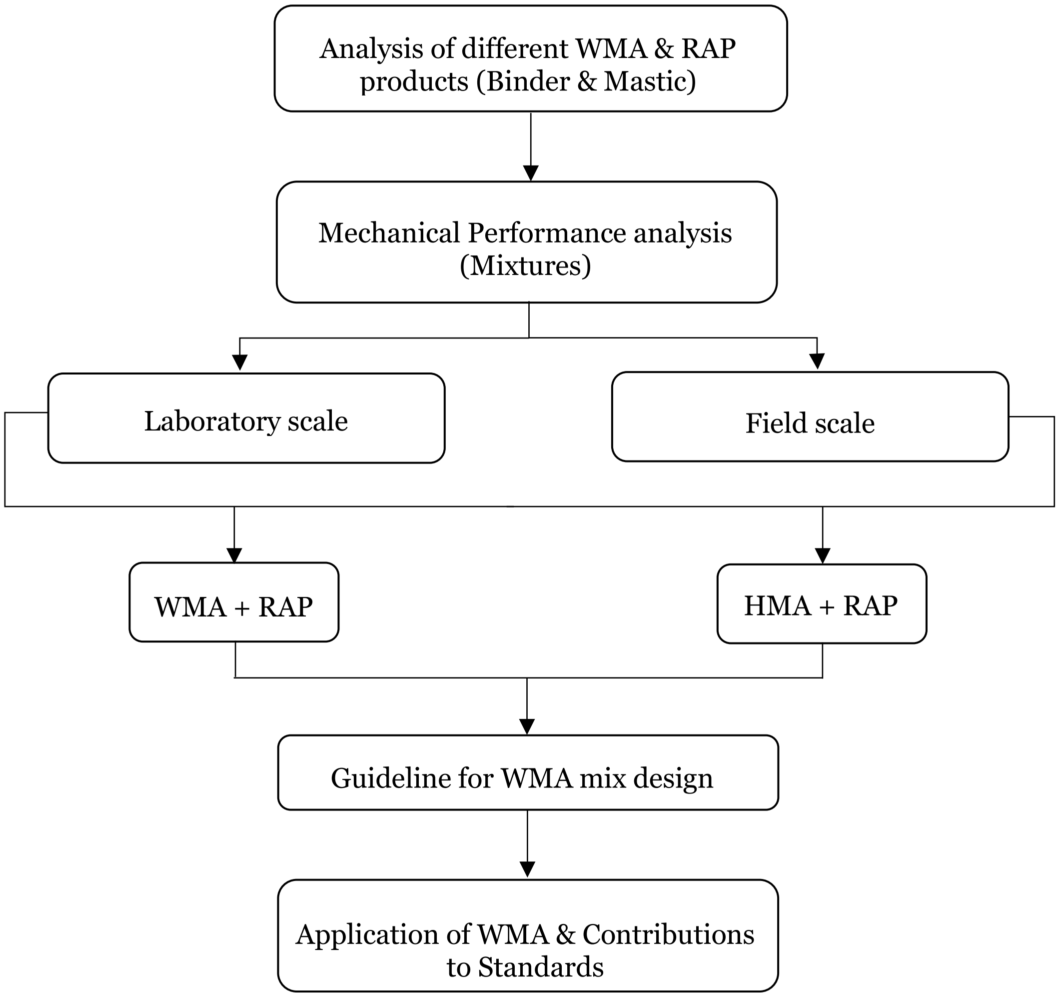


Figure 4: Details of project overview

4 Materials and methods

4.1 Materials

As mentioned earlier, the investigation in the frame of the project was based on the formulation of an asphalt concrete binder course recipe for heavily trafficked roads (AC B 16 S).

During the first BK meeting it was decided to take a standard recipe from Weibel AG with a non-modified binder (70/100) as reference mixture. Further, it was decided to investigate two different RAP contents, namely 30 % and 60 %. All WMA recipes have followed the chosen AC B16 S recipe and were adapted accordingly.

According to the project plan the investigation started with the selection of the WMA-additives using binder and mastic testing as described in Chapter 5. Here, two binders, namely 70/100 for WMA with 30 % recycling rate and 330/430 for WMA with 60 % recycling rate needed to compensate for the higher amount of RAP binder were chosen. All aggregates and RAP were collected from Weibel AG. The filler (Eigenfüller) used in the preparation of the mixtures was from BERAG. The basic properties of the binders, the RAP, the mineral aggregates and the filler are given in the Annex.

The selection of WMA additive was based on literature and previous experience, as well as on the commercial availability of the products in Switzerland.

From the beginning (project application) and based on research results and practical experience in Switzerland the following was decided (see also Table 1):

- The focus was placed on chemical additives, since a great variety of these products exists
- Foaming methods should only be included in situ, while based on earlier experience, zeolites were completely excluded
- Waxes were excluded for WAM mixtures and only used in the binder testing and in combination with a chemical additive
- Regarding the limitations of the extensive laboratory testing, the final selection of 2 chemical additives out of 4 commonly used products was based on the initial binder and mastic testing, while the wax for the Kombi-product (wax+chemical additive) was chosen as the commonly used product worldwide.

In a first step, 4 chemical additives were evaluated on the binder and mastic level (see Table 1).

WMA Additives		
Type of products	**Product Code**	**Description**
Foaming technology	Foam	Plant produced foam asphalt
Chemical additives	Chem1	Surfactant
	Chem2	Natural plant based
	Chem3	Surfactant
	Chem4	Natural oil-based additive
Organic additive	Wax	FT paraffin wax
Combination of chemical and organic additive	Kombi	Chem1 + Wax

Table 1: WMA product selection

Table 2 shows an overview of all mixtures and blends used in this project. The recycling content is given at the end (30 %, 50 % or 60 %). In the figures, the mixtures from the lab are labelled with L- and from the field with F-.

Blends and mixtures				
Lab Code	**Binder blend**	**Mastic blend**	**Lab mixture**	**Field mixture**
HMA 30%	X		X	
HMA 50%				X
HMA 60%	X	X	X	
WMA-Chem1 30%			X	
WMA- Chem1 60%	X	X	X	X
WMA- Chem2 30%			X	
WMA- Chem2 60%	X	X	X	
WMA- Chem3 60%	X	X		
WMA- Chem4 60%	X	X		
WMA- Wax 60%	X	X		
WMA- Kombi 30%			X	
WMA- Kombi 60%		X	X	X
WMA- Foam 60%				X

Table 2: Overview of blends and mixtures with different additives and recycling contents

4.1.1 RAP properties

The binder characteristics of RAP 0/11 material are given in Table 3. The binder content of 4.6 % was recovered during the laboratory extraction and was found to be similar to the reported values provided by the producer (Weibel AG). The penetration values for the recovered binder varied slightly, with Weibel AG reporting a range of 24–36 (mean 30), BFH recording a lower value of 26, and Empa reporting 31 (1/10 mm). In terms of softening point ring and ball values ranged from 60.4 °C (Empa) to 61.6 °C (BFH), suggesting similarity in binder stiffness. The consistency between laboratories results is generally within acceptable limits for the analysis of different tests conducted at BFH and Empa laboratories.

Figure 5 shows the grain size distribution of the RAP 0/11 materials.

RAP binder characteristics

Parameter	Weibel AG	BFH	Empa	Unit
Binder content	4.6	4.6	-	%
Penetration (Pen)	30 (24–36)	26	31	1/10 mm
Softening point (R&B)	61 (57–65)	61.6	60.4	°C

Table 3: RAP binder properties

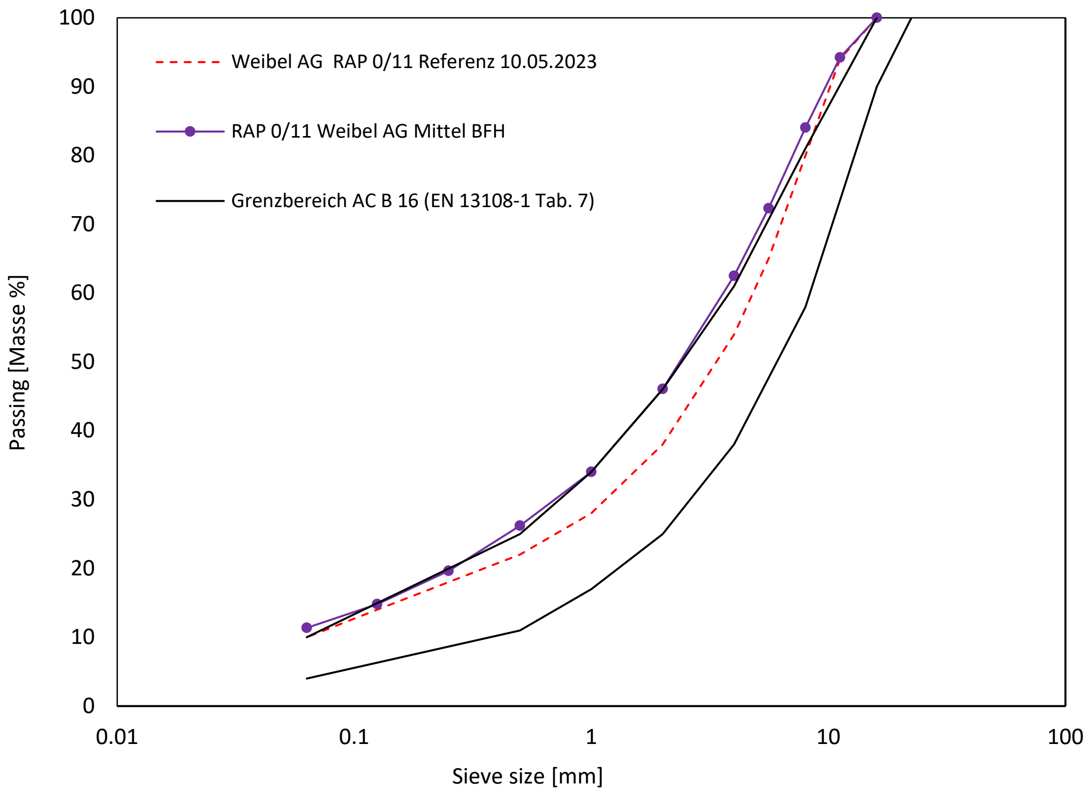


Figure 5: Grain size distribution of RAP 0/11

4.2 Mixtures

4.2.1 Plant mixtures

The material for the standard mixtures AC 16 B including 30 % and 60 % of RAP were obtained from the Weibel AG plant located in Oberwangen. Figure 6 shows the mixture declarations with aggregate gradation for the HMA AC B 16 S with 30 % and 60 % of RAP. The virgin aggregates consist of crushed sand (0/4 mm) and split aggregates (4/8 mm, 8/11 mm, 11/16 mm) supplied by Daepp, Oppligen, with respective proportions of 21 %, 21 %, 20 %, and 38 %. The binder used is a 50/70 (residual), with an additional 330/430 dosage. The total binder content in the mix is 4.6 %. The mineral aggregate density is 2.700 g/cm³, while the binder density is 1.03 g/cm³. Marshall properties include a bulk density of 2.40 g/cm³, a maximum density of 2.51 g/cm³, and a void content (V_m) of 4.5 %. The voids in mineral aggregate (VMA) amount to 15.2%. The mix fulfils the water sensitivity requirements with a minimum 70 % retained tensile strength according to EN 12697-12. The resistance against permanent deformation complies with SN EN 12697-22, ensuring rutting remains ≤10 %.

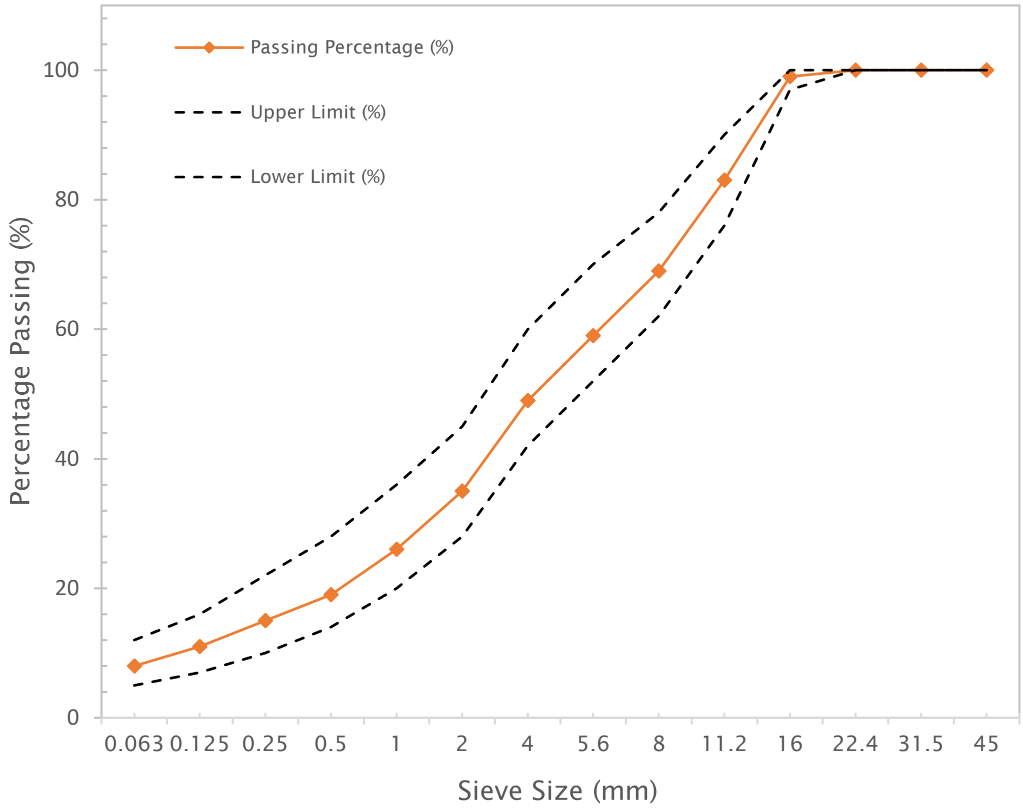


Figure 6: Grain size distribution of RAP mixtures (Plant Production)

4.2.2 Laboratory mixtures

The aggregate size distribution of the selected mixtures with 30 % and 60 % RAP content is shown in Figure 7 and Figure 8, respectively.

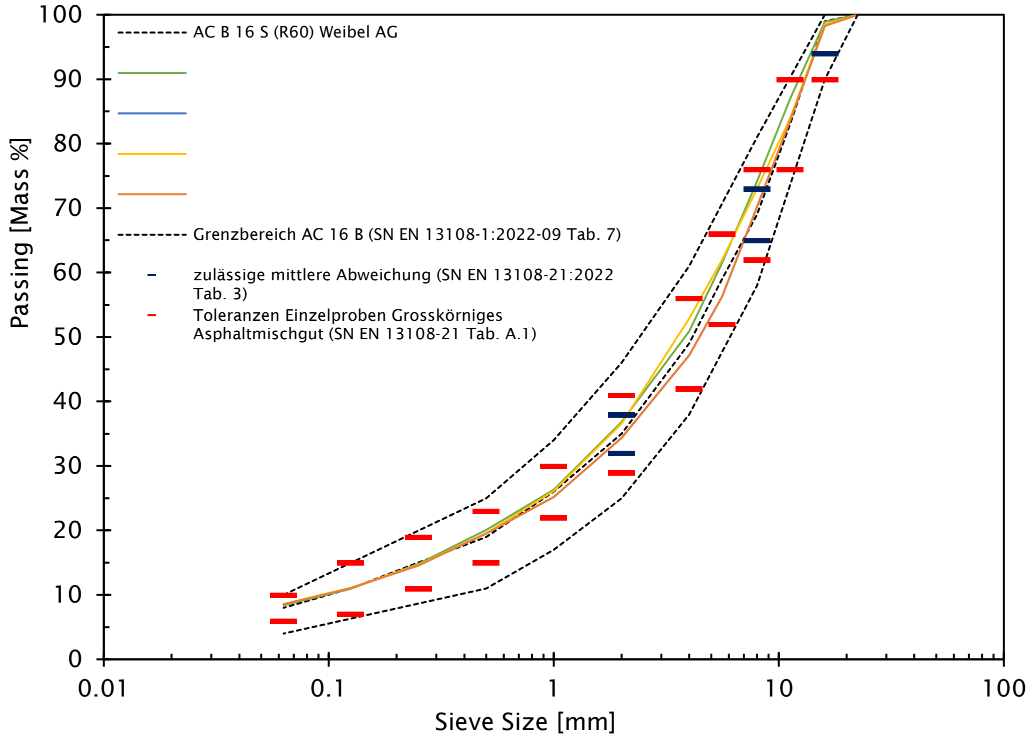


Figure 7: Grain size distribution of mixtures with 30% RAP (Laboratory Production)

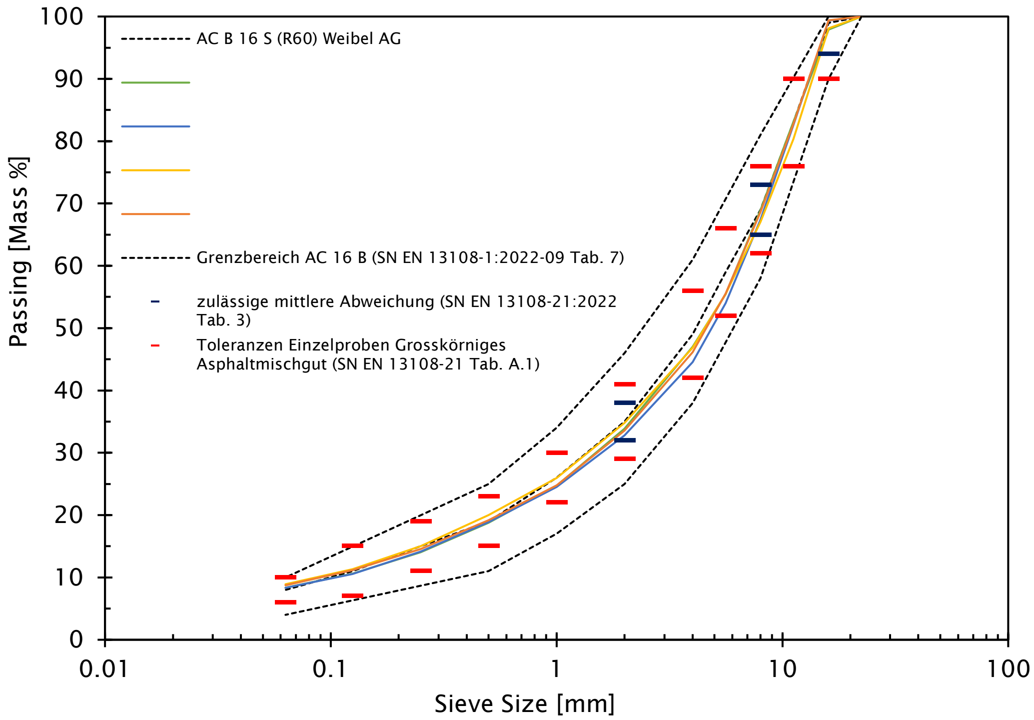


Figure 8: Grain size distribution of mixtures with 60% RAP (Laboratory Production)

All mixtures were produced according to the procedures defined by the European Standard EN 13108-1. The hot mixture production temperature was set at 160 °C and warm mixtures were prepared at a temperature of 130 °C.

4.2.3 Optimisation of the mixing process

RAP handling and processing was as short as possible to avoid any further aging of RAP materials. The RAP material was oven dried at 40 to 50 °C until its mass was constant before using it for the mixture production. Dry mixing time of RAP and virgin mineral aggregates was about 4 to 5 minutes followed by visual inspection which showed proper mixing of binder from RAP with virgin aggregate (i.e. no white spots, good bitumen coating). Mixing time of RAP and virgin mineral aggregates and fresh bitumen was between 4 to 5 minutes. In this way, a good mixing of the old with the new binder was ensured, which is particularly important for asphalt tests and the investigations on the homogeneous binder (measured value = expected value).

After the optimized mixing process, the penetration test results were checked and found to be close to each other (in the lower expected range). For a (resulting) bitumen 50/70, the recommended mixing temperature range was 140 °C to 180 °C. The compaction temperature for WMA mixtures was adopted as 125°C. The virgin mineral aggregates were overheated in order to lower the RAP temperature for the hot mixes. For 60 % RAP the temperature was 195 °C for the mineral aggregates and 140 °C for the RAP. For the WMA mixtures 130 °C for both mineral aggregates and RAP was used.

4.2.4 Mixing protocol:

The virgin bitumen was heated at 155 °C. Then the defined amount of additive was added to the bitumen. RAP was heated on a metal tray approximately 4 cm thick in oven at 135 °C and mixed immediately when the temperature was reached. The heating time (oven in and oven out) and the RAP temperature was recorded.

Asphalt mixer was preheated to 170 °C, first mineral aggregates were added, then the RAP and finally the binder. Mixing was performed for approximately 8 to 10 minutes. The end temperature of the mixed material was recorded. Finally, the mixture was filled into card boxes, with the amount necessary for the planned tests. Table 4 and Table 5 present the production and compaction details of the asphalt mixtures including HMA and WMA both at 30 % and 60 % RAP content.

HMA laboratory production details

Materials / Production (HMA)	*RAP	Virgin Binder + additive	Virgin Aggregates
Pre-heating (30 % RAP)	135 °C	155 °C	195 °C
Pre-heating (60 % RAP)	135 °C	155 °C	240 °C
Heating Duration (Oven)	Soon as materials reached the required temp.	2 hours (depending on the mass)	Overnight
Mixing Temperature	165 - 170 °C		
Cool down after mixing (Room Temperature)	Yes		
Sample Preparation (Pre-heating in Oven)	Mixture heating in the oven at compaction temperature (duration to be defined based on mass of samples reaching the required compaction temperature)		
Compaction Temperature	145 - 150 °C		

Table 4: HMA laboratory production and placement details (30 % & 60 % RAP)

**Note: RAP materials are handled to be air dried to avoid excessive moisture by keeping in over @ 40 to 50 °C until mass gets constant.*

WMA laboratory production details

Materials / Production (WMA)	*RAP	Virgin Binder + additive	Virgin Aggregates
Pre-heating (30 % RAP)	135 °C	130 °C	150 °C
Pre-heating (60 % RAP)	135 °C	130 °C	165 °C
Heating Duration (Oven)	Soon as materials reached the required temp.	2 hours (depending on the mass)	Overnight
Mixing Temperature	130 - 135 °C		
Cool down after mixing (Room Temperature)	Yes		
Sample Preparation (Pre-heating in Oven)	Mixture heating in the oven at compaction temperature (duration to be defined based on mass of samples reaching the required compaction temperature)		
Compaction Temperature	120 - 125 °C		

Table 5: WMA laboratory production and placement details (30 % RAP)

4.3 Binder testing

The penetration tests were conducted according to the European Standard test procedure SN EN 1426. Softening point ring & ball tests were conducted according to the European Standard test procedure SN EN 1427.
Fraass breaking point tests were conducted according to the European Standard test procedure SN EN 12593.

The complex shear modulus was measured using the dynamic shear rheometer and the method described in SN EN 14770. The temperatures ranged from +10 to 80 °C in steps of 10 °C and 20 frequencies between 0.1 and 10 Hz. Master curves were constructed using the WLF method.

The Binder-Fast-Characterisation-Test BTSV were carried out according to SN EN 17643 using the dynamic shear rheometer.

4.4 Mixture testing

4.4.1 Specimen preparation

All specimens were prepared in accordance with the European Standard EN 12697-35. After mixture preparation, the compaction for specimen preparation was performed at 150 °C and 125 °C for HMA and WMA, respectively. The test specimens were produced immediately, after the appropriate conditioning time for the compaction of the test specimens. The decisive factor for the target binder was the needle penetration of the recovered bitumen, examined on the day of mix production and the following day (after reheating).

4.4.2 Mixture compactability

The specimens were prepared according to EN 12697-31, and the compaction of asphalt mixture was performed under controlled conditions. The specimen had a cylindrical shape with a diameter of 100 mm. The degree of compaction as the percentage of maximum theoretical specific gravity of the compacted mixture were measured using the compactability method defined in EN 12697-10. The relationship between the degree of compaction and the number of gyrations was analysed.

4.4.3 Maniability test

The maniability test was developed to measure the increase in cohesion of hot and warm asphalt mixtures. The measurement of asphalt maniability at 145 °C and 125 °C temperatures for HMA and WMA, respectively, was performed according to EN 12697-53 standard using the Nynas workability meter. This device simulates the action of a paver on-site. The principle of the test is shown in Figure 9. The maniability test was performed on the mixture's specimen of mass approximately 6 kg. The test designed to assess the mixture workability properties. Asphalt mixture (approximately 6 kg) of HMA (145 °c) and WMA (125 °C) was placed in a mold and pushed by a hydraulic piston and a pushing blade. The principle corresponds to that of the Casagrande shear box, where a shear effort is applied at a controlled deformation speed.

During the test, a force sensor measures the force exerted by the piston to spread the asphalt sample, and the force needed to cause detachment of the asphalt mixture. This ultimately allows the characterization of the maniability of the asphalt based on the force applied by the piston to induce detachment. It should be noted that there are no strict performance requirements for this test.

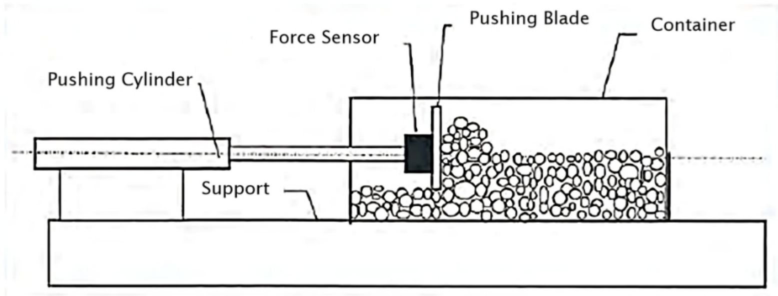


Figure 9: Principle of the Nynas maniability test (Des Essarts et al., 2016)

4.4.4 Marshall stability and Marshall air void content

Marshall stability and Marshall air void content were determined according to the European Standard SN EN 12697-34.

4.4.5 Indirect tensile strength ratio (ITSR)

Indirect tensile strength (ITS) and Tensile Strength Ratio (ITSR) water sensitivity were determined according to SN EN 12697-12. where three samples 99.5 ± 0.5 mm in diameter and 64.0 ± 2.0 mm in height were tested in dry and wet conditions at 25 °C. The wet condition consisted of submerging the sample in water for 70 ± 2 h at 40 °C.

4.4.6 Semi-circular bending test (SCB)

For determining crack propagation, the semi-circular bending test (SCB) according to the European standard EN 12697–44 was used. As shown in Figure 10, the standard SCB test typically employs specimens with a diameter of 150 mm, the dimensions of the 3.5 mm notch denoted as “a” and the test specimen with thickness of 50 mm denoted as "b" (see Figure 10). The test was conducted at a temperature of 0 °C and two replicates were tested at a speed of 5 mm/min.

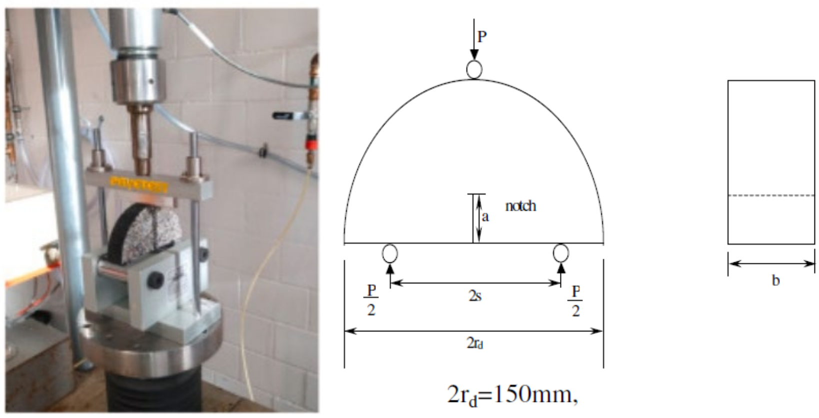


Figure 10: SCB test setup and configuration

4.4.7 Aging method AASHTO R30

The aging method AASHTO R30, performed during the lab procedure, simulates the long-term effects of heat and air on asphalt mixtures to assess their performance and durability over time. Asphalt mixture compacted samples were placed in a temperature-controlled oven at 85 °C, where they are exposed to air for a specific duration. For this test, the samples were aged for a period of 120 hours, during which they undergo a process that accelerates oxidation and other chemical changes that would naturally occur over extended periods of road service life. This procedure is crucial for simulating the hardening effects that asphalt binders experience as they age in real-world conditions, such as exposure to high temperatures and traffic-induced stresses.

4.4.8 Stiffness modulus (CIT-CY)

The stiffness modulus test was performed according to EN 12697-26 using the CIT-CY method. The test device is like the indirect tensile test, but a dynamic sinusoidal load is applied. The following temperatures and frequencies were used: –10 °C, 0 °C, +10 °C, 20 °C and 0.1, 1.0, 10 Hz. The specimens had been prepared from Marshall compacted samples, which were cut to a height of 40 mm. Master curves were prepared using the WLF-method.

4.4.9 Rutting resistance

The rutting test was performed according to the European standard EN 12697-22. According to the version adopted by Switzerland SN EN 12697-22 the large size device was used. For testing 2 specimens with dimensions of 500 mm x 180 mm and a height of 100 mm (binder course) were compacted to a desired air void content of 4.5 vol-% and tested at a temperature of 60 °C with 30'000 cycles (if possible).

4.4.10 Thermal stress restrained specimen test (TSRST)

The Thermal Stress Restrained Specimen Test (TSRST) was carried out according EN 12697-46. A prismatic specimen (160 x 60 x 60 mm) is held at a constant length, while its temperature is decreased with time. Because of the prohibited thermal shrinkage, the specimen is subjected to a (cryogenic) tension stress. The temperature is decreased with a rate of -10 K/h from +20 °C to -40 °C. When the cryogenic stress exceeds the material strength, the specimen fails, and failure stress and temperature are taken as characteristic properties. For the result the average value of three specimens is used.

4.4.11 Layer Adhesion tests according to Leutner on field cores

The layer adhesion test according to Leutner was conducted according to the standard SN EN 12697-48 using field cores of 150 mm and a test temperature of 20 °C.

5 Additive evaluation

5.1 WMA selected products and basic properties

Binder blends (Table 6) were produced using the recovered RAP binder, the added new binder and the WMA additive, representing the actual binder composition in the WMA. Assuming a similar binder content in RAP and recycling WMA, the recycling rate is identical to the content of the RAP binder in the binder blend. Hence, for WMA with 30 % recycling rate, 30 % of RAP binder was mixed with 70% of bitumen 70/100. For WMA with 60 % recycling rate, a softer binder was needed to compensate for the higher amount of RAP binder. Pre-testing showed that a soft bitumen 330/430 was suitable for this purpose.

Binder testing details		
Type of products	**Products**	**Proposal**
Foaming technology	Zeolites	NO
Chemical additives	Foam Asphalt	Only test section (in situ)
	Chem 1 – Chem 4	Decide on two Chem
Organic additive	Wax	NO
Kombi	Wax + Chem	Decide on one Chem from two Chems chosen

Table 6: Binder testing

5.1.1 Sample preparation

The binder composition (Table 7) at the binder level is identical to the composition in the asphalt mixture which depends on the recycling content (30 % and 60 %) and both the binder content in the asphalt mixture (4.6 %) and the RAP (4.6 %). For example, in the case of 60 % recycling ratio, the content of the RAP binder in the mixture is calculated to be 2.76 % (60 % into 4.6 %). The total binder content in the mixture is as well 4.6 % according to the recipe of the producer. Hence, 1.84 % virgin binder has to be added to reach the target binder content of 4.6 % in the mixture. The ratio of RAP binder to added binder is 2.76 % / 1.84 %, which is equivalent to 60 % / 40 %, because in this special case the binder content in RAP and asphalt mixture are identical. Additive dosage is given in % of the total binder content.

Although, rheology measurements with the dynamic shear rheometer don't need a large sample amount, because of the small additive concentration (0.5 to 2% in the binder blend), the dosage of the liquid additive becomes inaccurate below 50 mg, as a single drop weighs already around 10 mg. Therefore, binder blends of 20 g were prepared in a small metal container. For practical reasons the additive amount was added on top of the bitumen amount, resulting in a total amount larger than 100 % (Table 7). However, this causes only a slight deviation to the correct composition. Note, that no Kombi blend was used in the binder analysis.

A sample of cold bitumen was taken with a hot knife and heated in a 100 ml container to 130°C for 20 minutes. The exact amounts according to Table 7 were filled in 50 ml aluminum containers. Afterwards in the same way RAP binder was heated to 160°C and the exact amount added to the bitumen 330 in the small containers. For preparing the DSR samples the small container with the binder blend was heated at 160°C for 15 min until fluid. The cold additive was added to the hot blend with a pipette (if it contained a liquid additive) and mixed thoroughly by hand with a spatula for 2 minutes. The blend was put back in the oven for 10 minutes. Before pouring the blend into the DSR moulds, the blend was mixed again for 30 s. At least four 25 mm DSR moulds were filled for BTSV and modulus testing.

Details of binder blends

Code Experiment	RAP-binder (%)	Bitumen 330/430 (%)	Bitumen 70/100 (%)	Additive Dosage (%)	Comment
RAP	100	-	-	-	Pure RAP binder
B70	-	-	100	-	Bitumen 70/100
B330	-	100	-	-	Bitumen 330/430
HMA-30%	30	-	70	-	30% RAP blend
HMA-60%	60	40	-	-	60% RAP blend
Chem1a-60%	60	40	-	0.5	60% RAP blend + Chem1
Chem1b-60%	60	40	-	0.5	60% RAP blend + Chem1 (replicant)
Chem2-60%	60	40	-	0.5	60% RAP blend + Chem2
Chem3-60%	60	40	-	0.5	60% RAP blend + Chem3
Chem4-60%	60	40	-	1	60% RAP blend + Chem4
Wax-60%	60	40	-	2	60% RAP blend + Wax

Table 7: Binder blends for rheological characterisation

5.1.2 Binder rheology

The BTSV-results show that different additives have little impact on the rheology (Figure 11). The blends containing a chemical additive are all located in a narrow area together with the blend HMA 60 % without additive. There is a slight difference in BTSV of the four chemical additives which is larger than the repeatability of the measurement, as shown for the additive Chem1, where two replicants were prepared with no visible difference in the BTSV diagram (Figure 11). In contrast, the blend with wax increases the BTSV temperature considerably.

Stiffness moduli were measured every 10 °C between 20 °C and 80 °C and 20 frequencies between 0.1 and 10 Hz. The master curves of all blends and bitumen are displayed in Figure 12. The hardest binder, the reclaimed RAP binder is the highest, and the virgin binders are the lowest curves. All master curves of the blends converge at lower temperature (right side) with the target bitumen 70/100 (B 70), whereas at higher temperature (left side) more differences can be observed. All the master curves of the binder blends with chemical additives as well as the HMA with 30 % and 60 %

RAP are very close together, showing a similar rheological behavior. But they are all above the master curve of B70, indicating a slightly stiffer performance at higher service temperatures.

The master curve of the blend with wax has a lower slope and lies between RAP and the chemical blends. It is surprising that it is stiffer at higher temperatures, although the wax melting point lies above 80 °C, which leads to its unique rheological behavior.

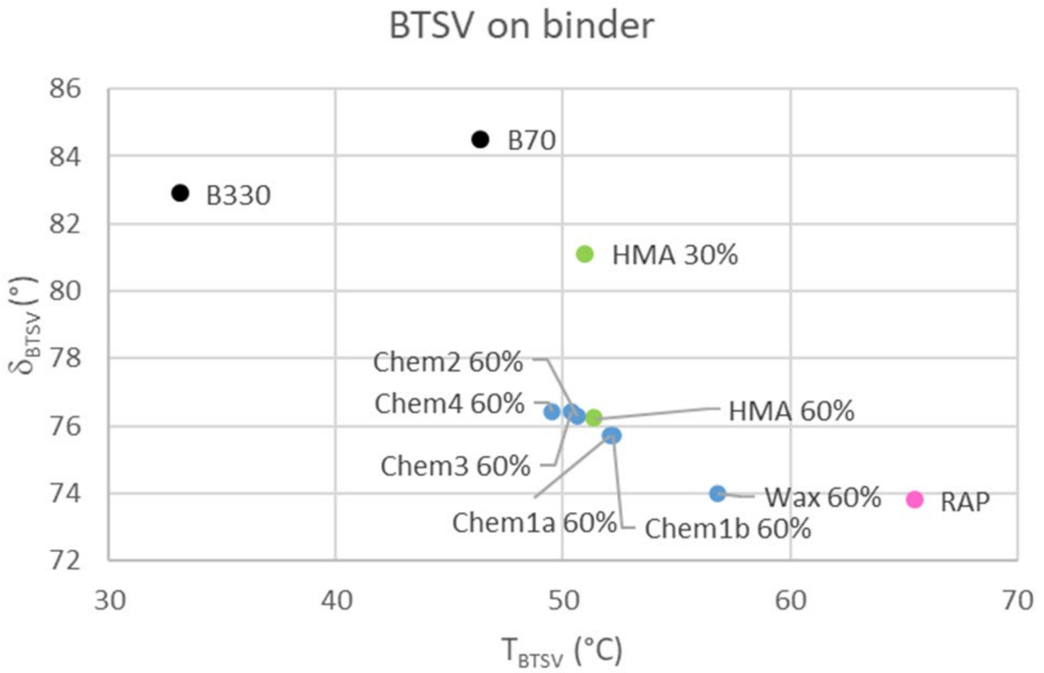


Figure 11: BTSV results of bitumen and binder blends

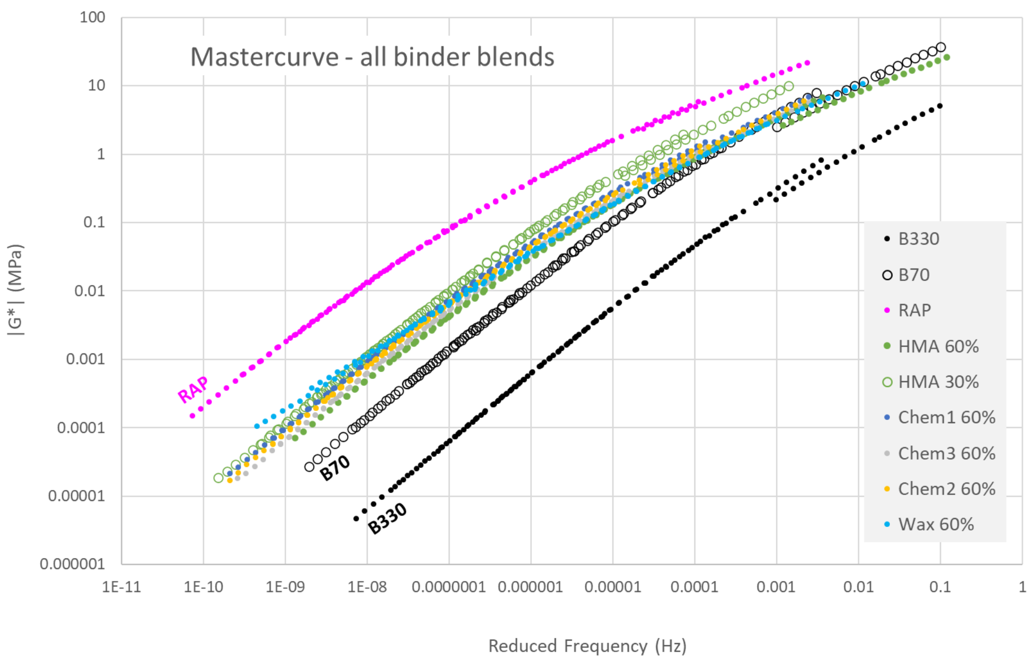


Figure 12: Master curves of bitumen and binder blends

5.2 Mastic testing

5.2.1 Sample preparation

In order to study the influence of the filler on the rheology and to investigate the difference to the binder blends, mastic testing was performed (Table 8). The RAP-filler was received from the extraction of RAP and the natural filler was produced by dry sieving of the sand fraction 0/4 mm through a 0.063 mm sieve.

The filler to bitumen ratio in the mastic was equal to the filler to bitumen ratio in the hot mix receipt of Weibel with 60 % of RAP (Figure 6):

Filler in aggregates 8 %, or 7.6 % in HMA respectively
Total binder in HMA 4.6 %

This corresponds to a filler to bitumen ratio of 1.66, whereas the content of virgin material is 40%.

Mastic blends

Mastic blend	Mass-%
RAP binder	23.7
Virgin binder + additive	13.9
Total binder	**37.6**
RAP filler	43.6
Plant filler	18.8
Total filler	**62.4**

Table 8: Composition of the mastic blends

Mastic blends of ca. 50 g were prepared as follows: In a first step the natural filler and RAP-filler were combined and dried in the oven at 160 °C for at least 12 h. The binder blend composed of RAP binder, virgin binder and additive was prepared as described before and heated to 160 °C as well. The mixing was performed manually on a hot plate heated to 200 °C. The binder was placed on the hot plate and the hot filler was added in 3 batches. Between each batch the blend was stirred with a metal spatula until no filler was visible anymore. When all filler had been added, the mastic blend was stirred again for 2 minutes carefully, to avoid the incorporation of air bubbles. Despite the hot plate, the mastic blend cools down, increasing its viscosity. Therefore, the samples were put in the oven at 160 °C for 10 minutes. To avoid filler segregation during oven storage, the mastic blends were stirred once more for 1 minute before filling into silicon moulds for DSR testing. The same rheological tests as for the binder were applied to the mastic.

5.2.2 Mastic rheology

Similar to the binder, all mastic results are grouped together in a narrow range (Figure Figure **13** and Figure 14). However, the mastic blends (labelled as M.xxx) are much stiffer compared to the binder blends (labelled as B.xxx), which can be seen in a shift to higher T_{BTSV} and δ_{BTSV} (Figure 15). This shift is for most of the mastic blends almost identical. Only the blend with the Chem3 additive behaves differently and shows a steeper slope. As expected, the Kombi 60 % blend, which is composed of half the additive amount of wax and Chem1 each, lies exactly between the points for Wax 60 % and Chem1 60 % (Figure 15). As a summary of the mastic testing, no additional information is obtained in the BTSV testing in comparison with the binder blends.

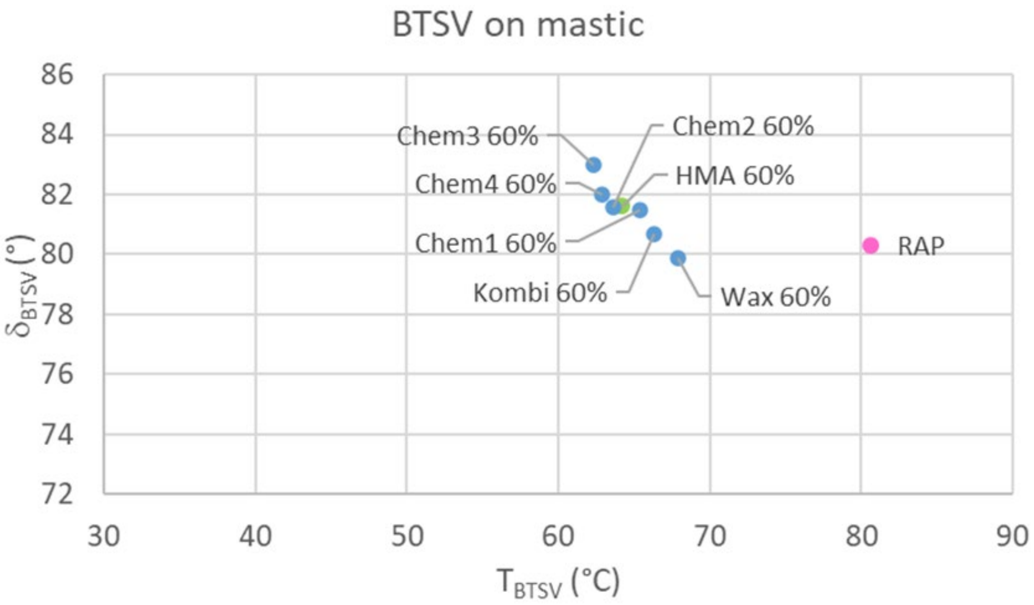


Figure 13: BTSV results of mastic blends

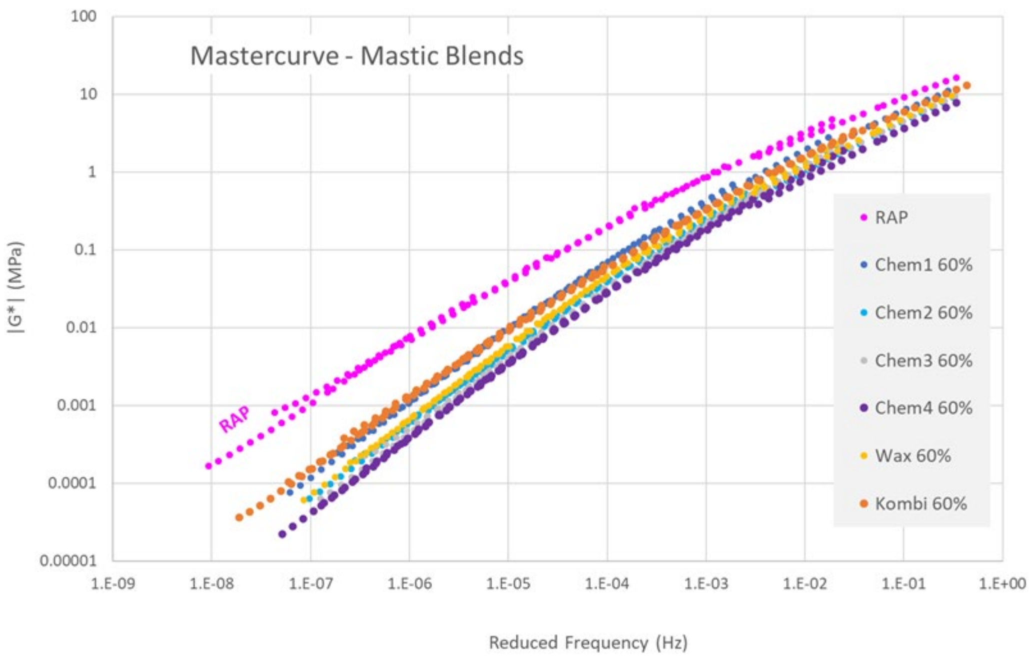


Figure 14: Master curves of mastic blends

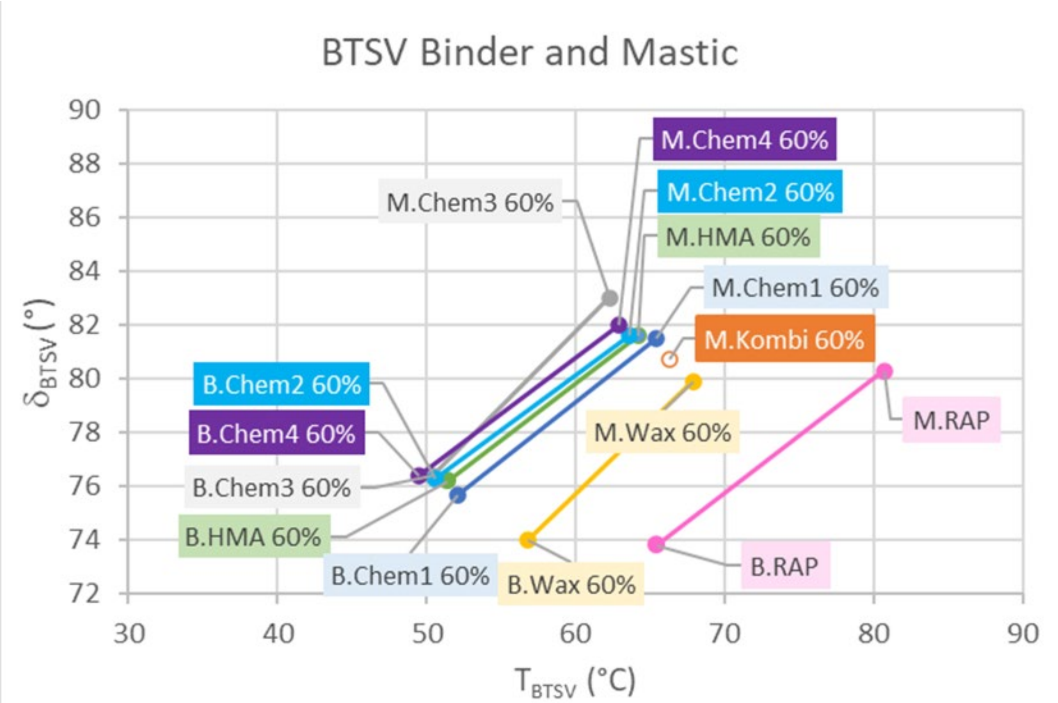


Figure 15: Comparison of BTSV results of binder (B.xxx) and mastic blends (M.xxx)

5.2.3 Low temperature performance and final additive selection

The results of the rheological binder and mastic tests on the 60 % blends did not show a clear difference between the four additives. Hence, it was decided to perform Fraass breaking point testing on blends of Chem2, Chem3 & Chem4 with 30 % and 60 % RAP content (Figure 16) to get information on the low temperature performance of the different additives.

The Fraass breaking point test results, illustrated in Figure 16, indicate the low-temperature behaviour of the different blends. Among the tested binders, Chem2-60% exhibits the lowest Fraass breaking point, around -17 °C, suggesting good resistance to thermal cracking. Conversely, Chem4-30% has the highest breaking point. Given the importance of selecting a binder with optimal low-temperature properties for preventing premature cracking, Chem2-60% was considered for further analysis.

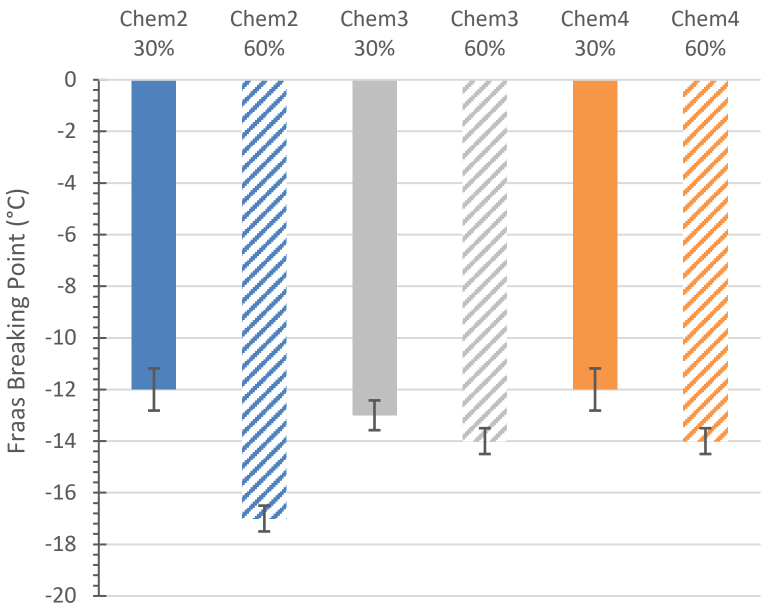


Figure 16: Fraass test results of Chem2, Chem3 and Chem4

6 Laboratory test results

The laboratory prepared asphalt mixtures were used to determine the properties of the mixtures, and the recovered binder. Table 9 gives an overview of the tests conducted for the different mixtures.

The following sections provide details of the test results.

Mixture test overview				
Test method	**Lab mix**	**Aged lab mix**	**Plant mix**	**Cores**
Maniability	X		X	
Compactability (Gyratory compaction)	X		X	
Marshall stability	X	X	X	
Air void content (Marshall)	X		X	
Semi-circular bending test	X		X	
Moisture resistance (ITSR)	X	X	X	
Rutting resistance (Wheel tracking)	X		X	
Stiffness modulus (CIT-CY)	X		X	
Thermal stress restrained specimen test (TSRST)	X		X	
Recovered binder testing (Penetration, Softening point R+B, Fraass breaking point, BTSV)	X		X	
Shear bond test (SBT)				X

Table 9: Overview of the mixture tests

6.1 Binder testing on recovered binder

The conventional binder tests include penetration, softening point R&B and Fraass breaking point. Additionally, the Binder-Fast-Characterization-Test BTSV was applied.

6.1.1 Penetration

Figure 17 shows the penetration for all hot and warm laboratory mixtures with RAP contents of 30 % and 60 %. Clear differences between HMA and WMA materials are visible for L-WMA-Chem2 60% (63 mm-1) compared to 45 mm-1 for L-HMA 60%. For L-WMA-Chem2 further a clear increase of penetration with the increase of RAP content can also be found.

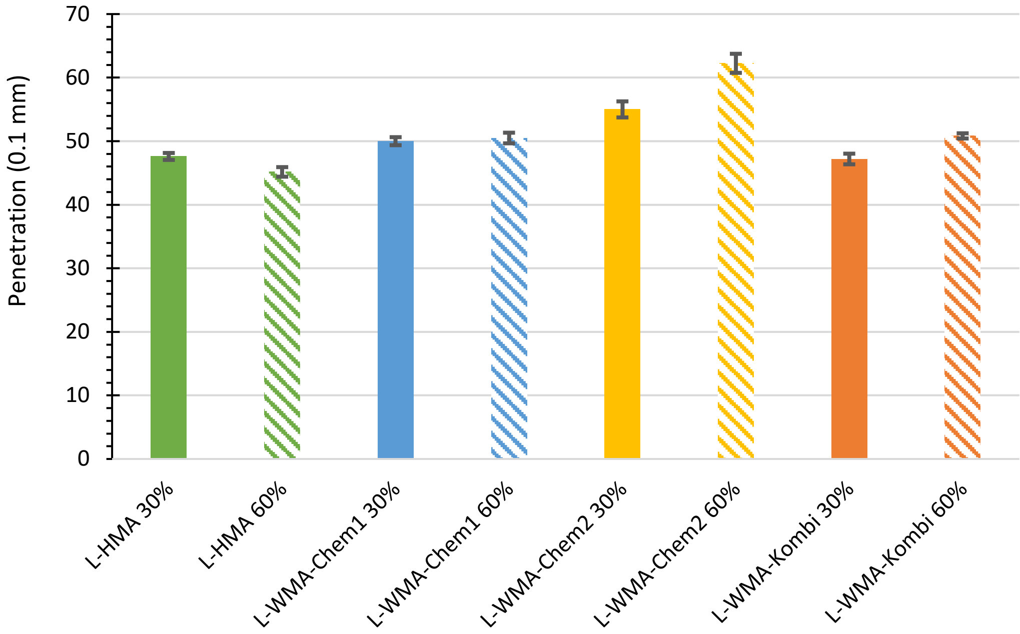


Figure 17: Penetration test results (Lab. mixtures)

6.1.2 Softening point ring and ball

The softening point test results are presented in Figure 18. The analysis shows that L-WMA-Kombi specimens exhibit the highest softening points at both 30 % and 60 % RAP percentages. Whereas, L-WMA-Chem2 has the lowest one, indicating it is less heat-resistant compared to other materials. The chemical additives (L-WMA-Chem1 and L-WMA-Chem2) show similar changes (2.0 %) with the increase of the RAP percentage. Increasing the RAP percentage from 30 % to 60 % improves the softening point for all materials, with L-HMA and WMA-Kombi showing the largest increase.

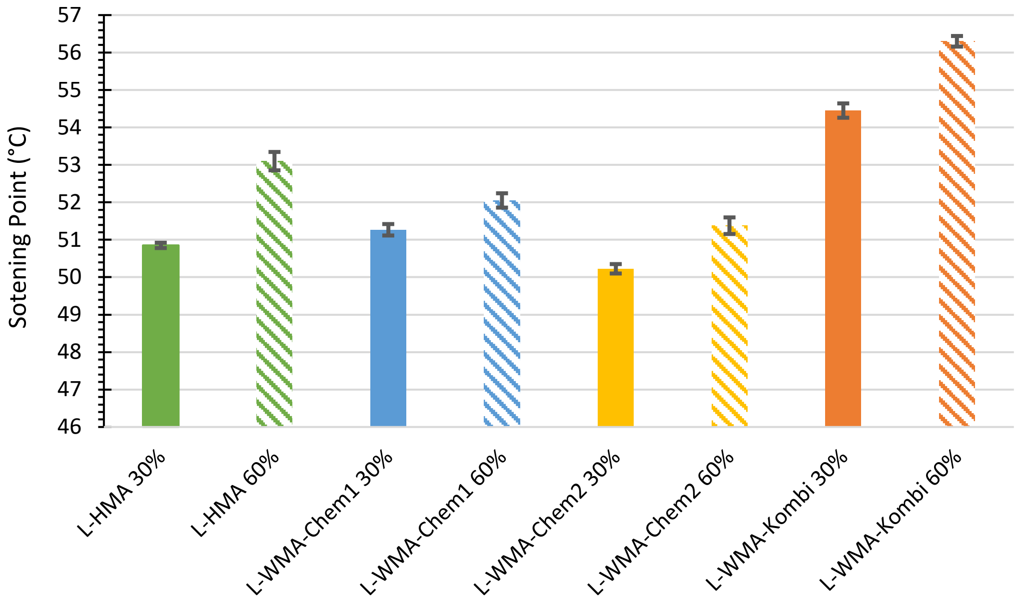


Figure 18: Softening point test results (Lab. mixtures)

6.1.3 BTSV

The BTSV temperatures (Figure 19) were shown to be different than the softening point R&B temperatures for the lab mixtures. This could be attributed to variations in the extraction/recovery process or to the fact that the correlation between BTSV and softening point is less pronounced for binders with WMA additives, similar to what is observed for polymer modified binders. The ranking of the additives is the same, but in contrast to the softening point, the BTSV results for the 60 % mixtures are not higher. Surprisingly, a better correlation is found with penetration results, where the differences between mixtures with 30 % and 60 % are smaller.

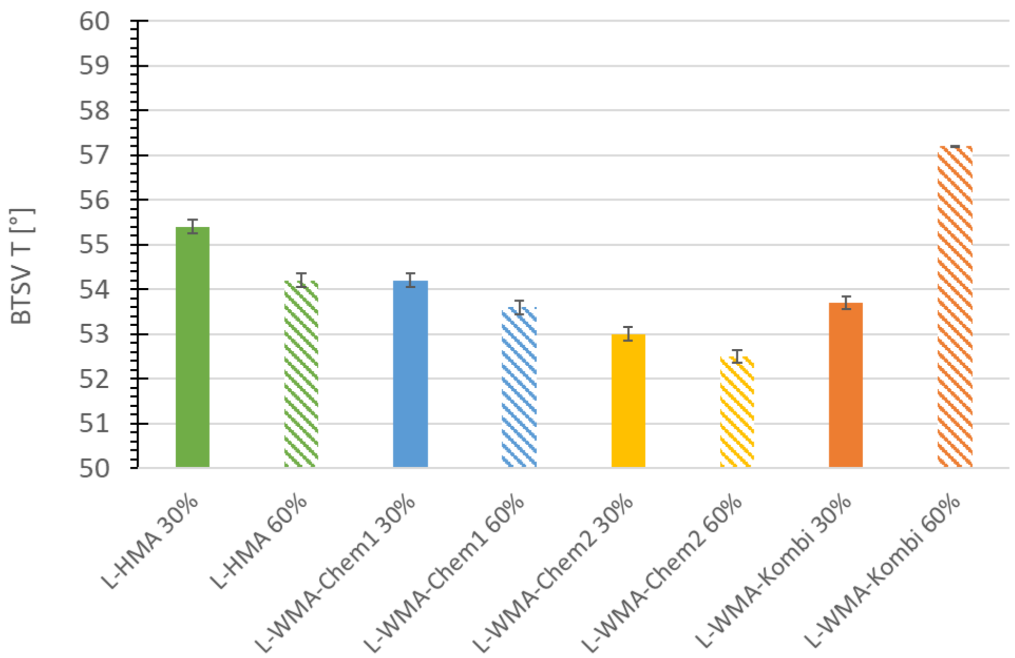


Figure 19: BTSV test results (Lab. mixtures)

6.1.4 Fraass breaking point

Figure 20 presents the Fraass Breaking Point (°C) for the recovered asphalt binder for the different mixtures. From the Figure 20 it is visible that increasing RAP content leads to improved (lower) Fraass breaking points. Although, the error bars show some variation in the results for L-WMA-Chem2 60%, reflecting inconsistencies in the measured values, no significant differences between the Fraass test results of both HMA and WMA mixes can be found.

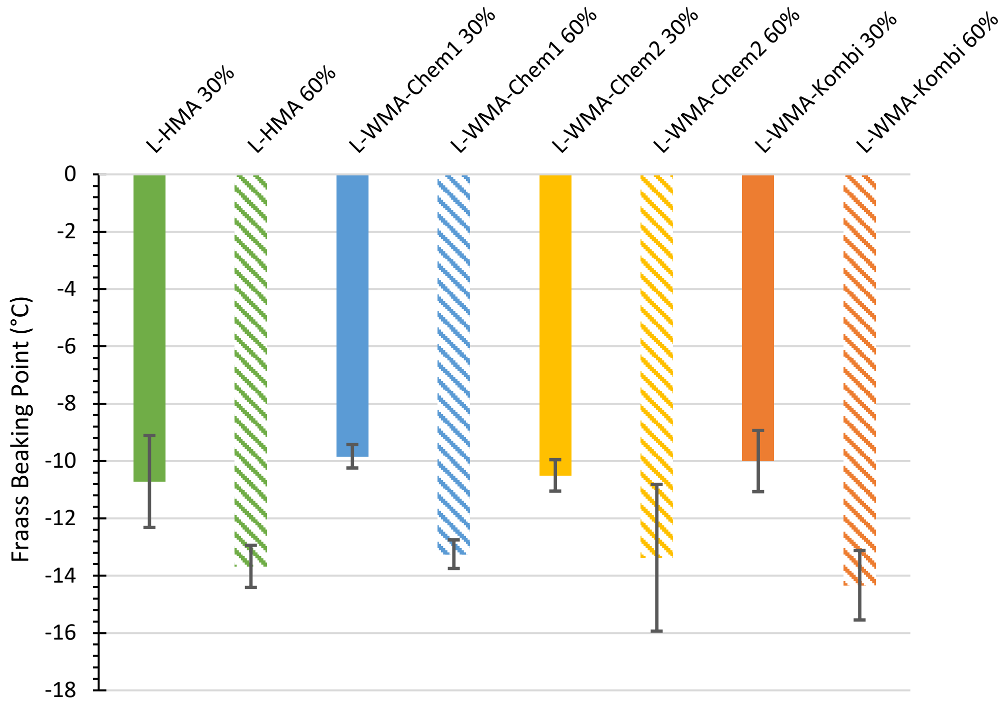


Figure 20: Fraass breaking point test results (Lab. mixtures)

6.2 Mixture testing

6.2.1 Marshall air void content

The Marshall air void (%) content of the mixtures is shown in Figure 21. The results indicate that the air void content ranges between 3.2 % to 5.2 %, respecting the requirements according to the Swiss standard (3.0 % to 6.0 %) as highlighted in the graph. Most WMA mixtures exhibit higher air void contents compared to HMA mixtures. Notably, L-WMA-Kombi 30% with 5.2 % and L-WMA Chem1 with 4.8 %, while L-HMA 30% has the lowest value of 3.2 %.

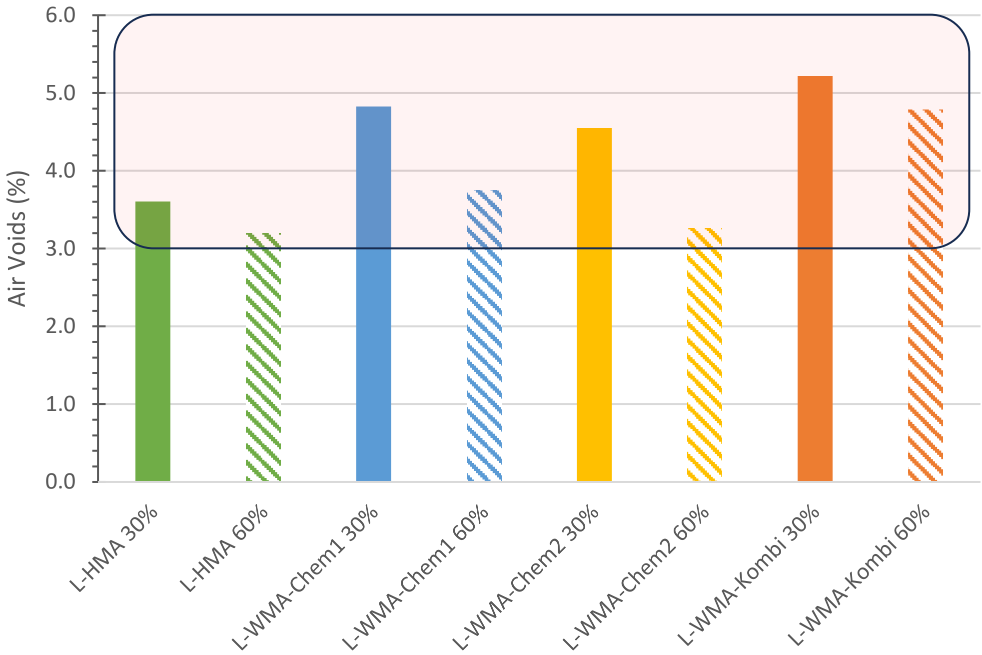


Figure 21: Marshall air voids distribution (Lab. mixtures)

6.2.2 Marshall stability

Figure 22 presents the Marshall stability for all laboratory mixtures. The HMA mixtures show the highest values with 12.3 kN for L-HMA 30% and 11.7 kN for L-HMA 60%. Looking at the warm mixtures, L-WMA-Chem1 30% receives the same value as HMA 60%, followed by L-WMA-Kombi 30% (10.7 kN). The lowest value of 7.6 kN can be found for L-WMA-Chem2 30%, improving with the increase of RAP content to 9.8 kN, while for all other mixtures Marshall stability decreases with increasing RAP content.

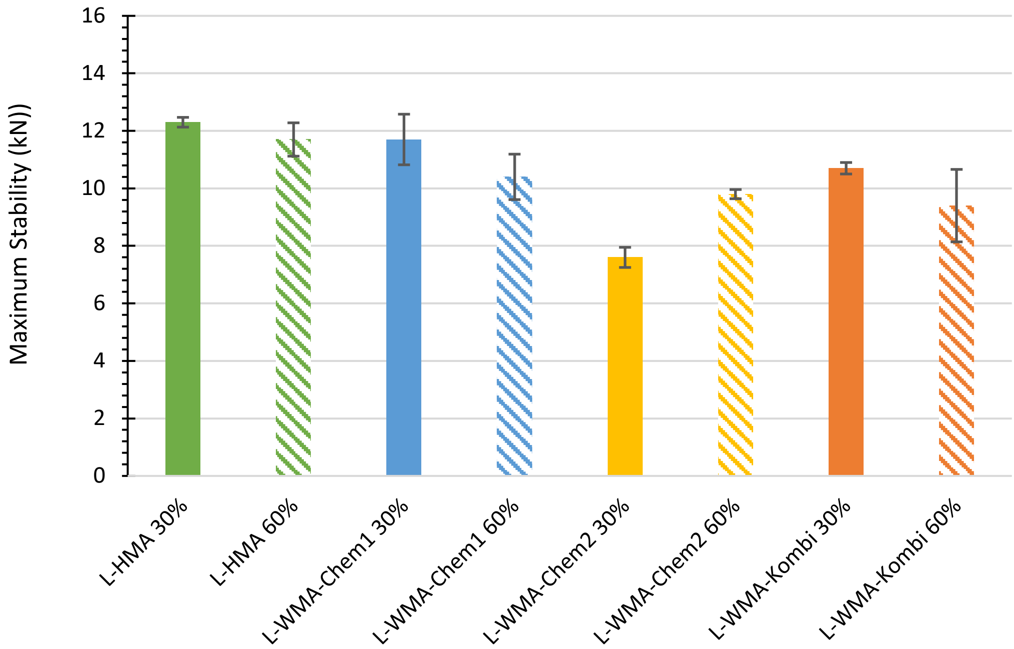


Figure 22: Marshall stability test results (Lab. mixtures)

6.2.3 Mixture maniability

Figure 23 shows the analysis of asphalt mixture workability (maniability) test results in terms of the maximum force (N). Higher forces indicate stiffer mixtures, which may be harder to compact, whereas lower forces suggest improved workability but may also imply weaker cohesion. All mixtures have values between 53 % and 57 %, except for L-WMA-Chem2 30% and L-WMA-Chem2 60% with values of 63 % and 89 % showing reduced workability. Note, that the maniability test was conducted on a single specimen due to the large quantity required for the test samples, which does not allow drawing final conclusions.

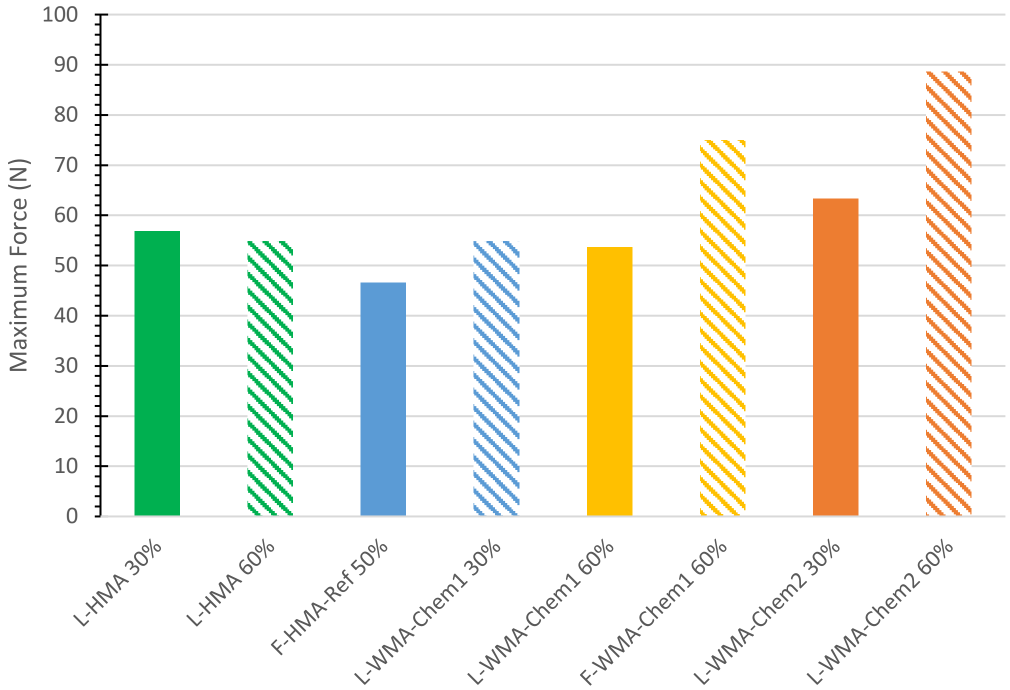


Figure 23: Mixture maniability test results (Lab. mixtures)

6.2.4 Mixture compactability

Figure 24 shows an example data of the HMA and WMA-Chem1 mixtures compactability in terms of the degree of compaction (%) as a function of the number of gyratory cycles for all laboratory mixtures. The degree of compaction increases with the number of cycles, showing the expected densification behavior during compaction. The high R^2 values suggest that the logarithmic models are statistically significant and effectively describe the relationship between compaction cycles and the degree of compaction. A comparison of slope coefficients indicates that L-WMA-Chem1 mixtures are more compactable, particularly at higher RAP content of 60 %.

Figure 25 presents the compactability (K) value and initial void content V (1) of the mixtures tested, indicating their compaction resistance and early densification behaviour. Where, compactability (K) measures how easily an asphalt mixture can be compacted during road construction. A higher K value means the mix compacts easily (good workability) and a lower K value means the mix is harder to compact (more resistance during compaction). V (1) refers to the voids after 1 gyration (or equivalent initial compaction step) reflecting the initial density or initial workability of the mixture.

For all mixture types (HMA and WMA), compactability tends to decrease when increasing the RAP content from 30% to 60%, except for L-WMA-Kombi, where compactability increased slightly from 30% to 60%. There is also a general trend of higher initial void content with 60% RAP content. L-WMA-Kombi 60% has the highest compactability overall. HMA generally offers better or at least more consistent compactability than WMA, particularly at higher RAP content.

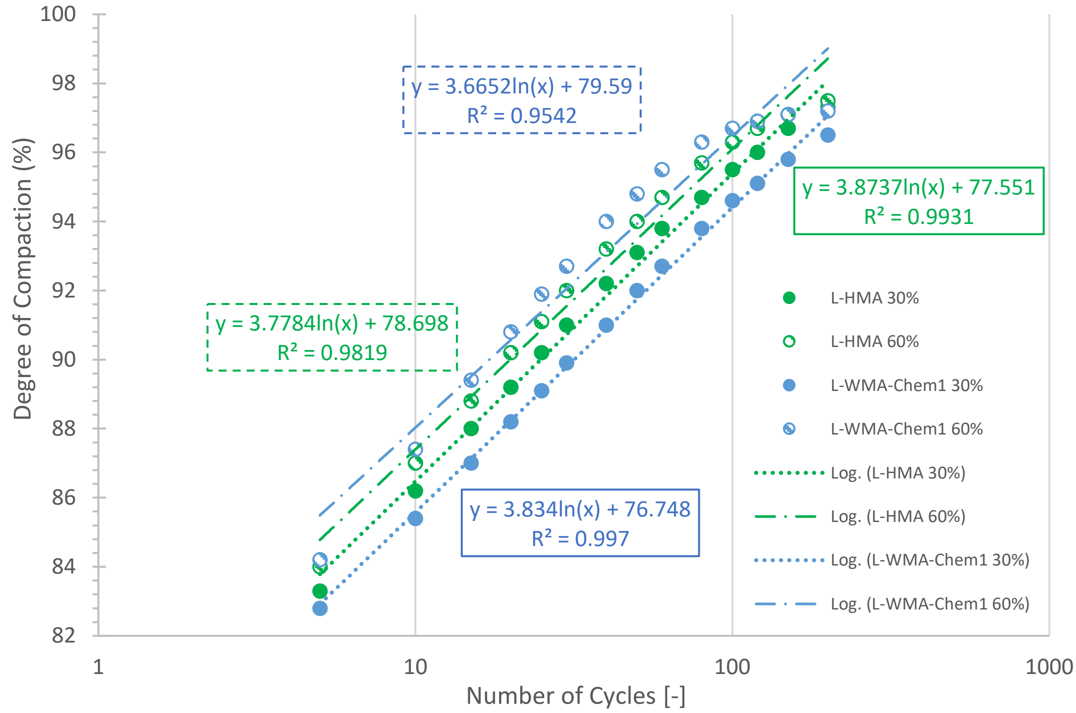


Figure 24: Mixtures compactability test results HMA vs WMA-Chem1 (Lab. mixtures)

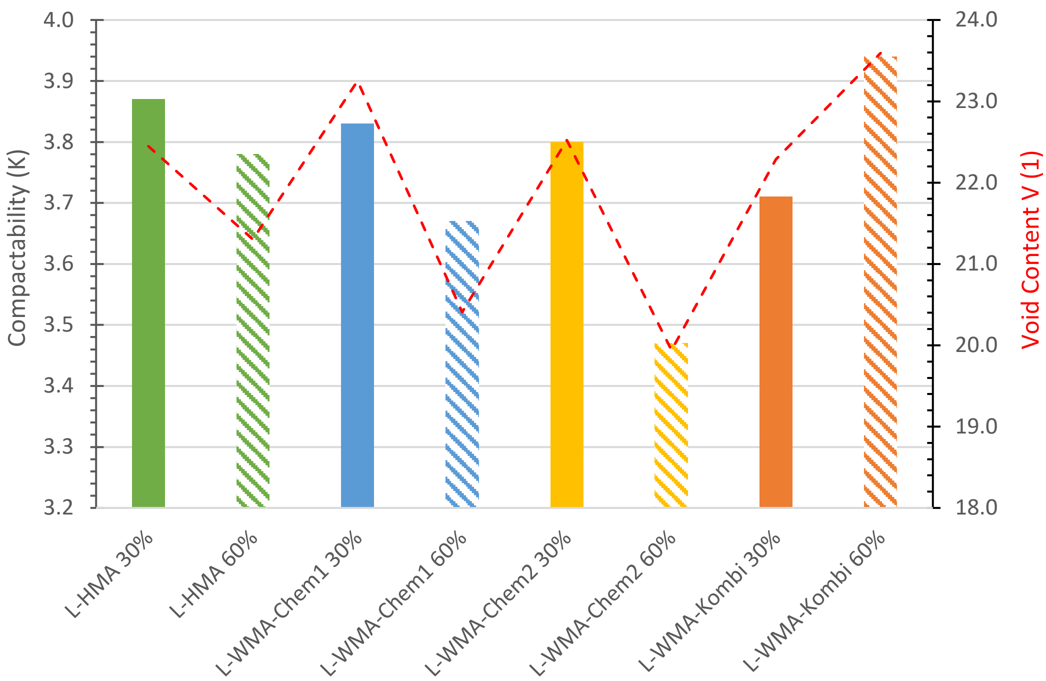


Figure 25: Mixtures compactability (K) and void content V (1) (Lab. mixtures)

6.2.5 Semi-circular bending (SCB)

Figure 26 presents the average results of the Semi-circular Bending (SCB) test, based on four replicate specimens. Increasing the RAP content (from 30 % to 60 %) improves toughness for all mixes (HMA and WMA). The effect of RAP-increase is most noticeable for the mixtures with chemical additives (L-WMA-Chem1 and L WMA-Chem2 with around 24.1 %), while HMA improves by only by 16.9 %, with L-WMA-Kombi having the lowest improvement (13.0 %).

The WMA additives show different effects. For a RAP content of 30 % L-Kombi achieves a similar behaviour as HMA, while both chemical additives have slightly lower values. For a RAP content of 60 % all WMA mixtures show similar values as HMA.

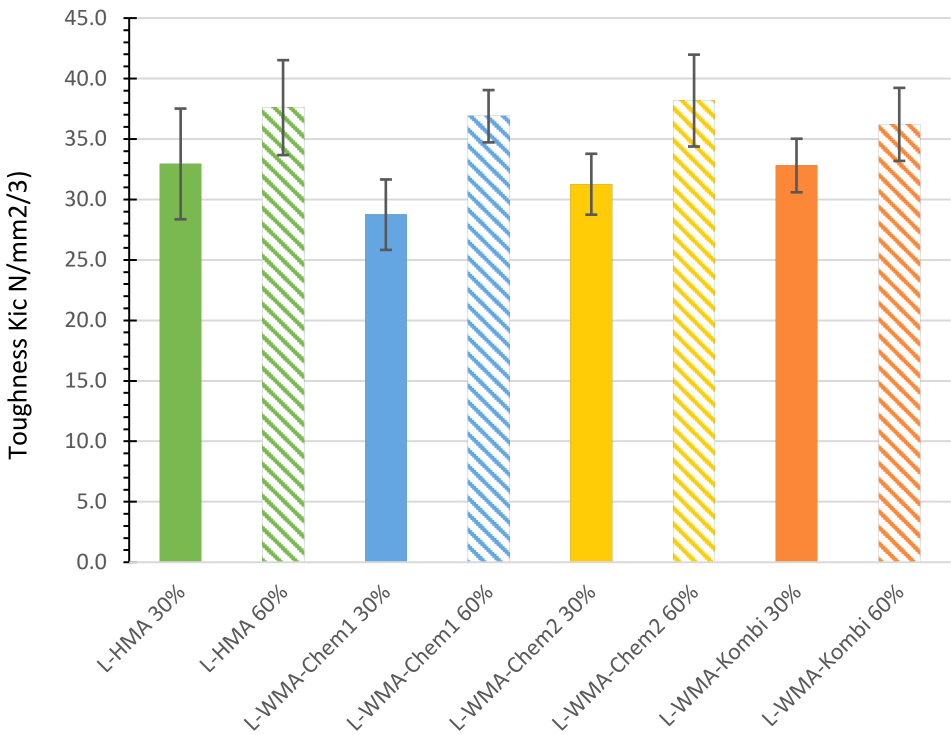


Figure 26: Semi-circular bending test toughness (Lab. mixtures)

6.2.6 Moisture resistance (ITSR)

Figure 27 shows the results of the moisture resistance in terms of the indirect tensile strength ratio, based on three replicate specimens. While all mixtures fulfil the standard requirement of 80 %, the values appear to be quite random, since in some cases mixtures with 30 % RAP achieve higher values whereas in other cases the opposite is valid. The HMA 30 % mixture shows a lower value (83 %) compared to the WMA 30 %, especially L-WMA-Chem2 30% with a value of 98 %. The HMA 60 % mixture achieves with 94 % the highest value compared to the WMA 60 % mixtures. Here, especially WMA-Kombi 60% has the lowest value with 82 %.

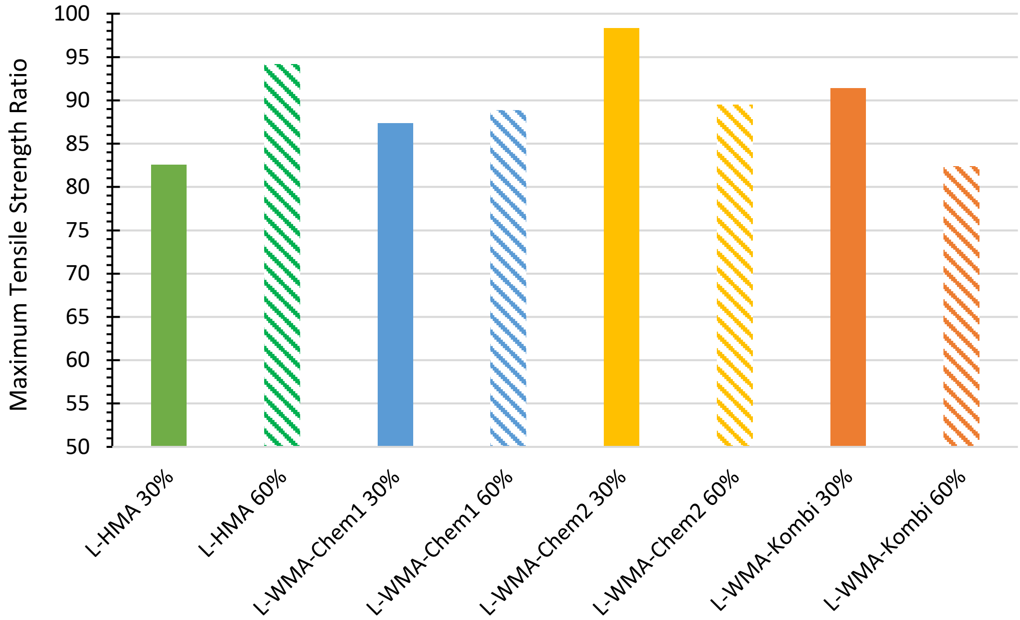


Figure 27: Maximum tensile strength ratio (ITSR) (Lab. mixtures)

6.2.7 Rutting resistance

Figure 28, Figure 29 and Figure 30 show the rutting test results for all lab mixtures. The target number of 30'000 cycles could not be achieved for all mixtures, as the rut depth exceeded the measuring limit of the device, which is why the results for 10'000 and 3'000 cycles are also given.

Only 4 laboratory mixtures could be tested to the aspired number of 30'000 cycles, while only L-WMA-Kombi 60% with a rut depth of 8.2% fulfils the requirement according to the Swiss standard of 10 %, followed by L-WMA-Chem1 60% with a value of 10.2 % and L-WMA-Chem1 30% with 13.8 %. The only HMA mixture that withstood 30'000 cycles was L-HMA 30%, but this mixture with a rut depth of 12.8 % could not achieve the standard requirement. When looking at the results after 10'000 cycles L-HMA 30% with a rut depth of 9.9 % and L-WMA-Chem1 60% with a value of 8.6 % fulfil the standard requirement.

Overall, the WMA mixtures with 30 % of RAP seem to perform slightly better. In summary, the rutting resistance of the lab mixtures are critical. This is not only true for the WMA mixtures, but also for the HMA mixtures. The reason for this behaviour could not be determined, especially since the air void content of all lab mixtures was close to the aspired value of 4.5 vol-%.

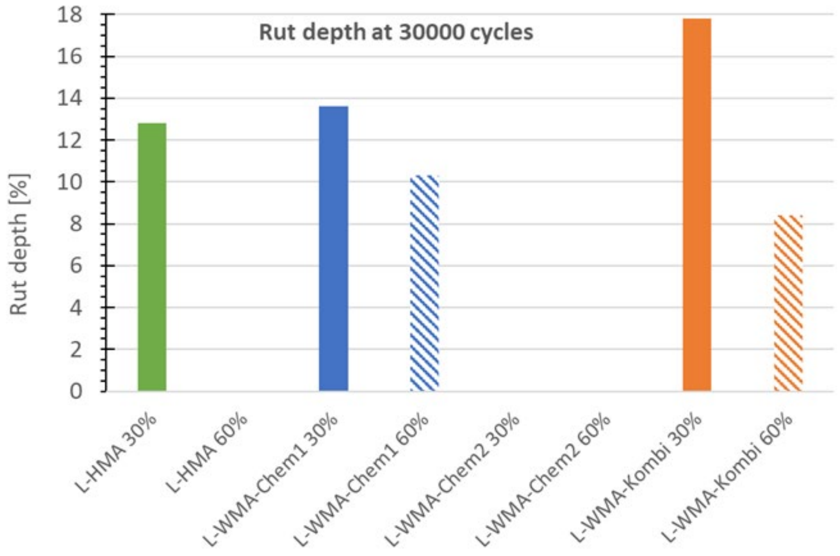


Figure 28: Rut depth of lab mixtures at 30'000 cycles

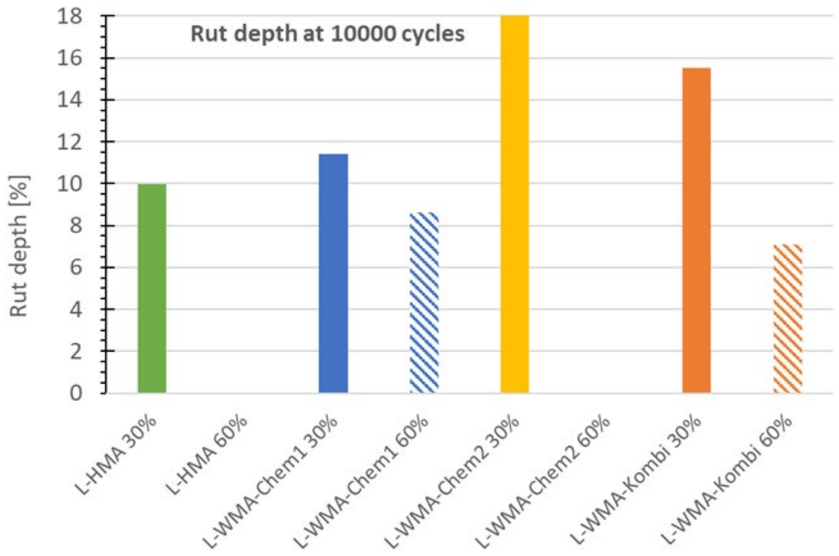


Figure 29: Rut depth of lab mixtures at 10'000 cycles

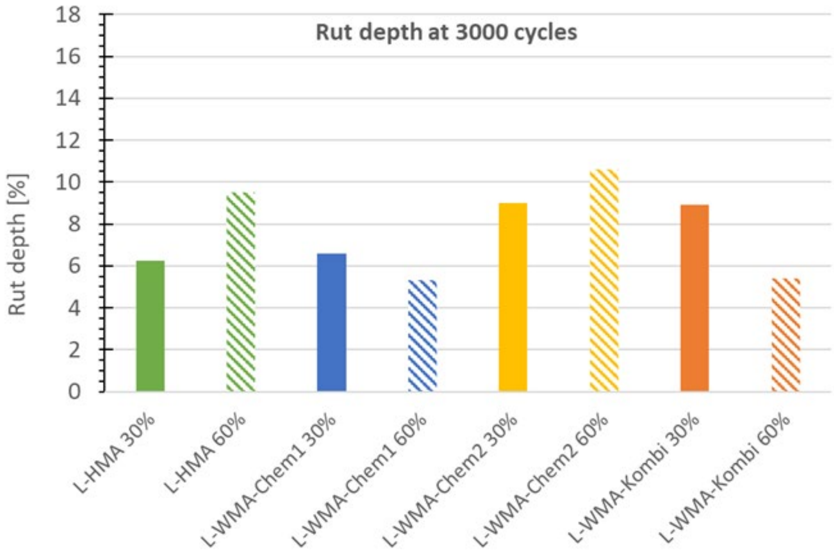


Figure 30: Rut depth of lab mixtures at 3'000 cycles

6.2.8 Stiffness (Modulus CIT-CY)

Figure 31 displays the stiffness modulus at -10 °C and 1 Hz for all laboratory mixtures. The results show that laboratory mixtures with 30 % RAP are about 10 % stiffer than the mixtures with 60 % RAP. The stiffness values of the WAM mixtures (are slightly higher or equal (L-Chem1 30%) compared the reference hot mix asphalt.

The overlayed master curves of all laboratory mixtures (Figure 32) are situated in narrow range. The highest stiffness value is observed for the Kombi mixture with 30 % RAP, followed by the other 30 % mixtures (HMA). On the softer side are the two mixtures with 60 % RAP. The mixture L-Chem1-30% stands out because it has the lowest stiffness values at high temperatures/frequencies but the highest stiffness values at low temperatures/frequencies.

The master curves of the laboratory mixtures with 60 % of RAP (Figure 33) are almost identical for all mixtures. The master curves of the mixtures with 30 % RAP (Figure 34) show more variability. The curves of the reference HMA and the mixture with Chem2 however have similar values. The Kombi mixture is clearly the stiffest mixture. The WAM mixture with additive Chem1 exhibits a different behaviour: it is harder at higher temperature but softer at lower temperatures.

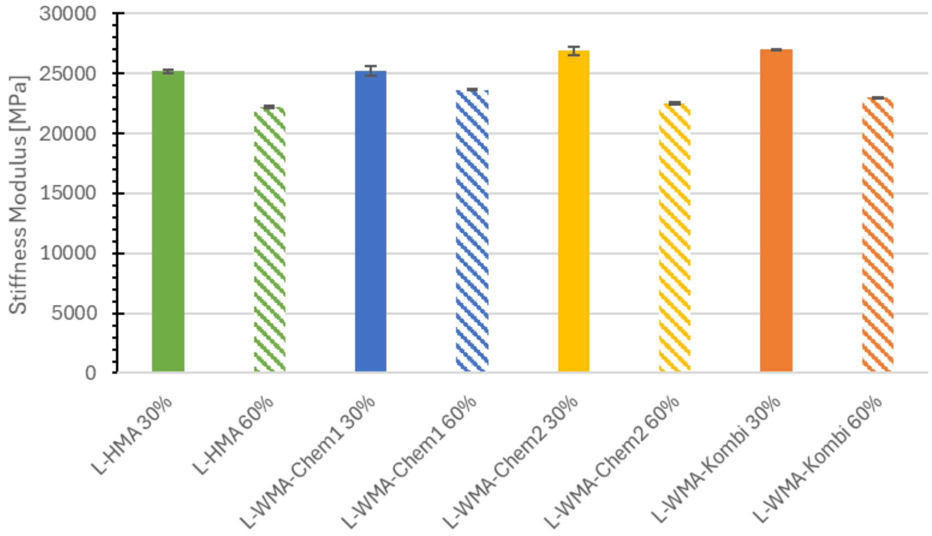


Figure 31: Stiffness modulus at -10°C and 1 Hz

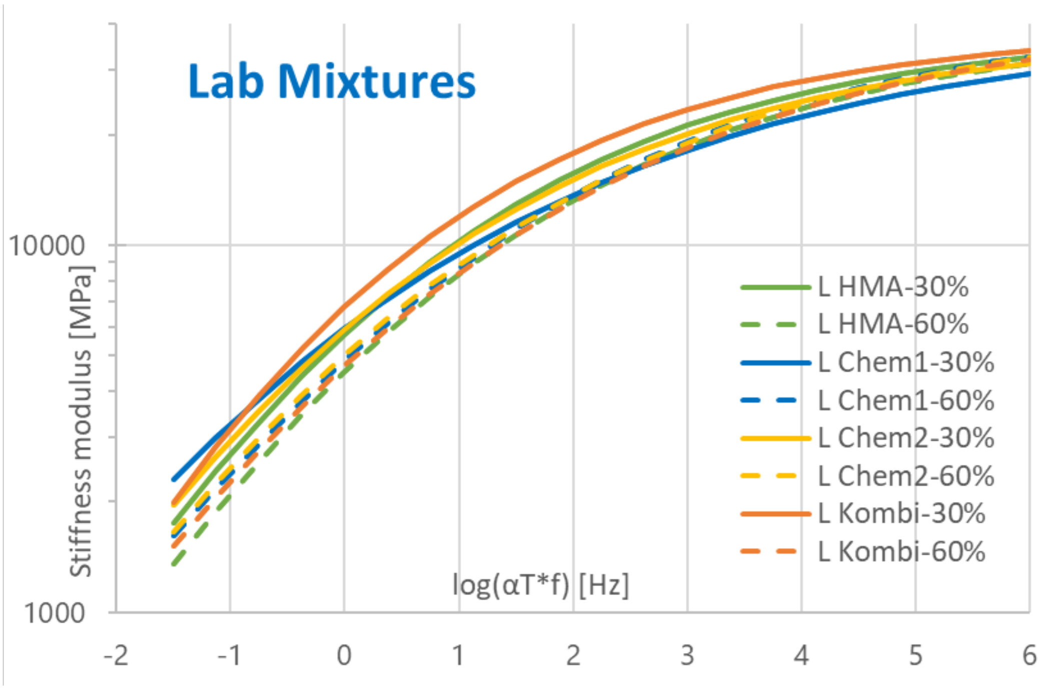


Figure 32: Stiffness modulus master curves for all laboratory mixtures

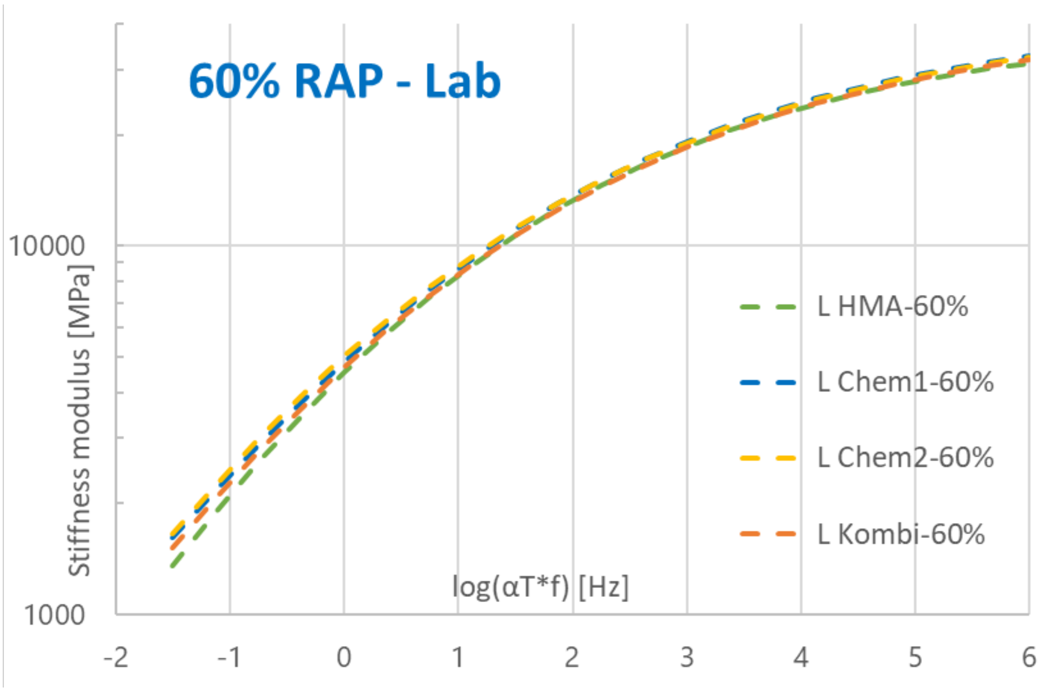


Figure 33: Stiffness modulus of the labotatory mixtures containing 60% RAP

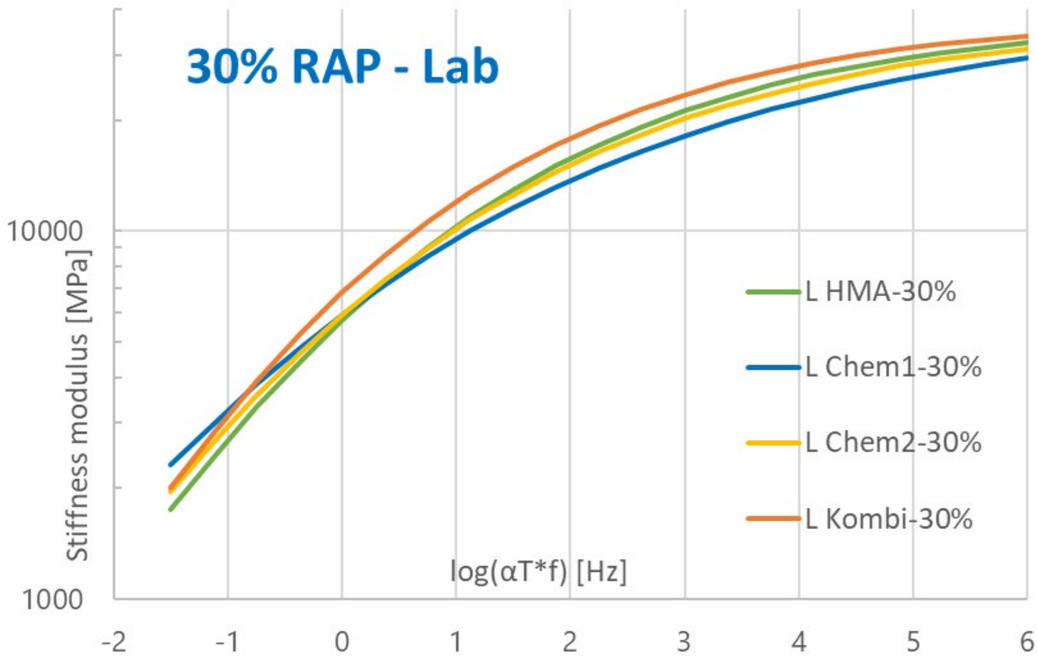


Figure 34: Stiffness modulus of the laboratory mixtures containing 30% RAP

6.2.9 Thermal stress restrained specimen test (TSRST)

The TSRST results in Figure 35 show that all WMA failure temperatures are rather low and similar to the HMA failure temperatures. The additive Chem1 with 30 % RAP shows the highest failure temperature (-34 °C), but the difference to the lowest failure temperature (-38 °C) is not large. Although the lab mixtures with 60 % showed in most other tests a higher stiffness, the TSRST temperatures do not reflect this trend. Comparing mixtures with 30 % and 60 % RAP, the failure temperature with 30 % RAP is lower for the reference hot mix, but the opposite for Chem1 and equal for Chem2 and the Kombi mixture. For the 60 % RAP, the failure temperatures of the WAM mixtures are slightly lower than for the HMA. In case of the 30%, the variation is higher, and no trend is observed.

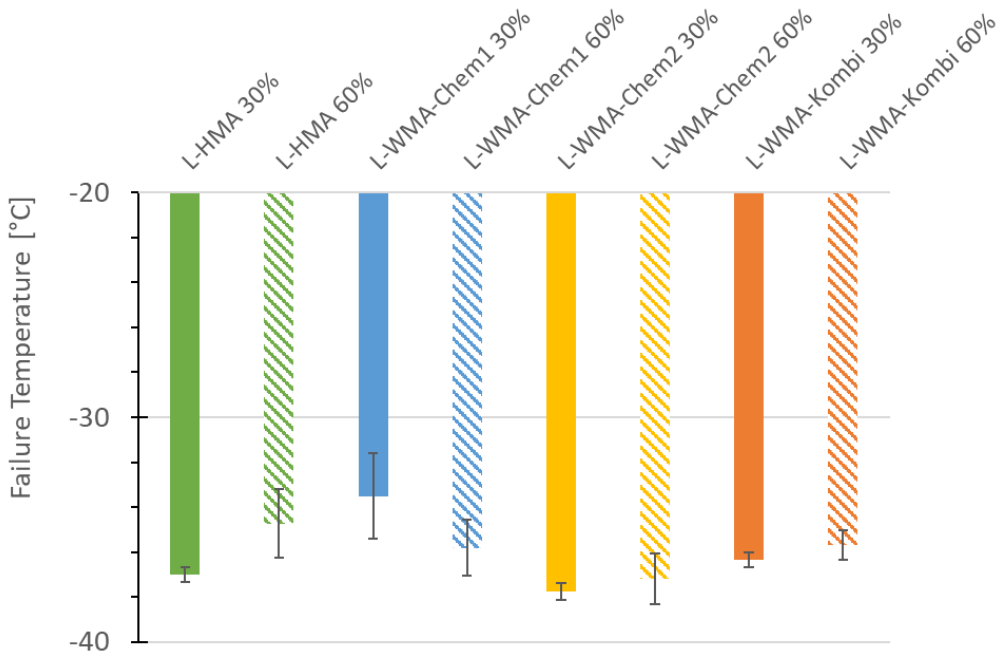


Figure 35: TSRST failure temperature

The failure stress results (Figure 36) of the different lab mixtures are within a narrow range. The values of the mixtures with 60 % RAP show a slightly higher failure stress than the mixtures with 30 % RAP.

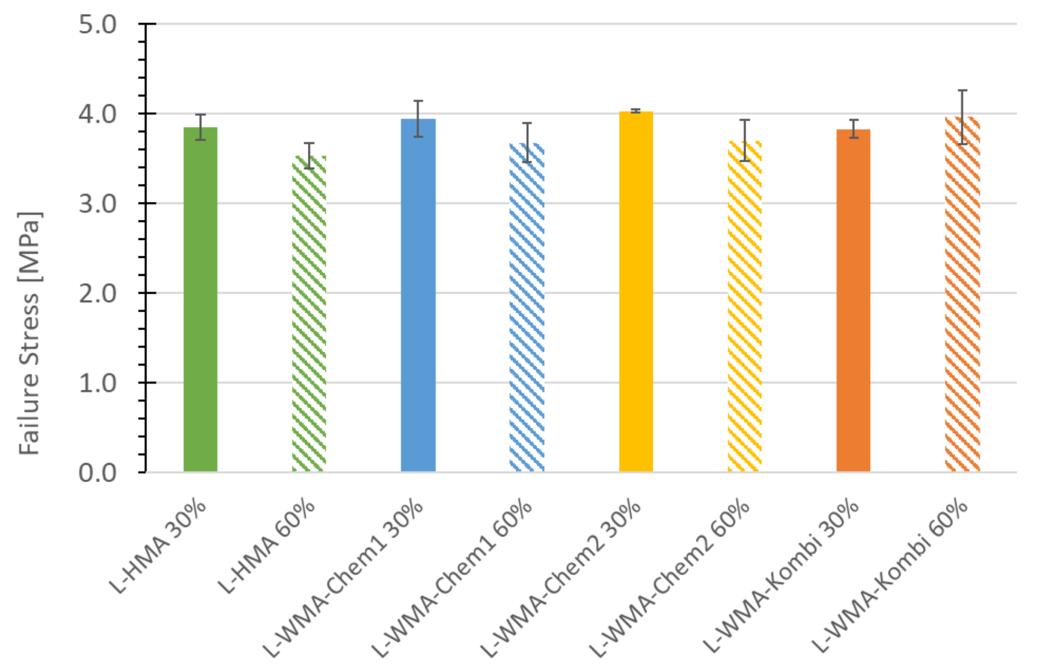


Figure 36: TSRST failure stress

6.3 Mechanical tests on aged materials

The evaluation of the long-term aging effects of the laboratory produced mixtures was performed to assess Marshall stability and indirect tensile strength ratio. For the ageing the method according to AASHTO R30 was used.

6.3.1 Marshall stability

The Marshall stability of the mixtures after aging illustrated in Figure 37 shows an increase in stability for most asphalt mixtures with a higher RAP percentage, particularly for L-HMA 60. However, while some WMA mixtures (such as L-WMA-Kombi 30% and L-WMA-Chem2 60%) exhibit comparable increases in stability, others, such as L-WMA-Chem1 30%, display a relatively smaller increase or even a slight reduction in stability. This indicates that the long-term performance of WMA mixtures is variable and dependent on the type of additive used. Comparing the Marshall stability results before ageing (Figure 22), it is evident that HMA mixtures experience a more consistent increase in stability after aging, whereas WMA mixtures show a varied behaviour.

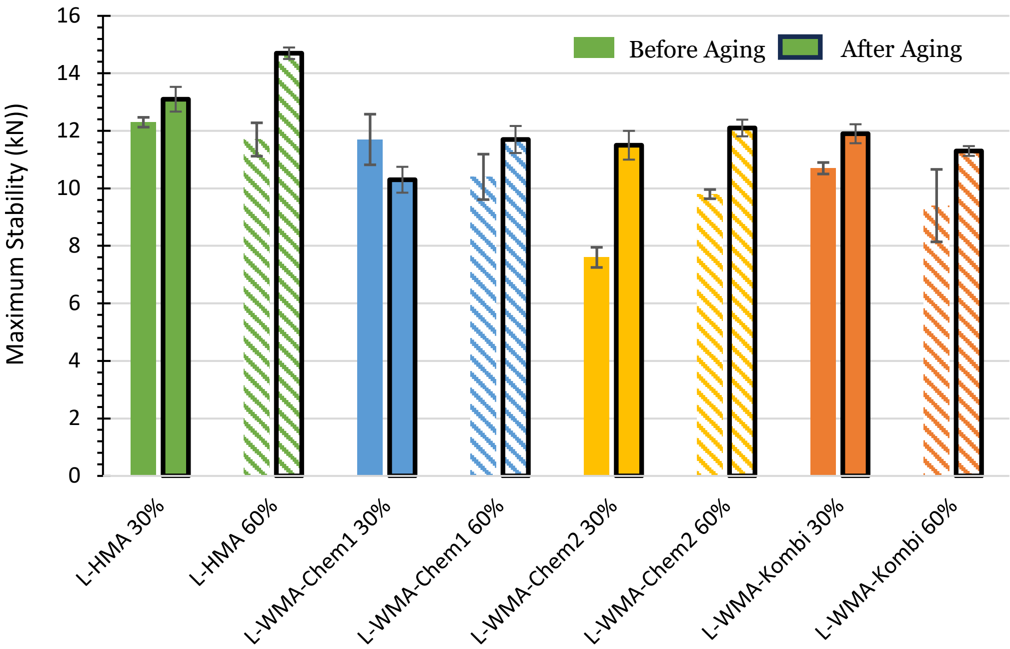


Figure 37: Marshall stability after mixture aging (Lab. mixtures)

6.3.2 Moisture resistance (ITSR)

The results of the indirect tensile strength ratio (ITSR) after artificial aging using AASHTO R30, as presented in Figure 38, demonstrate a general increase in ITSR across most asphalt mixtures compared to their values before aging. This indicates that aging positively impacts moisture resistance. Among the mixtures tested, L-HMA 30% retained a relatively high ITSR after aging, but L-HMA 60% exhibited a more noticeable reduction, suggesting that a higher reclaimed asphalt pavement (RAP) content in HMA may lead to greater sensitivity to aging. Similarly, the L-WMA-Chem1 30% and L-WMA-Chem1 60% mixtures performed exceptionally well, maintaining some of the highest ITSR values after aging, with L-WMA-Chem1 30% nearly reaching 100%. This indicates that the chemical additive used in WMA-Chem1 enhances resistance to moisture damage even after aging. On the other hand, L-WMA-Chem2 30% and L-WMA-Chem2 60% experienced moderate reductions in ITSR, with the 30% mixes showing a more significant decrease, suggesting that the aging effect was more pronounced in this mixture type. The L-WMA-Kombi 30% and L-WMA-Kombi 60% mixtures exhibited some of the best aging resistance, maintaining high ITSR values close to their unaged levels, indicating that the combination of WMA technology and additives effectively mitigates aging-induced deterioration.

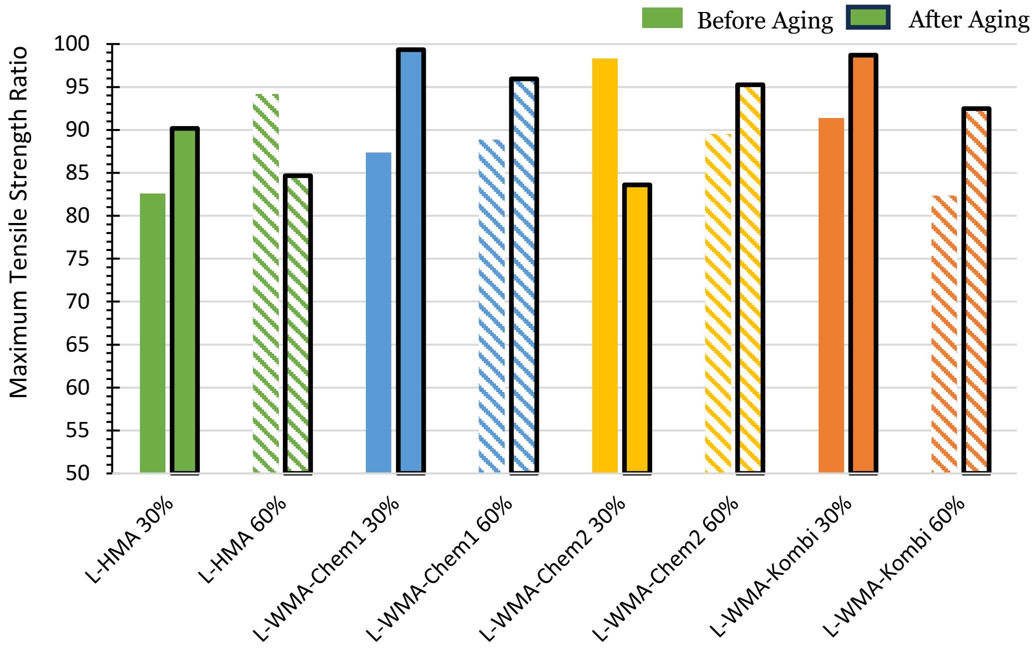


Figure 38: Maximum tensile strength ratio (ITSR) after mixture aging (Lab. mixtures)

7 Field test track

7.1 Organisation and selection of test track

The test track was constructed based on the results of the mixtures analysis (WP-3). For the binder layer it was decided to construct besides the reference (HMA), a section with WMA-Chem1, a section with WMA-Kombi (wax +Chem1) and a WMA-Foam section. It should be noted that all sections except the HMA containing only 50 % RAP, which was not in line with the original plan incorporated 60 % RAP. The binder layers were put on a base layer consisting of WMA AC T 22 S with a thickness of 80 mm and a penetration grade binder 50/70. The base layer itself had been put on a foundation layer AC F 32 with a thickness of 140 mm.

Table 10 gives detailed information on the test sections and the track construction between Worb and Bern.

Test track

Test Section	Direction	Construction Date	Material		Type
			Base Layer	Binder Layer	
1	Bern-Worb	03/02/2024	WMA ACT22S	WMA ACB16S	WMA-Kombi
2	Worb-Bern	04/06/2024	WMA ACT22S	WMA ACB16S	WMA-Foam
3	Bern-Worb	09/07/2024	WMA ACT22S	WMA ACB16S	HMA-Ref
1	Worb-Bern	28/08/2024	WMA ACT22S	WMA ACB16S	WMA-Chem

Table 10: Details of test track

7.2 Construction of test track

Table 11 provides production details of hot mix asphalt (HMA) and warm mix asphalt (WMA) in terms of the temperatures during production and the order in which the different ingredients (bitumen, aggregate, RAP and additives) were added. WMA additives, used to reduce the production temperature, were added at ambient temperature.

Table 12 shows the details of the plant operational sequence of mixing process to produce test track mixture. The production of the asphalt mixtures for the test track involved the use of four different asphalt technologies, WMA methods and a conventional HMA as the reference. All mixtures were based on AC B 16 S, using a consistent blend of virgin mineral aggregates and RAP. The mixing process was carried out in three main sequences. In Sequence 1, the virgin aggregates and RAP were charged into the mixer, followed by a uniform dry mixing time of 10 seconds for all mixtures. In Sequence 2, the type of binder and additive incorporation varied by mixture type: for WMA-Kombi, bitumen was mixed with a Chem1 and Wax was directly introduced into the mixer and mixed for 25 seconds; WMA-Foam used soft bitumen with a 15-second mixing time, followed by foamed bitumen in Sequence 3 to reduce production temperatures; reference HMA used standard bitumen without additives, with a total mixing time of 25 seconds.; and WMA-Chem1 was similar to WMA-Kombi but without the wax additive, with a mixing duration of 25 seconds.

Plant production details of HMA & WMA

Material \ Mixture	HMA (165°C to 170°C)	WMA (125 °C to 130 °C)	Mixing Order
Bitumen	160°C	130°C	3
Aggregates	195°C	140°C	1
RAP	135°C	135°C	2
Additives	-	Room Temperature	3

Table 11: HMA & WMA plant production details

Plant mixture production sequence

Operational Sequence	WMA-Kombi (AC B 16 S, R60)	WMA-Foam (AC B 16 S, R60)	HMA-Ref (AC B 16 S, R60)	WMA-Chem1 (AC B 16 S, R60)
Sequence 1	Virgin Mineral + RAP	Virgin Mineral + RAP	Virgin Mineral + RAP	Virgin Mineral + RAP
Mixing time	10 sec.	10 sec.	10 sec.	10 sec.
Sequence 2a	Bitumen + Additive (Chem1) via bitumen scale	Soft bitumen (pre-coating)	Bitumen	Bitumen + Additive (Chem1) via bitumen scale
Sequence 2b	Additive (Wax) direct introduction into mixer			
Mixing time	25 sec.	15 sec.	25 sec.	25 sec.
Sequence 3	-	Foamed bitumen	-	-
Mixing time	-	25 sec.	-	-

Table 12: HMA & WMA plant production sequence

Figure 39 shows an example of the recorded temperature for the WMA-Kombi 60% when applied on the construction site, with 129 °C. Maintaining the proper temperature is essential for achieving optimal workability and compaction of the asphalt mixture during construction. Mixture temperature data were collected for four test sections constructed as part of the field trials. These sections included various WMA and a conventional HMA. For the WMA-Kombi section constructed on 03/02/2024, the mixture temperatures measured at the plant and at the construction site were 132 °C and 129 °C, respectively. The WMA-Foam section, constructed on 04/06/2024, showed slightly higher temperatures of 139 °C at the plant and 133 °C on-site. The HMA reference section (HMA-Ref), built on 09/07/2024, exhibited higher temperatures, with 163 °C recorded at the plant and 164 °C at the site. Lastly, the WMA-Chem section, constructed on 28/08/2024, showed temperatures of 141 °C at the plant and 136 °C at the site. These values confirm the expected reduction in mixing and compaction temperatures for WMA compared to conventional HMA.

Figure 40 and Figure 41 illustrates the asphalt laying and compaction process during the construction of the test track. The desired compaction level was attained efficiently, without requiring excessive effort. Overall, the compaction process during the test track construction using both HMA and WMA mixtures aligned with the expectations based on expertise of the construction crew.

Figure 39: F-WMA-Kombi 60% mix temperature on site 129 °C

Figure 40: Laying of asphalt mixture during construction of test track

Figure 41: Compaction of test track

7.3 Investigation of field mixtures in comparison to laboratory mixtures

The field mixtures were collected from Weibel AG asphalt production plant to conduct further performance evaluations in the laboratory. These samples, called field or F, were tested and the results were compared with those of the mixtures produced in the laboratory called lab or L. The binder analysis of the field mixtures was performed on the extracted (recovered) binder.

7.3.1 Binder analysis (Recovered binder)

Figure 42 to Figure 45 illustrate the results of the binder analysis in terms of penetration, softening point, BTSV and Fraass breaking point for all laboratory mixtures in comparison with the field mixtures. The comparison between laboratory and field mixtures reveals slight differences in the penetration and softening point values of the recovered binders. The binders extracted from reference and Kombi mixtures tend to exhibit lower penetration values, indicating a brittle consistency compared to their laboratory counterparts. It is worth to be noted here that the field reference mixture contains 50 % RAP content compared to laboratory produced mixtures. The F-WMA-Chem1 60% results show consistent penetration values than their corresponding lab mixtures, suggesting that field aging is less severe or that the compaction and storage conditions contribute to maintaining mixture properties. Similarly, the softening point values are generally higher in field samples such as F-HMA 50% and F-WMA-Kombi 60%, indicating a potentially more temperature-resistant behaviour compared to the lab variants.

The Fraass Breaking Point results presented in Figure 45 illustrate that the values tend to become lower for the reference field mixtures showing less low temperature resistance compared to laboratory mixtures. Field mixtures (F-WMA-Chem1 and F-WMA-Kombi) exhibit slightly better low-temperature performance than laboratory samples, potentially due to aging effects or mixing differences. Field mixtures with Kombi and Foam techniques tend to improve low-temperature flexibility, as seen in the slightly higher negative values. In general, field mixtures exhibit higher softening points (Figure 43) and lower penetration values (Figure 42) compared to laboratory-prepared samples. This suggests that the short-term aging during construction leads to a stiffer binder. It is interesting to see, that for the chemical additive WMA-Chem1 the differences in penetration between field and laboratory mix are neglectable, while for the softening point and the BTSV they are rather profound.

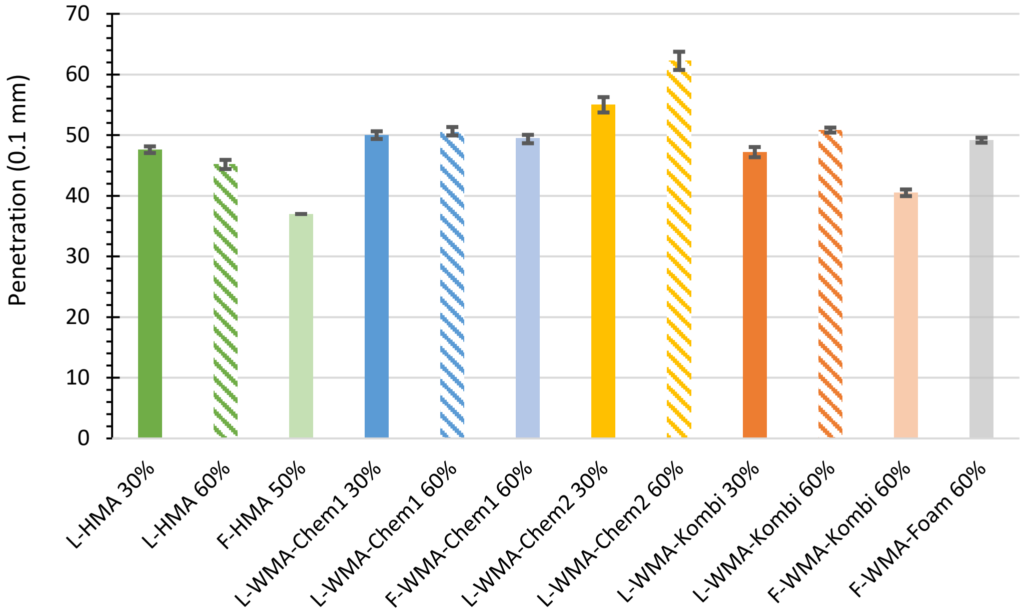


Figure 42: Penetration test results of laboratory and field mixtures (Lab. vs field mixtures)

As expected, the BTSV (Figure 44) gives similar trends as the softening point (Figure 43), while for the Fraass breaking point (Figure 45) the differences especially for the WMA mixtures are very small and for all mixtures including HMA within the precision of the test (see Figure 45).

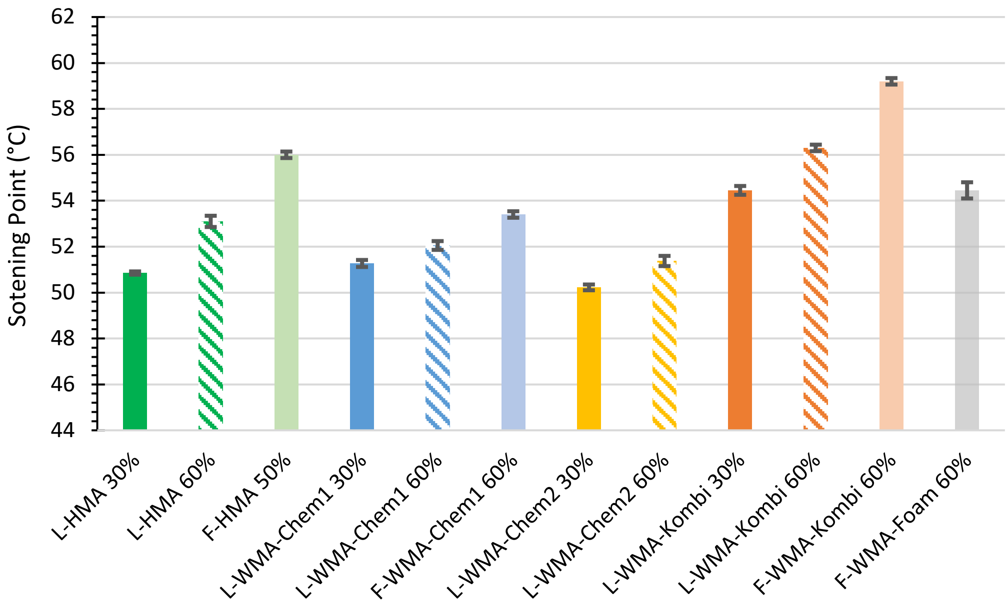


Figure 43: Softening point test results of laboratory and field mixtures (Lab. vs field mixtures)

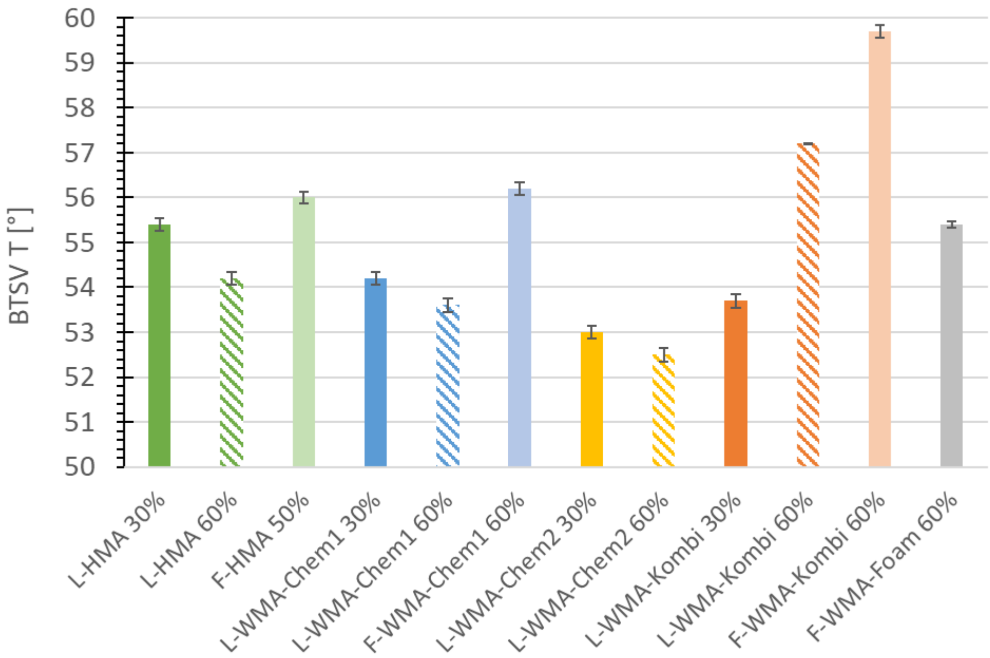


Figure 44: BTSV test results (Lab. vs field mixtures)

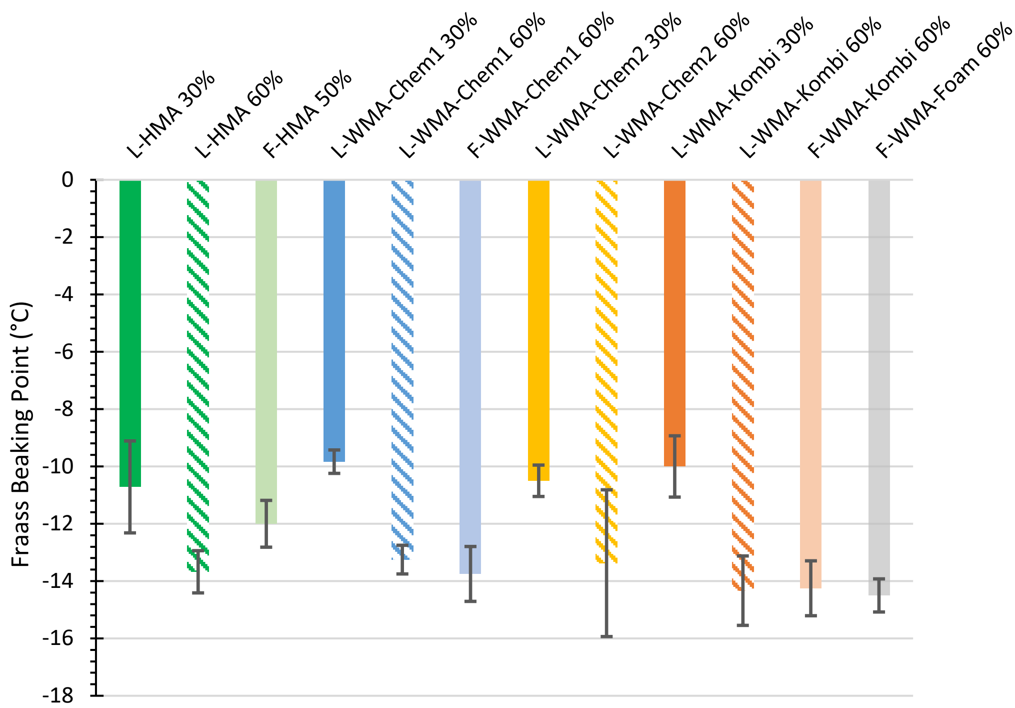


Figure 45: Fraass breaking point test results of laboratory and field mixtures (Lab. vs field mixtures)

7.3.2 Marshall air void content

Figure 46 illustrates the air voids (%) distribution for laboratory and field asphalt mixture. The results indicate that air void content varies between approximately 3.2 % and 5.2 %. Among the specimens, L-WMA-Kombi 30% exhibits the highest air voids percentage, exceeding 5.0 %, followed closely by L-WMA-Kombi 60%. In contrast, the lowest air void content is observed in L-HMA 30% and F-HMA 50%, both falling slightly above 3.0 %. The inclusion of WMA additives, particularly chemical and foam-based modifiers, appears to influence the air void content, with some mixtures demonstrating increased porosity compared to traditional HMA. These findings suggest that the selection of WMA technology and replacement levels can significantly impact the volumetric properties of asphalt mixtures, potentially affecting their compaction characteristics and long-term performance. Overall, the difference air voids between the laboratory and field mixtures were not significant.

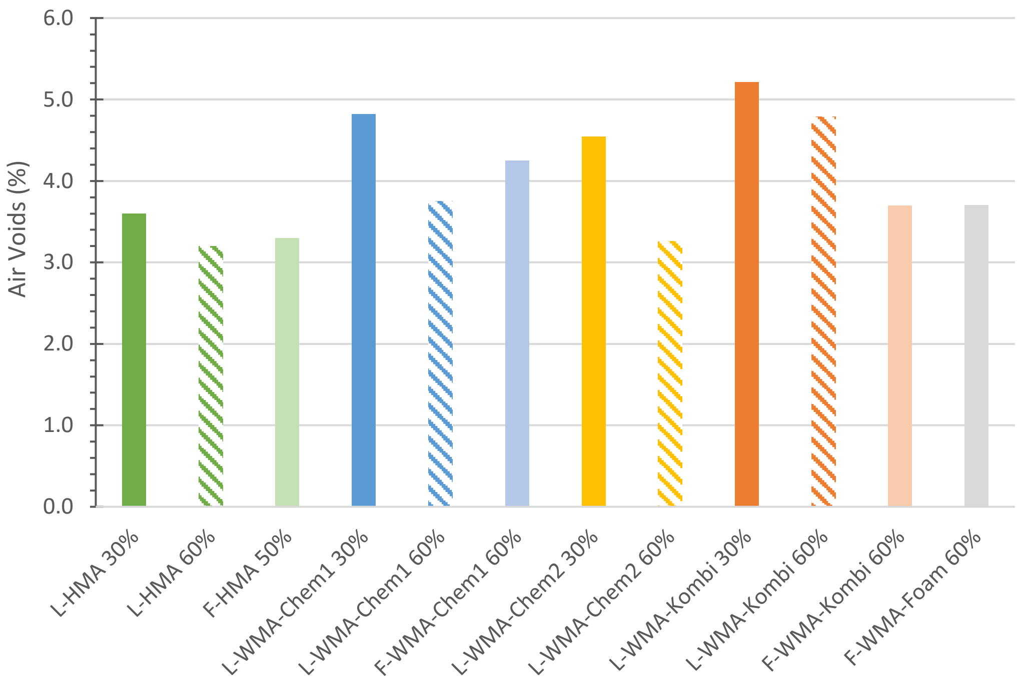


Figure 46: Marshall air voids distribution (Lab. vs field mixtures)

7.3.3 Marshall stability

Figure 47 illustrates the maximum stability (kN) of both laboratory and field obtained asphalt mixtures. The results show that the laboratory produced mixtures L-HMA 30% and L-HMA 60% exhibit high stability, confirming the well-established strength of traditional hot-mix asphalt. L-WMA-Chem1 30% and L-WMA-Chem1 60% also show high stability, suggesting that Chemical WMA additives (Chem1) maintain structural integrity even with RAP incorporation. WMA-Chem2 (30 % and 60 % RAP) exhibit lower stability, indicating that this chemical additive might not enhance stability as effectively as Chem1. Therefore, field mixtures concluded with the production of mixture with Chem1.

Field-Produced mixtures F-HMA 50% has the highest stability, confirming that HMA maintains its strength even in field conditions. F-WMA-Chem1 60% and F-WMA-Kombi 60% show competitive stability, indicating that WMA additives contribute positively to field performance. F-WMA-Foam 60% exhibits slightly better stability, indicating that foam-based WMA mixtures may be more effective than those using chemical additives. F-HMA 50% still achieves high stability, reinforcing the fact that HMA remains reliable with moderate RAP inclusion.

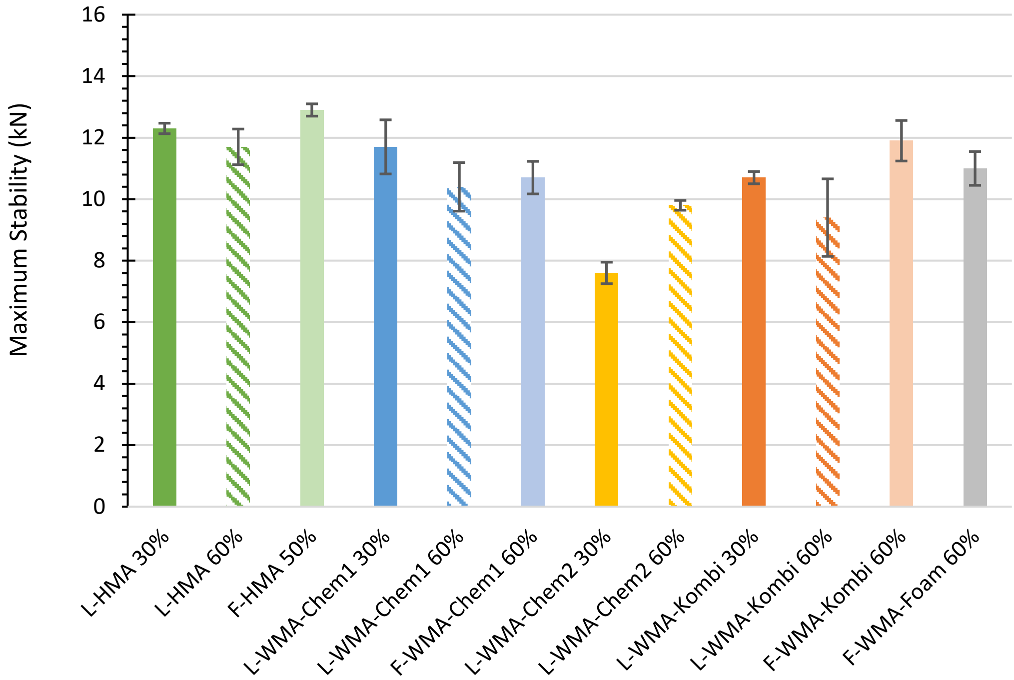


Figure 47: Marshall stability of laboratory and field produced mixtures (Lab. vs field mixtures)

7.3.4 Maniability

The maniability test results as shown in Figure 48 indicate that the higher RAP content (60 %) generally leads to increased maximum force values, indicating reduced workability. The results of a maniability test, which measures the workability of asphalt samples in terms of force (N). The test values are plotted for different samples, with the field samples labeled as F-WMA and the rest being laboratory-produced samples. The y-axis shows the maximum force (N) required for workability. The field samples (F-WMA) are likely to represent real-world conditions, while the laboratory samples are controlled and produced under specific conditions. Comparing these two sets helps in validating the laboratory methods and ensuring they accurately replicate field conditions.

Field produced WMA mixtures (F-WMA) consistently exhibited higher maximum force values compared to their laboratory prepared counterparts, confirming that short-term aging during production and placement increases stiffness and reduces workability. However, the field produced HMA mixture F-HMA 50% exhibited a lower force requirement relative to its counterpart and other field-aged samples, likely due to its reduced RAP content. Among field WMA mixtures, F-WMA-Chem1 60% demonstrated particularly higher force values compared to F-WMA-Foam 60% and F-WMA-Kombi 60%, further highlighting the stiffer effect of both RAP and aging. The Kombi mixtures, which include both wax and Chem1 additives, showed lower maximum forces, indicating they are more workable than mixtures with only chemical additives. In laboratory mixtures, L-WMA-Kombi 60% also showed a lower force requirement, supporting the observation that the Kombi additive system increases mixture workability. Interestingly, despite the generally favorable performance of

Chem1 in lab mixtures, the F-Chem1 field mixture required a high maximum force, suggesting that workability may be reduced under field conditions even with chemical modification.

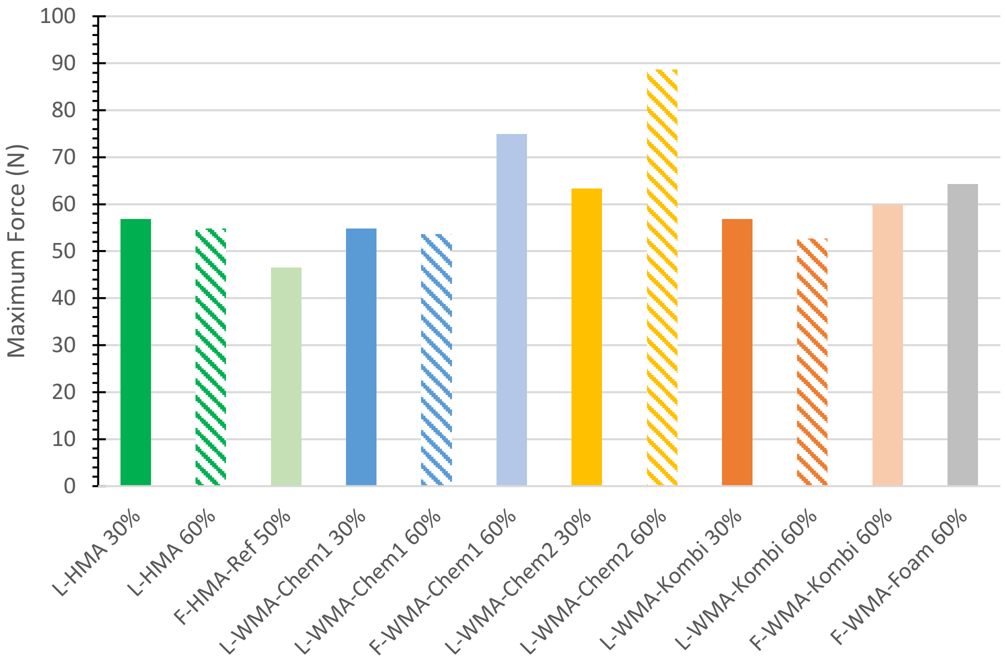


Figure 48: Maniability test results of laboratory and field mixtures (Lab. vs field mixtures)

7.4 Compactability

The gyratory compaction results of the field mixtures are presented in Figure 49. The X-axis shows the number of compaction cycles (on a log scale), and the y-axis shows the degree of compaction (%). F-HMA-Ref 50% reaches slightly higher compaction levels than WMA mixtures. The WMA mixtures reached the same level of compaction after 200 gyrations. There is no significant difference in the initial densification of the mixtures. F-WMA-Foam has the steepest slope (3.8737), meaning it responds most efficiently to compaction.

Figure 50 presents a comparative analysis of laboratory and field-produced asphalt mixtures, with all samples compacted under identical laboratory conditions to isolate the effect of production method on compactability (K) and initial void content V (1). The plant-produced mixtures generally exhibited lower initial void contents than the laboratory-produced ones, suggesting that the production method can influence the material's compactability and early densification behaviour. L-WMA-Kombi 60% has still the best compactability among all field and lab mixes. The field mixes have similar compactability, except F-WMA-Chem 1 60%, which has relatively lower compactability. Laboratory mixes generally show higher compactability (K-values) than their field counterparts.

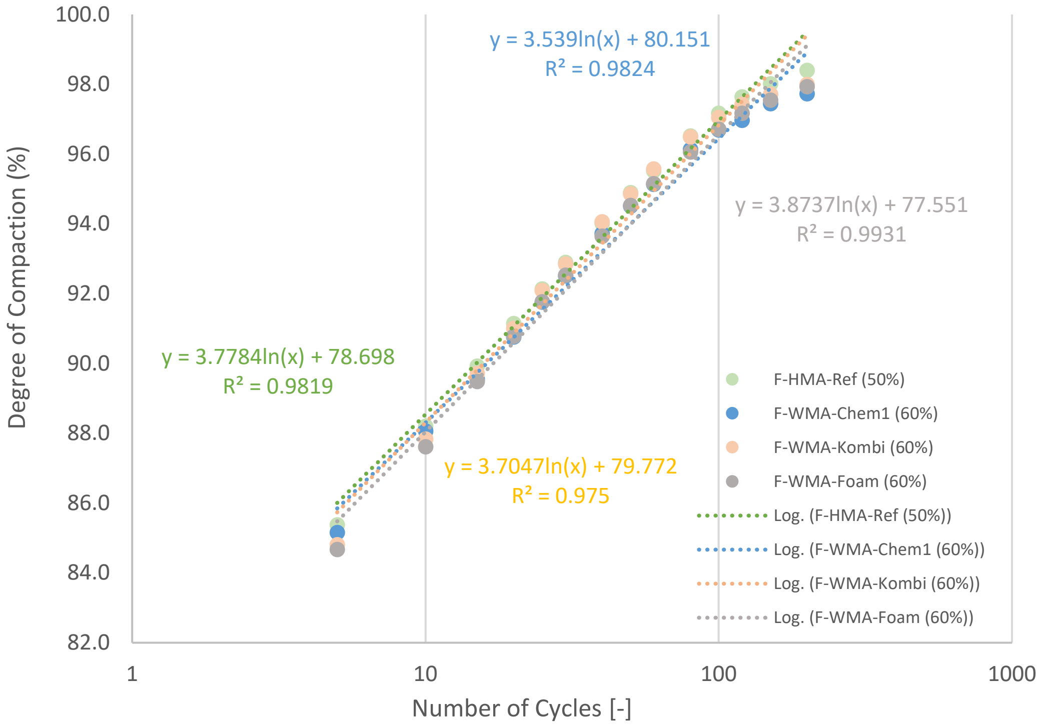


Figure 49: Field mixture compactability (Field mixtures)

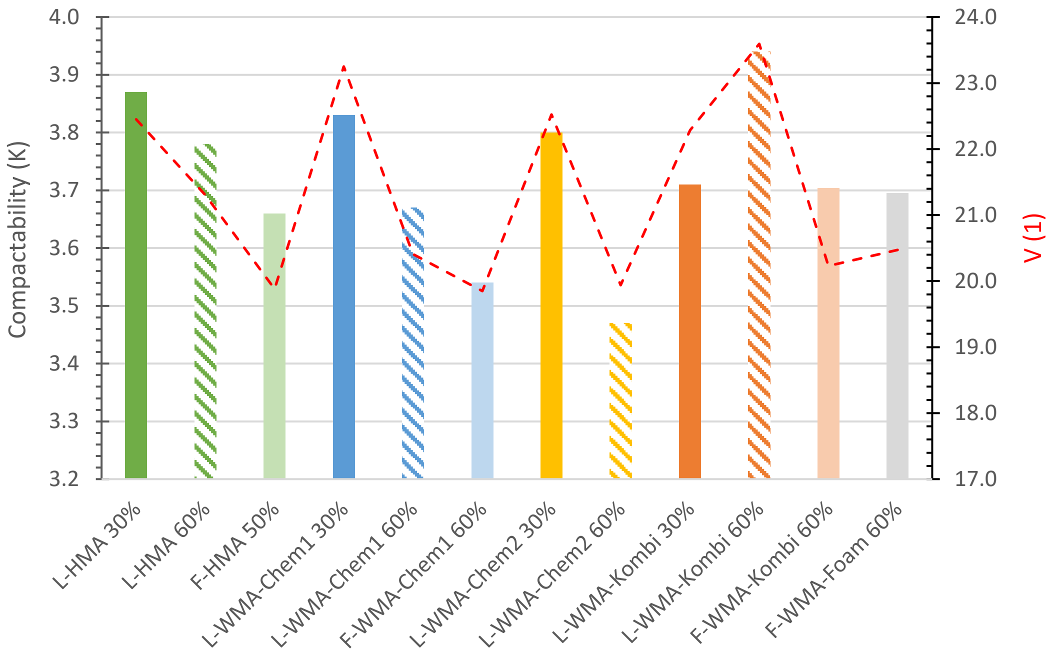


Figure 50: Mixtures compactability (K) and void content V (1) (Lab. vs field mixtures)

7.5 Semi-circular bending (SCB)

The SCB test results of mixtures produced in laboratory and field obtained mixtures are presented in Figure 51. Each set of results is based on four replicate test specimens. The laboratory mixtures L-HMA 30% and L-HMA 60% show high toughness, confirming that hot mix asphalt remains structurally resilient. L-WMA-Chem 1 (30 % RAP) and (60 % RAP) exhibit slightly lower toughness, suggesting that Chem1 reduces toughness compared to HMA. L-WMA-Chem2 and L-WMA-Kombi exhibit some of the highest toughness values, indicating that these additives enhance fracture resistance. Field produced mixtures F-HMA 50% shows strong toughness, reinforcing that field-produced HMA maintains durability. F-WMA-Kombi 60% exhibits one of the highest toughness values, confirming that the wax Chem1 combination enhances fracture resistance even in field conditions. F-WMA-Foam 60% and F-WMA-Chem1 60% display moderate toughness, suggesting that different chemical additives vary in effectiveness.

The influence of higher RAP content (60 %) does not always reduce toughness as some WMA mixtures (e.g., Kombi and Chem2) still perform well. F-WMA-Chem1 shows a noticeable decrease in toughness with RAP, suggesting that Chem1 might not optimize RAP integration as effectively as Kombi or Chem2. The field mixtures F-HMA 50% exhibits strong performance, reinforcing that traditional HMA remains a reliable choice for RAP incorporation. Overall, HMA and WMA lab samples generally show slightly higher toughness than field-prepared counterparts, likely due to controlled manufacturing conditions in laboratory settings, ensuring consistent material blending, compaction, and curing. Field-prepared mixtures are subject to environmental factors, variations in compaction, and on-site inconsistencies, leading to slight reductions in performance. Field prepared WMA mixtures with Chem1, Kombi and Foam maintain high fracture resistance, showing that these additives work well in real-world conditions. F-HMA 50% has one of the lowest variabilities, showing that traditional HMA offers consistent and predictable performance. WMA-Chem1 (30 % and 60 %) shows greater variability, indicating that its performance is less consistent, possibly due to RAP-related stiffness effects. Moreover, these analyses confirm that combining WMA technologies with high RAP content is achievable without sacrificing toughness, but the choice of additive plays a critical role.

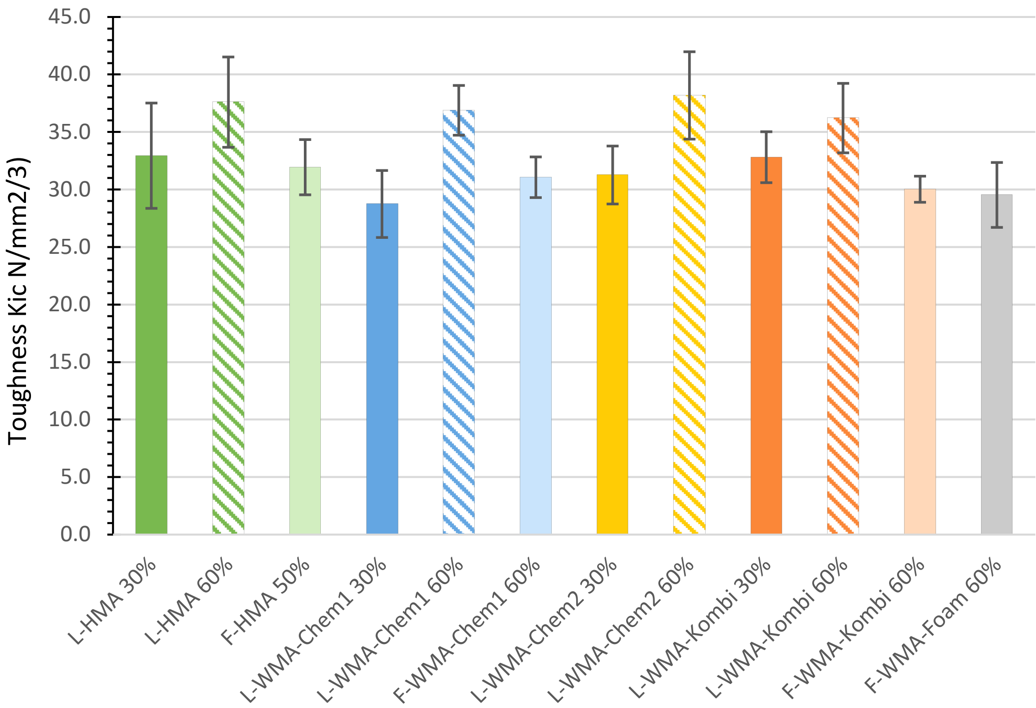


Figure 51: SCB test results of laboratory and field mixtures (Lab. vs field mixtures)

7.6 Moisture resistance (ITSR)

Figure 52 compares the maximum tensile strength (ITS) in dry and wet conditions for different asphalt mixtures, based on three replicate specimens tested. Dry Condition generally shows higher strength compared to Wet Condition across all mixtures, indicating moisture susceptibility. HMA (RAP 30 %) has the highest ITS in dry conditions, while other mixtures, especially WMA and field mixes F-WMA, exhibit slightly lower ITS values. Some warm mix asphalt (WMA) and field-produced (F-WMA) mixtures still maintain competitive ITS values, suggesting that specific additives help retain strength in wet conditions.

Figure 53 shows the Tensile Strength Ratio (TSR) indicating moisture Resistance. TSR is the ratio of wet to dry tensile strength, demonstrating how well the mixture resists moisture damage. A higher TSR (closer to 100 %) means better moisture resistance. Some mixtures exceed 90 %, suggesting strong moisture resistance. Other mixtures show relatively lower TSR values, indicating greater susceptibility to moisture damage. Field-produced mixtures (F-WMA) seem to maintain higher TSR values compared to some laboratory-produced ones, which could be due to real-world compaction and short-term aging effects. Overall, the moisture conditioning weakens asphalt mixes. The dry condition strengths are always higher, and RAP content also affects strength, i.e. higher RAP content (50 % to 60 %) can influence both ITS and TSR. Field mixtures (F-WMA) seem to perform better in some cases, possibly due to aging or additives. Most mixtures exhibit a decrease in ITS under wet conditions, indicating the impact of moisture. The decrease varies among different mixtures, with some showing better moisture resistance. TSR values above 85 % to 90 % are considered high moisture resistance. TSR values below 80% indicate potential moisture susceptibility.

Higher RAP content (50 % and 60 %) may reduce ITS slightly but can improve moisture resistance due to aged binder. The RAP mixture F-HMA-Ref (RAP 50 %) show good TSR, suggesting they maintain strength under wet conditions. However, lab-produced WMA mixes with 60 % RAP show lower TSR. Field mixtures (F-WMA) generally have higher TSR, meaning they perform better in resisting moisture. Laboratory produced WMA mixes tend to show a more significant drop in ITS under wet conditions. Lab mixtures might lack certain field conditioning effects, leading to greater moisture sensitivity.

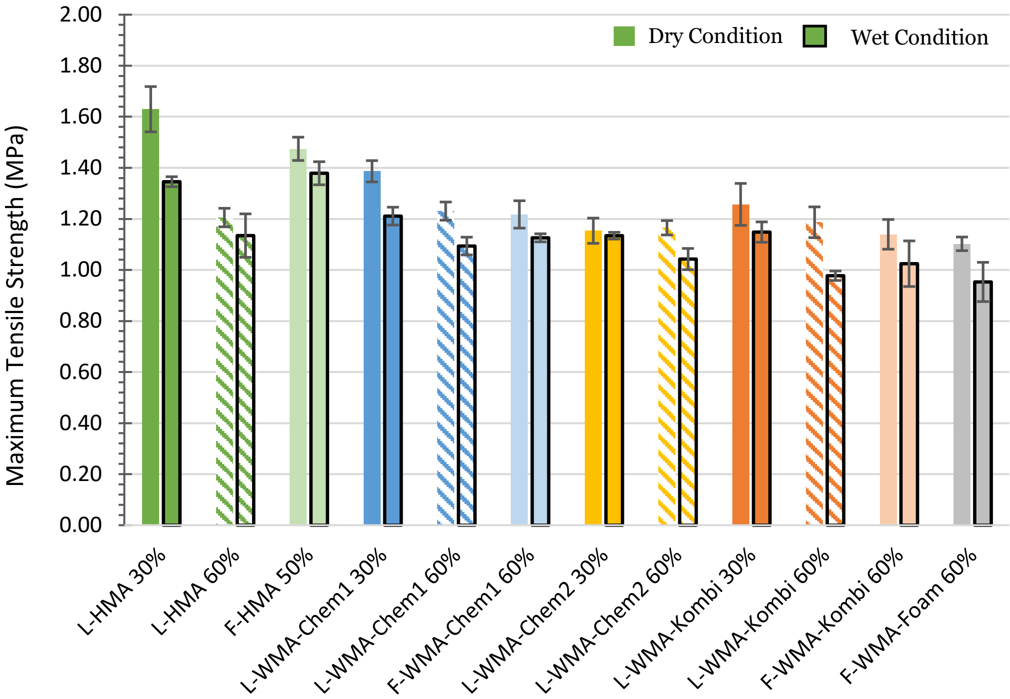


Figure 52: Maximum tensile strength of mixtures in dry and wet condition (Lab. vs field mixtures)

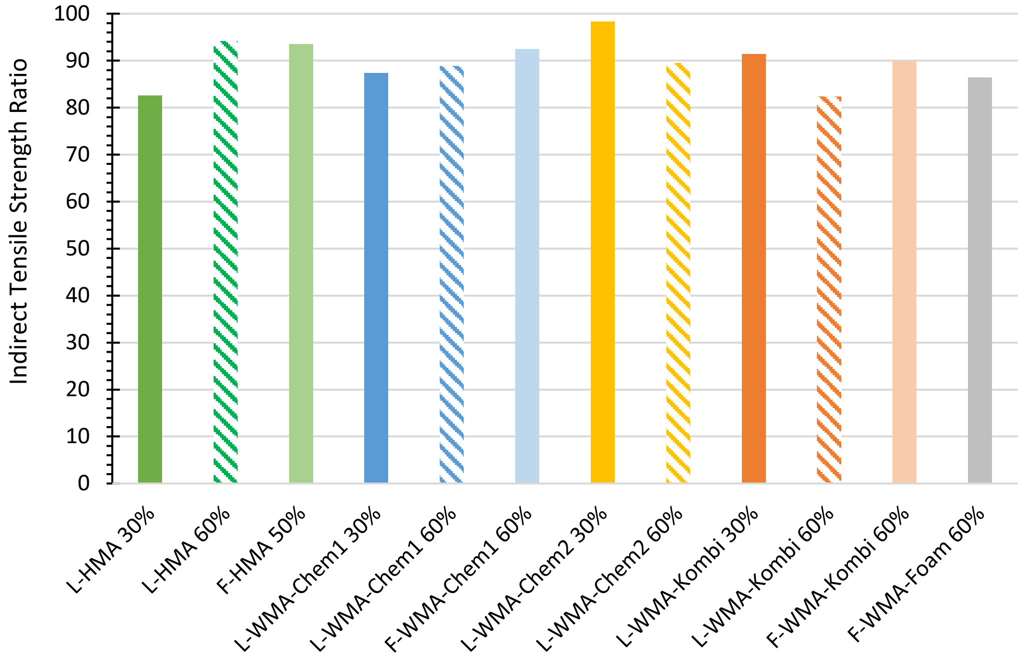


Figure 53: Indirect tensile strength ratio (Lab. vs field mixtures)

7.7 Rutting resistance

Figure 56, Figure 57 and Figure 57 show the rutting test results for all lab and field mixtures. Again, the results for 10'000 and 3'000 cycles are also provided.

In Addition, the void content for all rutting specimens is given in Figure 55.

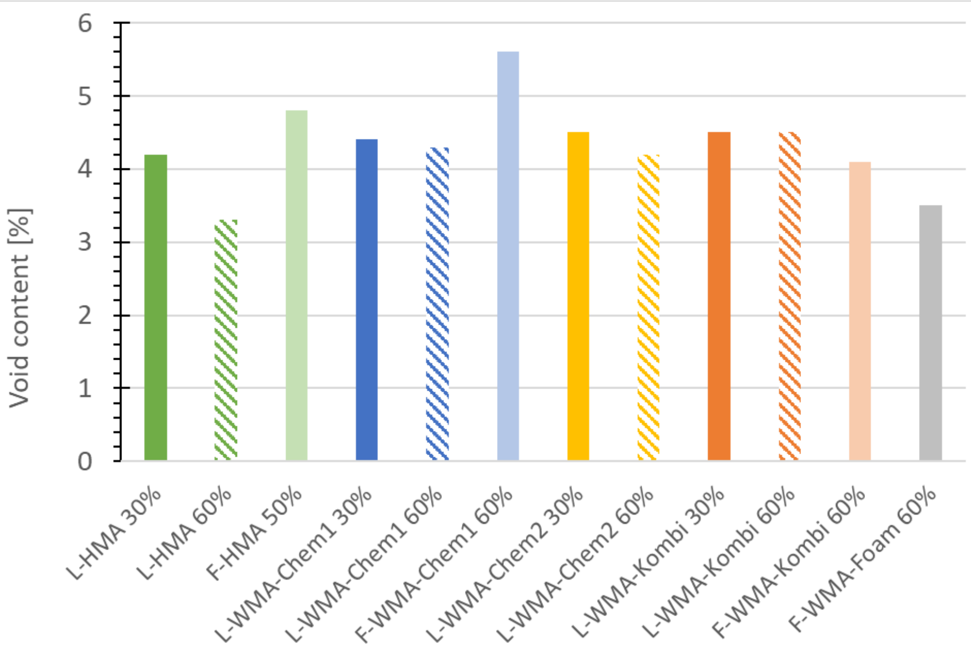


Figure 54: Void content of all rutting specimens

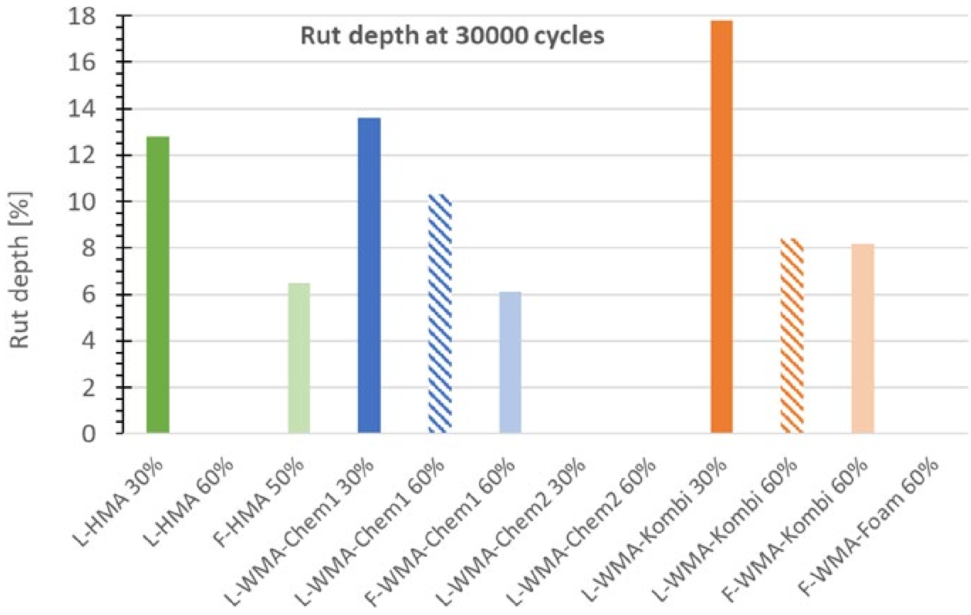


Figure 55: Rut depth of lab and field mixtures at 30'000 cycles

All field mixtures, except F-WMA-Foam 60% could be tested with 30'000 cycles. The measured rut depths' lie between the values of 6.1% for F-WMA-Chem1 60%, 6.5 % for F-HMA-50% and 8.4% for F-WMA-Kombi 60% and therefore fulfil the standard requirement.

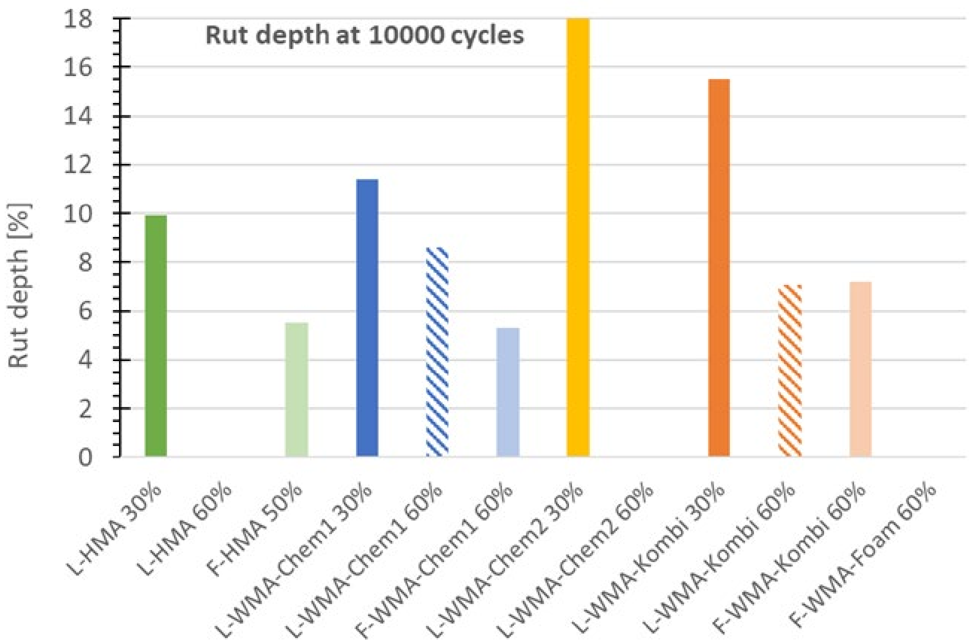


Figure 56: Rut depth of lab and field mixtures at 10'000 cycles

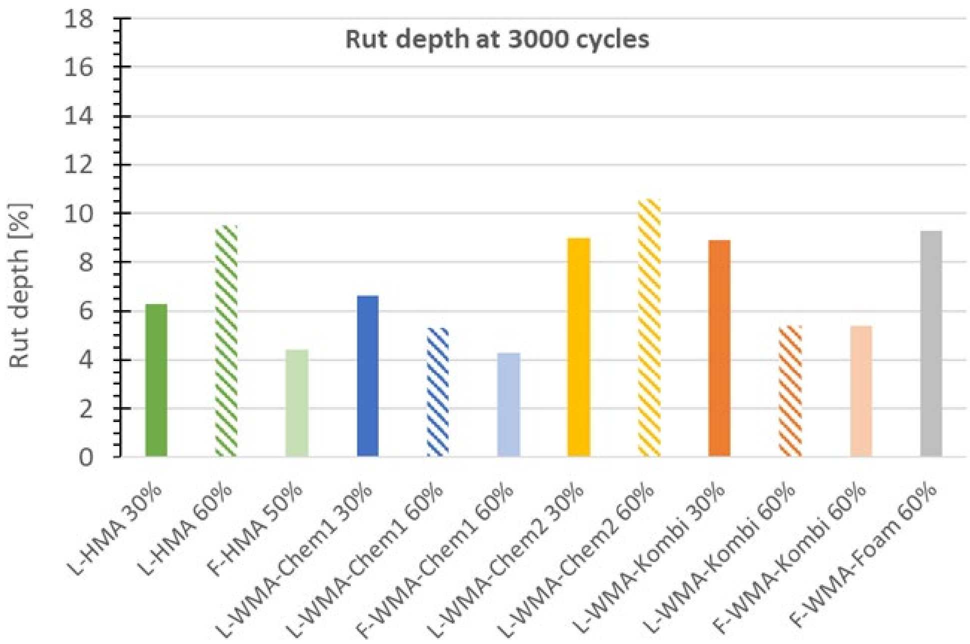


Figure 57: Rut depth of lab and field mixtures at 3'000 cycles

The field mixture F-WMA-Foam 60% could not be tested with 10'000 cycles. After 3000 cycles its rut depth was determined to be 9.3 %.

All field mixtures except WMA-Foam fulfil the standard requirements according to the Swiss standard (≤10%). A comparison between field and laboratory mixtures reveals a better resistance against permanent deformation for the field mixtures. Although the RAP content was different for the HMA field mix (50 %), the WMA 60% field mixtures, except F-Foam 60% show a good and comparable behaviour with the HMA.

7.8 Stiffness (Modul CIT-CY)

The master curves (Figure 58) of all asphalt mixtures are situated in a narrow range, especially at lower temperature and high frequency. At higher temperature the differences are more pronounced. At first glance, no major trend is detected, which makes it necessary to discuss the results in groups. Figure 59

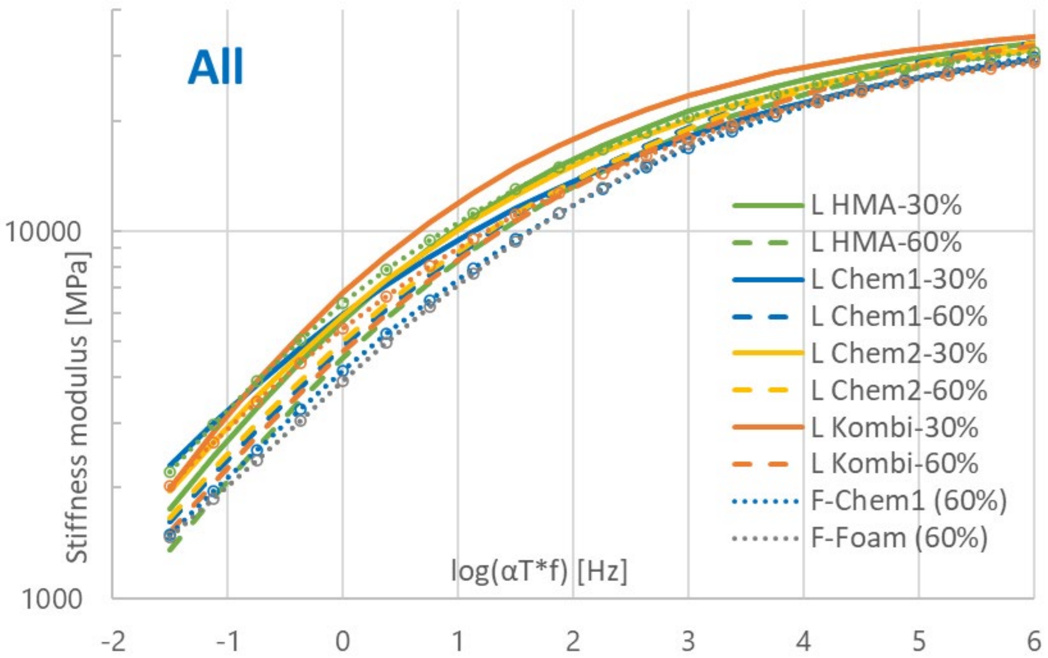


Figure 58: Stiffness master curves for all asphalt mixtures

Investigating only the results of the mixes with 60 % RAP in the field (Figure 59) makes it possible to detect some differences. Chem1 and the Foam mixtures are identical with the lowest values at low stiffness. The differences at high stiffness are generally smaller than at low stiffness. The HMA is the hardest and the F-Kombi lies in between. Obviously, the added wax results in a higher stiffness at higher temperature. However, because only three frequencies have been used in testing, the extended range, which is gained by the temperature time superposition is limited. The highest temperature obtained by this process has been calculated to be around 40°C. In theory, stiffness at any temperature can be calculated but with high uncertainty outside the measurement range.

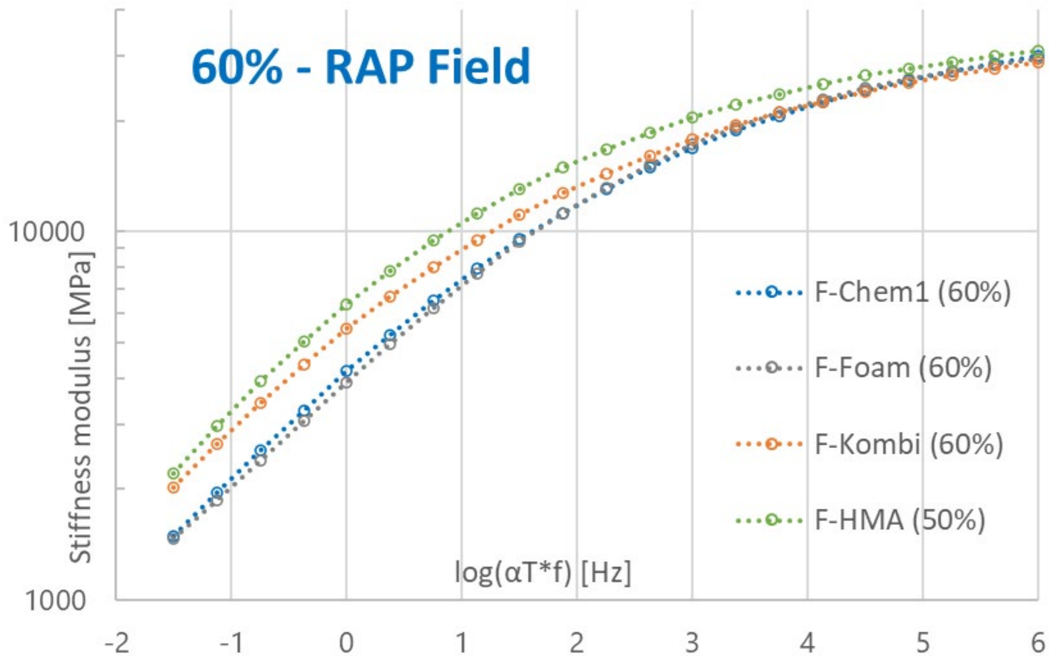
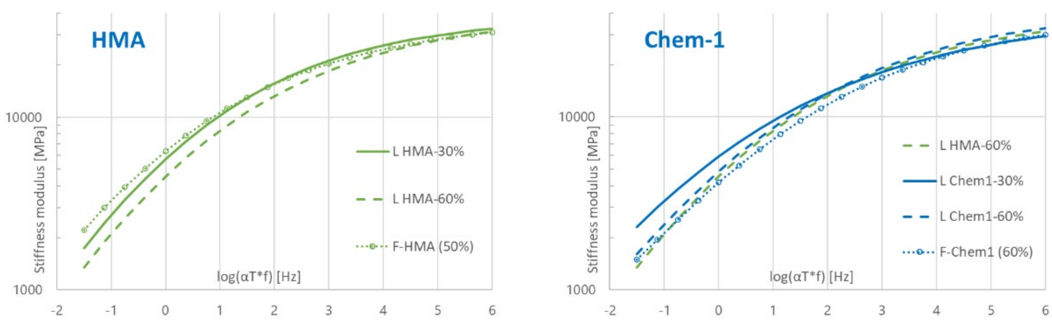


Figure 59: Stiffness master curves for all field mixtures

Analysing the WMA mixtures with the three different additives and the reference HMA separately, allows to identify some trends, although the differences are not very pronounced (Figure 60). Except for the HMA all mixtures with 30 % RAP have the highest stiffness. The field mixtures are not consistently lower or higher than the laboratory mixtures. In the case of the HMA, the field mixture is slightly stiffer than the 30 % lab mix, but for Chem-1 it is the lowest, but very close to the 60 % lab mixture. The field mixture of the Kombi shows a different curve form, which is similar to the curve of the mixture L-Chem-1-30%: lower at high stiffness but higher at low stiffness.



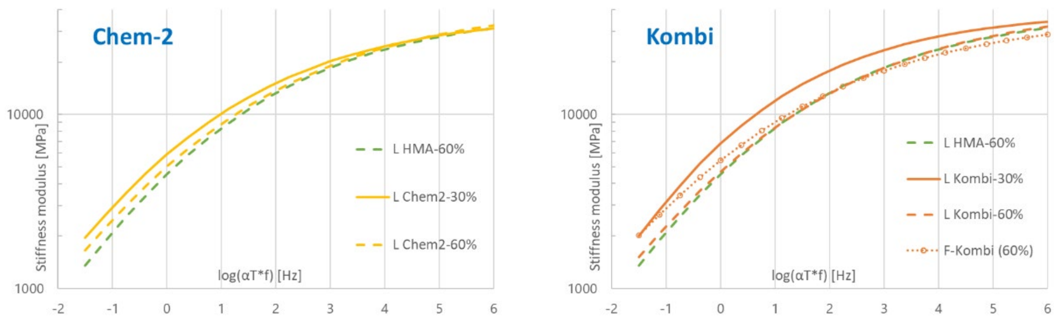


Figure 60: Master curves for the different additives and the reference HMA

There are two trends for the stiffness modulus, which are revealed at low temperature of -10 °C (Figure 61). All field mixes show a lower stiffness modulus compared to the respective lab mixtures. The same is observed for the mixes containing 60 % (50 %) RAP versus 30 % RAP. Comparing the different WMA procedures or additives, no significant differences can be recognized, neither for the field nor the lab mixtures with one exemption. The HMA field mix with 50 % RAP is significantly higher than all the WMA field mixes.

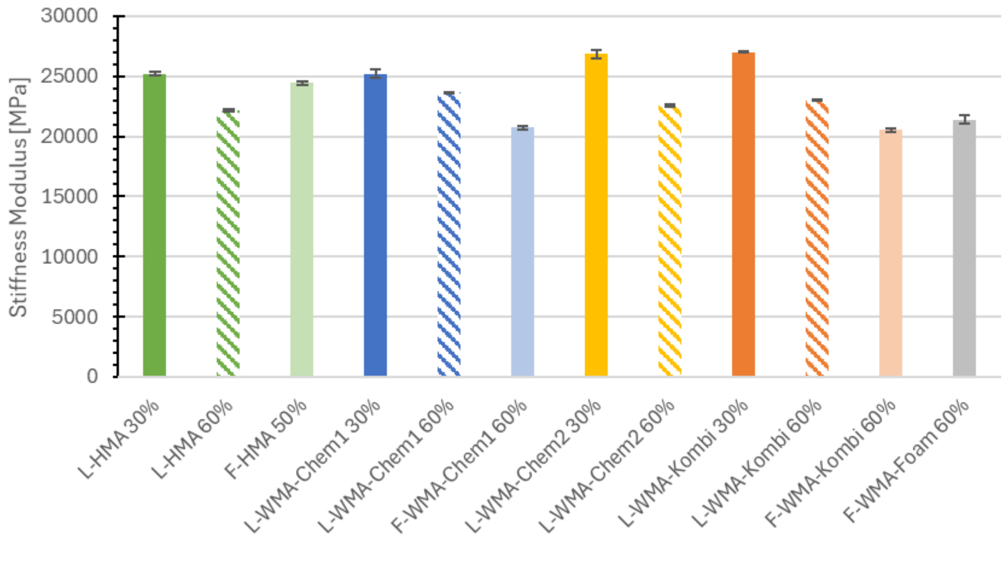


Figure 61: Stiffness modulus at -10°C and 1 Hz for all asphalt mixtures

7.9 Thermal stress restrained specimen test (TSRST)

Figure 62 shows the failure temperatures of the mixtures from the field in comparison to the laboratory mixtures. The field mixtures with Chem1 and the Kombi show a slightly lower failure temperature than the laboratory mixtures, but for the hot mix reference this is the opposite and results in the highest failure temperature. But this is still a good result, and it has to be considered that the standard deviation for this sample is rather high. The failure temperature of the foam asphalt (-34 °C) is higher compared to the mixtures with a chemical additive, but similar to the hot mix reference of the field.

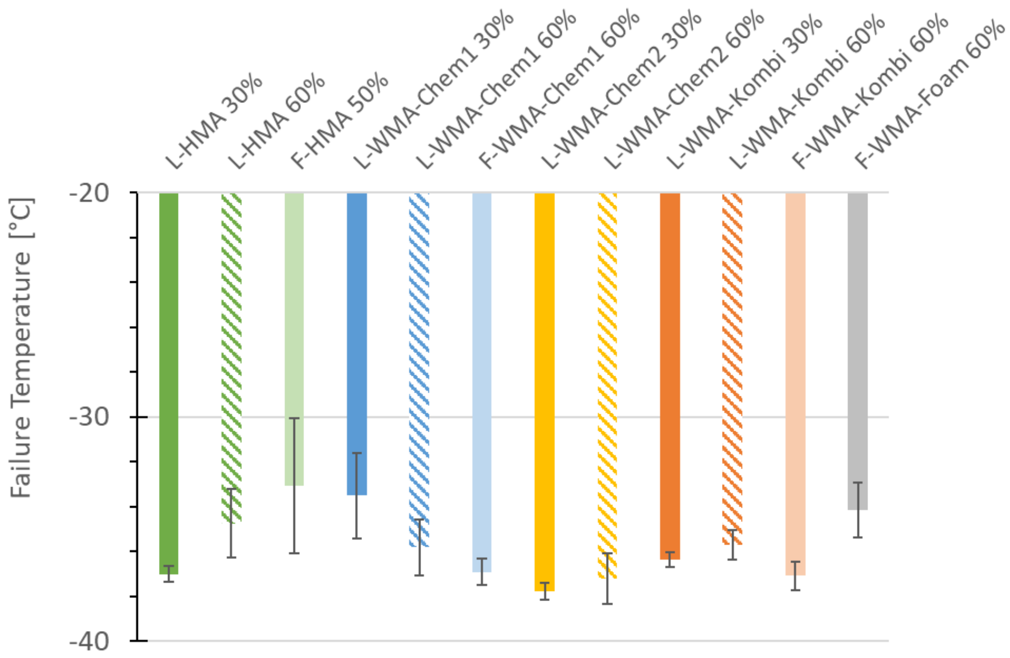


Figure 62: TSRST failure temperature

The failure stress for all field mixes is around 1 MPa lower than for the corresponding laboratory mixtures (Figure 63). The lowest value for the field mixtures was obtained for the Chem1 additive and the highest value for the Kombi mixture, indicating that the addition of wax is not beneficial. The failure stress for the foam asphalt lies in the middle, but still lower than the laboratory mixtures. In summary, the field mixtures with a chemical additive showed a slightly better or equal low temperature performance compared to the field HMA.

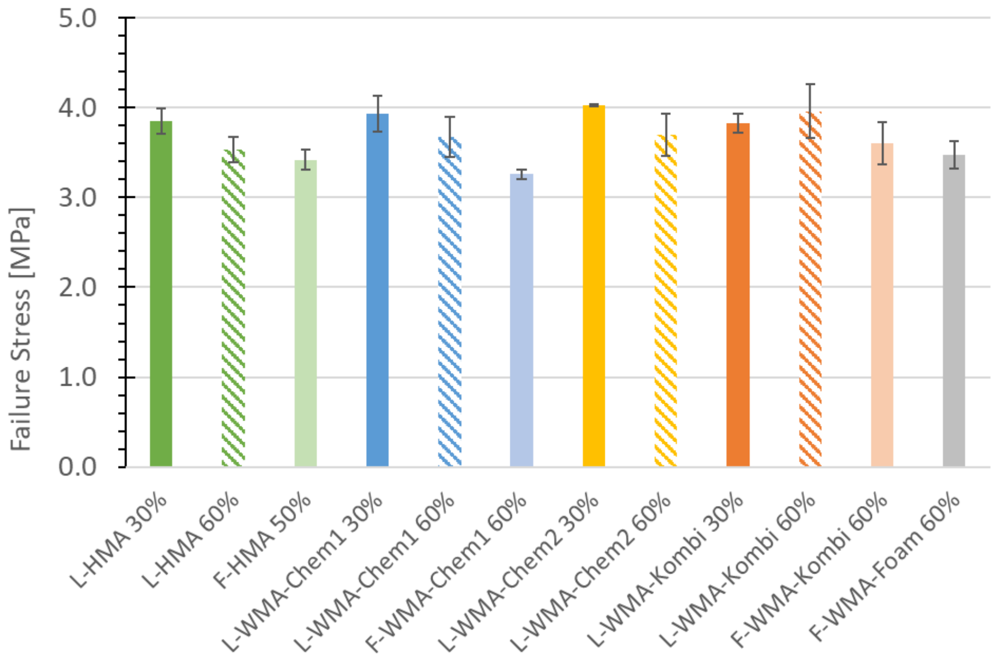


Figure 63: TSRST failure stress

7.10 Investigation of Field Cores

The evaluation of layer adhesion test was done on the cores taken from the four different test sections (i.e. F-HMA, F-Chem1, F-Kombi and F-Foam). On 22.01.2025, 2 cores were extracted from each section: one inside the wheel path (W) and one outside the wheel path (O).

Note, that since the test sections had not been covered with a surface layer, the layer adhesion test was conducted between binder and base layer. Further, note that due to different construction time of the different test sections the time of trafficking was not the same for the different sections.

Table 13 shows the measured layer thicknesses of the extracted cores. Overall, the measured thicknesses of AC B 16 and ACT 22 S were found to be consistent with the planned thicknesses of 6 cm and 8 cm, respectively.

Field extracted cores data

Extracted Core Sample	Sample ID	Layer Thickness (cm)			Total Thickness (cm)
		AC B 16 S	AC T 22 S	AC F 32	
Ref Section (inside wheel path)	RW	6.0	7.5	14.87	28.37
		6.0	7.0	14.81	27.81
		6.0	7.5	14.81	28.31
Ref Section (outside wheel path)	RO	6.5	7.5	14.85	28.88
		6.5	7.5	14.83	28.86
		6.5	7.5	14.84	28.88
Chem1 Section (inside wheel path)	CW	6.0	8.0	14.81	28.81
		6.0	7.5	14.84	28.34
		6.0	7.5	14.81	28.31
Chem1 Section (outside wheel path)	CO	6.0	8.0	14.83	28.83
		6.0	8.3	14.81	29.11
		6.0	8.0	14.83	28.83
Kombi Section (inside wheel path)	KW	6.0	7.0	14.81	27.81
		6.0	7.3	14.83	28.13
		6.0	7.3	14.85	28.15
Kombi Section (outside wheel path)	KO	6.0	7.5	14.83	28.33
		6.0	7.0	14.8	27.8
		6.0	7.0	14.82	27.82
Foam Section (inside wheel path)	FW	5.5	7.5	14.85	27.85
		5.5	7.5	14.82	27.82
		5.5	7.5	14.81	27.81
Foam Section (outside wheel path)	FO	6.0	8.0	14.86	28.86
		6.0	7.5	14.86	28.36
		6.0	8.0	14.83	28.83

Table 13: Layer thickness data of field extracted cores

7.10.1 Analysis of layer adhesion (Leutner test)

The Leutner layer adhesion test results between the binder and base layer for the field cores (within or outside the wheel path) are presented in Figure 64. The Leutner test results show very high shear forces well above the Swiss standard requirement of 12 kN for the bond between base and binder layers. F-HMA-50% shows the highest values of more than 30 kN, while F-Chem1-60% has values only around 26 KN. Regarding the measurement precision and the fact that only one core was tested no difference between the values within and outside the wheel path can be found. Only for F-Foam-60% an increase in adhesion strength in the wheel path according to trafficking and curing seems possible (with a value similar to F-HMA-50%).

Note, that due to time constrains it was decided not to wait for the construction of the surface layer. Therefore, the adhesion between surface and binder layer, which is relevant regarding the actual shear stresses in a pavement could not be determined. Nevertheless, the values between base and binder layer show that the WMA process leads to good interlayer bonding. Although, the results show the best values for F-

Foam, a general statement regarding the different additives is due to the different times of section construction and trafficking not possible.

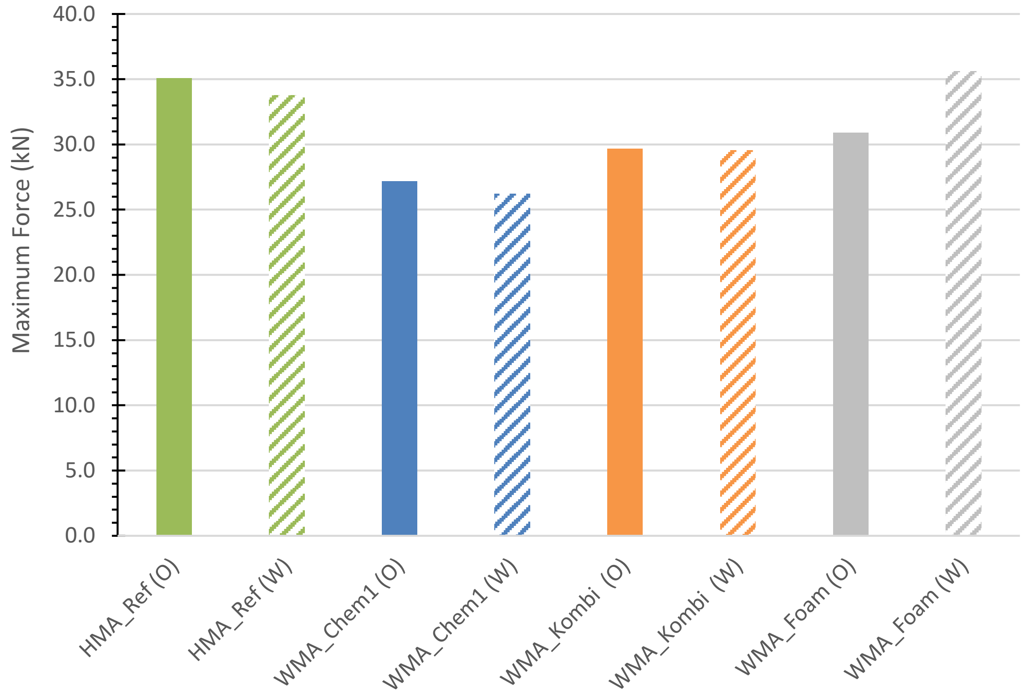


Figure 64: Leutner test results of extracted field cores (Layer adhesion)

8 Discussion

The selection of WMA additive according to the project proposal was mainly based on previous experience and the use of the products in Switzerland. Therefore, the focus was on chemical additives, while zeolites were excluded, and the use of waxes was only indented in combination with a chemical additive.

Regarding the limitations of the extensive laboratory testing, the final selection of 2 chemical additives out of 4 commonly used products was based on the initial binder and mastic testing, while the wax for the Kombi product (wax + chemical additive) was chosen as the commonly used product worldwide. Since binder and mastic evaluation could not result in clear differences between the 4 chemical additives, the second additive was chosen based on the Fraass breaking point as low temperature characteristic.

The addition of WMA additives was found to result in a higher Marshall air void content compared to HMA. Marshall stability results indicated that WMA could achieve strength comparable to HMA except for L-Chem2 30%, especially in field applications, even with high RAP content of 60 %. In terms of maniability, higher RAP content generally resulted in comparable maniability values except for L-Chem2 60%. Field mixtures demonstrated less favourable workability for F-Chem1 at 60% RAP compared to HMA. A clear trend in compactability was observed: laboratory mixtures performed best with 30% and then 60% RAP except for the Kombi mixtures, followed by field mixtures. This trend was also reflected in the corresponding air void contents. Laboratory-produced WMA mixtures exhibited improved compactability compared to HMA, particularly at 30% RAP; however, this improvement was not observed in the field-produced mixtures.

Like for HMA, the tensile strength of WMA in dry conditions consistently shows higher tensile strength (ITS) compared to wet conditions, indicating that moisture negatively affects the strength of asphalt mixtures. HMA (RAP 30 %) shows the highest ITS in dry conditions, while WMA and field-produced mixtures (F-WMA) tend to exhibit slightly lower ITS values. Some L-WMA and F-WMA mixtures maintain competitive ITS values even in wet conditions, suggesting that specific additives or treatment processes help retain strength under moisture exposure. All ITSR results were very good, exceeding 80 %, both for lab and field mixtures. This suggests that lower production temperatures in combination with additives or foam bitumen do not negatively affect water sensitivity, even in the case of high RAP addition. However, in the literature the influence of WMA additives on the water sensitivity of WMA is not uniform, depending on the test method for the evaluation and void content of the mixture. Especially open porous mixtures with additives based on wax, zeolithes or foam bitumen resulted in poor performance (Guo et al., 2020). For WMA with chemical additives no detrimental effect was observed compared to HMA, probably because these additives are chemically often similar to conventional anti-stripping agents (Oliveira et al., 2012). The addition of RAP resulted in controversial results too.

Fracture resistance (SCB) tests highlight that there is no significant difference between HMA and WMA. Surprisingly, the higher RAP content of 60% had a positive impact on the fracture toughness values in general, while no difference was found between field mixtures and lab mixtures. Rutting results were unexpectedly high for all lab mixtures, even for the HMA, which is very unusual. This did not depend on the RAP content or the type of WMA process. Only the field mixes provided acceptable rutting depths. However, increased rutting sensitivity was described in some literature as well (Guo et al., 2020), specifically when high RAP content was used. In general, wax based WMA additives improved the rutting behavior, whereas foam asphalt showed inferior rutting performance. But the crucial parameter is the correct dosage of the low viscosity additive, which are making the binder and the mixture if the additive amount is too high. The mixing energy is another criterion to be considered. In the asphalt plant fast, high energy twin shaft mixers are used, whereas laboratories are mostly equipped with "bakery type" single shaft mixers, which are slow and are not able to produce the same quality of asphalt mixtures. This is especially important, when a high percentage of RAP is added, where the old RAP binder needs to be blended with the small amount of virgin binder and additives.

Based on this, it is questionable to conclude that high temperature properties and permanent deformation might be problematic for WMA, although Marshall stability was rather low as well. The stiffness modulus at -10 °C and 1 Hz shows a similar trend for all the mixtures: L-30% RAP > L-60% RAP > field mixtures. The only exception is the field HMA with 50 % RAP, which is on the same level as the corresponding L-30% WMA. There are some differences between HMA and WMA, but no clear trend can be found. The master curves show that the differences in stiffness modulus are larger at high temperatures and that ranking at high and low temperatures can be different. The low temperature properties of WMA are in most cases equivalent to HMA and some cases even better, but all very good ranging from –33 to -38 °C. In the case of field mixtures, the HMA has a higher failure temperature then WMA with additives, but similar to WMA with foam asphalt. There is no consistent conclusion about the effect of WMA additives on low temperature cracking resistance of WMA-RAP in the literature, when RAP content was below 40% (Guo et al., 2020). Some studies observed better or equivalent cracking performance for WAM compared to HMA with RAP, while others the opposite. However, when more than 40% RAP was added, the cracking resistance decreased.

Overall, in the present research project, all WMA mixtures perform very similar to HMA. There is no WMA process, which is significantly better. However, some differences were observed, for example between the additive Chem1 and Chem2. In one test, additive Chem1 shows better results, but this was the opposite in another test. For foam asphalt, although only the results from the field tests with 60 % of RAP were available, it was mostly comparable with the other WMA mixtures.

9 Conclusions and recommendations

The main conclusion of this research is obvious. All warm mix asphalt mixtures performed very similar to the reference hot mix asphalt. There are some minor differences in the test results, but they are generally not consistent. The following conclusions are drawn based on the project specific results and analysis:

- There was no WMA process which was superior to others. However, as the additive selection was based on prior experience, it is not granted that all WMA additives on the market are suitable.
- In some tests the 60 % RAP mixtures show a stiffer behavior (softening point ring and ball), in other tests it is the opposite (stiffness modulus at -10 °C, Fraass breaking point) and sometimes it is random (Marshall stability, TSRST failure temperature). Nevertheless, the difference in stiffness cannot be attributed to a higher RAP content, as the stiffness is adjusted by the type of the added binder.
- It is surprising, that the mixtures with 30% RAP and bitumen 70/100 show similar performance like the ones with 60% RAP and a very soft added bitumen 330/400, because no fine tuning was made to fit the commercial binders (e.g. mixing two virgin binders to a target value).
- The rutting results were inconclusive and should be supplemented with additional tests to better characterize high-temperature performance. In any case, special attention should be given to monitoring permanent deformations on the test tracks in the coming years.
- HMA mixtures, both laboratory and field-produced, demonstrate consistently high Marshall stability, confirming their strong performance even with up to 60 % RAP.
- Maniability and compactability of WMA were not affected negatively by the lower production and compaction temperature.
- The long-term behaviour of WMA was not investigated in this study but should be addressed in a follow-up project. In this context special attention should be paid to the rutting behaviour. Further, the interlayer bond between the binder and the surface layer needs to be determined. A US study observed that WMA mixtures begin their service lives with lower stiffness and tend to age in place more rapidly, but ultimately their stiffness and rutting resistance are comparable to HMA (NCHRP, 2015).
- Higher RAP content (up to 60 %) can be successfully incorporated into both HMA and WMA mixtures without significantly compromising mechanical performance. The study should be extended to additional mixture types and even higher RAP content.

The results of this research suggested that the WMA technologies, particularly those incorporating chemical additives such as Chem1 and Kombi, present a promising sustainable alternative to traditional HMA, without compromising the key performance of their mechanical properties.

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Annex

Binder results

Base binder properties

Property	70-100	330-430_VJ
Penetration (1/10 mm)	79 (25°C)	109 (15°C)
Softening Point (°C)	46.4	32.8
Fraas Breaking Point (°C)	-11	-19

Table A1: Standard binder test results (BFH)

Fraass test results

Specimen	Fraass (°C)	Sample ID	St. Dev.
Chem4 30%	-12	G-30	0.816497
Chem4 60%	-14	G-60	0.5
Chem3 30%	-13	C-30	0.57735
Chem3 60%	-14	C-60	0.5
Chem2 30%	-12	I-30	0.816497
Chem2 60%	-17	I-60	0.5

Table A2: Fraass test results (BFH)

BTSV results

Binder testing	BTSV T	Std. dev.	BTSV δ	Std. dev.
	°C	°C	°	°
B70	**46.4**	0.22	**84.5**	0.07
B330	**33.2**	0.21	**82.9**	0.02
RAP	**65.5**	0.05	**73.8**	0.06
HMA 30%	**51.0**	0.14	**81.1**	0.02
HMA 60%	**51.4**	0.04	**76.2**	0.03
WMA-Chem1a 60%	**52.1**	0.02	**75.7**	0.07
WMA-Chem1b 60%	**52.2**	nd	**75.7**	nd
WMA-Chem2 60%	**50.6**	nd	**76.3**	nd
WMA-Chem3 60%	**50.4**	0.05	**76.4**	0.01
WMA-Chem4 60%	**49.5**	0.11	**76.4**	0.00
WMA-Wax 60%	**56.8**	0.17	**74.0**	0.22

Results of temperature frequency sweeps

Virgin bitumen B70

Complex modulus (Pa)									80°C
Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	80
0.1	1.22E+07	2.53E+06	2.72E+05	2.40E+04	2.68E+03	4.56E+02	1.03E+02	2.74E+01	9.05E+00
0.127	1.39E+07	2.99E+06	3.31E+05	3.01E+04	3.41E+03	5.78E+02	1.31E+02	3.53E+01	1.16E+01
0.162	1.58E+07	3.50E+06	4.03E+05	3.75E+04	4.32E+03	7.33E+02	1.67E+02	4.45E+01	1.54E+01
0.207	1.79E+07	4.08E+06	4.91E+05	4.67E+04	5.43E+03	9.32E+02	2.12E+02	5.81E+01	1.96E+01
0.264	2.03E+07	4.76E+06	5.96E+05	5.80E+04	6.87E+03	1.19E+03	2.70E+02	7.37E+01	2.29E+01
0.336	2.28E+07	5.52E+06	7.20E+05	7.19E+04	8.70E+03	1.50E+03	3.44E+02	9.52E+01	3.17E+01
0.428	2.55E+07	6.42E+06	8.69E+05	8.90E+04	1.10E+04	1.90E+03	4.35E+02	1.18E+02	3.99E+01
0.546	2.84E+07	7.45E+06	1.05E+06	1.10E+05	1.39E+04	2.40E+03	5.55E+02	1.51E+02	5.10E+01
0.695	3.13E+07	8.61E+06	1.26E+06	1.36E+05	1.76E+04	3.03E+03	7.02E+02	1.95E+02	6.44E+01
0.886	3.43E+07	9.94E+06	1.50E+06	1.67E+05	2.22E+04	3.84E+03	8.90E+02	2.50E+02	8.57E+01
1.13	3.72E+07	1.14E+07	1.80E+06	2.06E+05	2.80E+04	4.85E+03	1.13E+03	3.12E+02	1.05E+02
1.59	4.16E+07	1.39E+07	2.29E+06	2.75E+05	3.83E+04	6.73E+03	1.58E+03	4.39E+02	1.52E+02
1.83	4.31E+07	1.50E+07	2.54E+06	3.10E+05	4.36E+04	7.70E+03	1.82E+03	5.06E+02	1.74E+02
2.34	4.62E+07	1.72E+07	3.01E+06	3.80E+05	5.45E+04	9.72E+03	2.32E+03	6.47E+02	2.23E+02
2.98	4.94E+07	1.96E+07	3.55E+06	4.64E+05	6.78E+04	1.22E+04	2.92E+03	8.15E+02	2.76E+02
3.79	5.25E+07	2.23E+07	4.18E+06	5.64E+05	8.41E+04	1.53E+04	3.69E+03	1.04E+03	3.62E+02
4.83	5.58E+07	2.54E+07	4.91E+06	6.86E+05	1.04E+05	1.91E+04	4.68E+03	1.32E+03	4.49E+02
6.16	5.92E+07	2.88E+07	5.75E+06	8.33E+05	1.30E+05	2.42E+04	5.91E+03	1.67E+03	5.83E+02
7.85	6.27E+07	3.26E+07	6.72E+06	1.01E+06	1.60E+05	3.04E+04	7.45E+03	2.12E+03	7.44E+02
10	6.64E+07	3.68E+07	7.84E+06	1.22E+06	1.98E+05	3.80E+04	9.43E+03	2.70E+03	9.51E+02

Phase angle (°)									
Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	80
0.1	52.52	62.54	74.05	81.61	85.89	88.71	89.53	88.02	88.57
0.127	51.53	61.64	73.27	81.2	85.35	88.67	89.6	89.19	88.7
0.162	51.1	60.47	72.48	80.79	86.37	88.36	89.31	90	89.08
0.207	50.45	59.49	71.69	80.28	85.19	88.15	89.4	88.84	90
0.264	49.99	58.77	70.84	79.82	85.19	87.77	89.18	89.57	87.28
0.336	49.84	57.77	69.98	79.27	84.66	87.59	89.02	89.54	89.1
0.428	49.62	57.06	69.11	78.74	84.46	87.3	88.93	89.61	89.26
0.546	49.69	56.17	68.2	78.16	83.85	87.06	88.73	89.64	90
0.695	49.93	55.44	67.29	77.57	83.84	86.89	88.5	89.77	90
0.886	50.36	54.74	66.36	76.98	83.29	86.64	88.47	89.55	88.94
1.13	51.05	54.13	65.45	76.35	82.72	86.27	88.19	89.79	89.78
1.59	52.37	53.42	64.15	75.42	82.08	85.82	87.96	88.95	90
1.83	53.1	53.17	63.63	75.01	81.82	85.66	87.87	88.93	90
2.34	54.47	52.87	62.72	74.31	81.36	85.31	87.56	88.76	90
2.98	56.03	52.7	61.87	73.57	80.88	85.09	87.35	88.58	90
3.79	57.77	52.68	61.05	72.82	80.38	84.54	87.16	88.36	90
4.83	59.65	52.85	60.25	72.06	79.88	84.17	86.93	88.26	90
6.16	61.86	53.17	59.52	71.27	79.33	83.66	86.77	87.88	90
7.85	64.23	53.67	58.85	70.45	78.79	83.41	86.57	87.38	90
10	66.74	54.36	58.24	69.64	78.24	82.96	86.37	86.99	90

Virgin bitumen B330

Complex modulus (Pa)									80°C
Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	80
0.1	1.02E+06	2.16E+05	1.85E+04	1.72E+03	2.46E+02	5.06E+01	1.37E+01	4.73E+00	1.96E+00
0.127	1.21E+06	2.60E+05	2.28E+04	2.15E+03	3.11E+02	6.42E+01	1.73E+01	6.01E+00	2.48E+00
0.162	1.44E+06	3.13E+05	2.81E+04	2.70E+03	3.96E+02	8.18E+01	2.20E+01	7.59E+00	3.16E+00
0.207	1.70E+06	3.77E+05	3.48E+04	3.40E+03	5.03E+02	1.04E+02	2.82E+01	9.68E+00	4.12E+00
0.264	2.00E+06	4.52E+05	4.28E+04	4.27E+03	6.37E+02	1.33E+02	3.60E+01	1.24E+01	5.11E+00
0.336	2.35E+06	5.41E+05	5.27E+04	5.35E+03	8.06E+02	1.69E+02	4.56E+01	1.58E+01	6.59E+00
0.428	2.74E+06	6.46E+05	6.47E+04	6.70E+03	1.02E+03	2.15E+02	5.82E+01	2.00E+01	8.37E+00
0.546	3.18E+06	7.71E+05	7.95E+04	8.39E+03	1.29E+03	2.74E+02	7.43E+01	2.55E+01	1.07E+01
0.695	3.66E+06	9.16E+05	9.73E+04	1.05E+04	1.63E+03	3.48E+02	9.43E+01	3.25E+01	1.35E+01
0.886	4.18E+06	1.09E+06	1.19E+05	1.31E+04	2.06E+03	4.42E+02	1.20E+02	4.14E+01	1.72E+01
1.13	4.72E+06	1.29E+06	1.46E+05	1.64E+04	2.60E+03	5.62E+02	1.53E+02	5.27E+01	2.21E+01
1.59	5.61E+06	1.63E+06	1.93E+05	2.24E+04	3.61E+03	7.86E+02	2.16E+02	7.45E+01	3.11E+01
1.83	6.00E+06	1.79E+06	2.16E+05	2.54E+04	4.12E+03	9.02E+02	2.48E+02	8.53E+01	3.58E+01
2.34	6.84E+06	2.10E+06	2.63E+05	3.17E+04	5.21E+03	1.15E+03	3.17E+02	1.10E+02	4.57E+01
2.98	7.78E+06	2.46E+06	3.20E+05	3.94E+04	6.55E+03	1.45E+03	4.02E+02	1.39E+02	5.82E+01
3.79	8.83E+06	2.86E+06	3.87E+05	4.89E+04	8.23E+03	1.83E+03	5.10E+02	1.77E+02	7.35E+01
4.83	1.00E+07	3.32E+06	4.68E+05	6.06E+04	1.03E+04	2.32E+03	6.48E+02	2.25E+02	9.39E+01
6.16	1.14E+07	3.84E+06	5.64E+05	7.51E+04	1.30E+04	2.94E+03	8.24E+02	2.86E+02	1.19E+02
7.85	1.29E+07	4.41E+06	6.80E+05	9.29E+04	1.63E+04	3.71E+03	1.05E+03	3.64E+02	1.52E+02
10	1.46E+07	5.05E+06	8.16E+05	1.15E+05	2.04E+04	4.69E+03	1.32E+03	4.62E+02	1.93E+02

Phase angle (°)									
Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	80
0.1	63.8	70.2	78.9	84.8	88.4	89.6	89.8	89.3	90.0
0.127	63.1	69.7	78.6	84.7	88.2	89.5	89.6	89.7	87.8
0.162	62.3	69.1	78.3	84.6	88.1	89.5	89.7	89.7	90.0
0.207	61.5	68.5	77.9	84.3	87.9	89.4	89.7	89.7	88.2
0.264	60.7	67.8	77.4	84.1	87.7	89.3	89.7	89.6	90.0
0.336	60.0	67.1	77.0	83.9	87.5	89.2	89.7	89.8	89.5
0.428	59.2	66.5	76.5	83.6	87.2	89.1	89.7	90.0	88.9
0.546	58.5	65.7	76.0	83.3	87.0	89.0	89.6	89.9	89.8
0.695	57.8	65.0	75.5	82.9	86.8	88.8	89.6	89.6	89.3
0.886	57.3	64.3	75.0	82.6	86.5	88.7	89.5	89.6	89.6
1.13	57.0	63.5	74.5	82.2	86.3	88.5	89.4	89.6	89.1
1.59	56.5	62.5	73.7	81.7	85.9	88.2	89.3	89.6	89.3
1.83	56.4	62.0	73.3	81.5	85.7	88.1	89.2	89.5	89.1
2.34	56.0	61.3	72.7	81.0	85.5	87.8	89.0	89.3	89.2
2.98	55.7	60.6	72.1	80.6	85.2	87.6	88.9	89.1	88.5
3.79	55.4	59.9	71.4	80.2	84.9	87.4	88.8	89.3	88.7
4.83	55.1	59.2	70.8	79.7	84.6	87.2	88.6	89.2	88.4
6.16	55.0	58.7	70.1	79.2	84.2	86.9	88.4	89.0	87.7
7.85	54.9	58.2	69.4	78.8	83.9	86.6	88.2	88.8	87.4
10	55.1	57.8	68.7	78.3	83.6	86.4	88.0	88.5	86.8

RAP binder

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	9.19E+06	2.36E+06	4.25E+05	7.49E+04	1.32E+04	2.55E+03	5.99E+02	1.51E+02
0.127	1.03E+07	2.68E+06	4.94E+05	8.90E+04	1.61E+04	3.13E+03	7.50E+02	1.91E+02
0.162	1.15E+07	3.05E+06	5.75E+05	1.06E+05	1.96E+04	3.89E+03	9.37E+02	2.40E+02
0.207	1.30E+07	3.46E+06	6.69E+05	1.25E+05	2.39E+04	4.83E+03	1.18E+03	3.05E+02
0.264	1.46E+07	3.92E+06	7.75E+05	1.48E+05	2.91E+04	5.97E+03	1.46E+03	3.83E+02
0.336	1.62E+07	4.43E+06	8.95E+05	1.75E+05	3.49E+04	7.32E+03	1.83E+03	4.84E+02
0.428	1.81E+07	5.00E+06	1.03E+06	2.06E+05	4.19E+04	8.95E+03	2.27E+03	6.08E+02
0.546	2.01E+07	5.65E+06	1.19E+06	2.42E+05	5.03E+04	1.11E+04	2.82E+03	7.68E+02
0.695	2.23E+07	6.36E+06	1.37E+06	2.84E+05	6.02E+04	1.35E+04	3.49E+03	9.60E+02
0.886	2.48E+07	7.15E+06	1.57E+06	3.33E+05	7.19E+04	1.65E+04	4.32E+03	1.20E+03
1.13	2.75E+07	8.04E+06	1.81E+06	3.90E+05	8.57E+04	2.01E+04	5.34E+03	1.50E+03
1.59	3.17E+07	9.45E+06	2.19E+06	4.86E+05	1.10E+05	2.68E+04	7.12E+03	2.05E+03
1.83	3.36E+07	1.01E+07	2.36E+06	5.31E+05	1.21E+05	2.99E+04	8.05E+03	2.33E+03
2.34	3.72E+07	1.13E+07	2.70E+06	6.20E+05	1.44E+05	3.62E+04	9.90E+03	2.90E+03
2.98	4.10E+07	1.26E+07	3.08E+06	7.22E+05	1.71E+05	4.36E+04	1.21E+04	3.60E+03
3.79	4.51E+07	1.41E+07	3.51E+06	8.38E+05	2.02E+05	5.23E+04	1.47E+04	4.45E+03
4.83	4.97E+07	1.58E+07	3.99E+06	9.73E+05	2.38E+05	6.29E+04	1.79E+04	5.52E+03
6.16	5.46E+07	1.76E+07	4.53E+06	1.13E+06	2.82E+05	7.54E+04	2.17E+04	6.80E+03
7.85	6.01E+07	1.96E+07	5.14E+06	1.31E+06	3.32E+05	9.03E+04	2.66E+04	8.38E+03
10	6.58E+07	2.18E+07	5.83E+06	1.51E+06	3.91E+05	1.08E+05	3.24E+04	1.03E+04

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	42.86	48.66	56.74	64.34	72.32	79.09	84.23	87.6
0.127	42.75	47.98	56.12	63.83	71.5	78.51	83.66	87.14
0.162	42.51	47.47	55.49	63.14	70.81	77.72	82.92	86.65
0.207	42.28	46.94	54.87	62.46	70.11	76.82	82.52	86.06
0.264	42.12	46.4	54.28	61.81	69.25	76.33	81.83	85.44
0.336	42.06	45.89	53.66	61.19	68.48	75.29	81.14	85.05
0.428	42.07	45.46	53.08	60.61	67.85	74.66	80.45	84.59
0.546	42.19	45.04	52.54	60	67.15	74	79.71	84.14
0.695	42.39	44.68	51.97	59.43	66.48	72.87	79	83.38
0.886	42.66	44.35	51.42	58.88	65.85	72.46	78.36	83.06
1.13	42.99	44.04	50.9	58.33	65.24	71.57	77.6	82.41
1.59	43.63	43.72	50.18	57.56	64.41	70.78	76.62	81.49
1.83	43.93	43.6	49.9	57.26	64.07	70.37	76.29	81.19
2.34	44.57	43.45	49.41	56.72	63.5	69.71	75.63	80.58
2.98	45.35	43.37	48.96	56.2	62.95	69.07	74.88	79.87
3.79	46.22	43.35	48.53	55.69	62.43	68.49	74.08	79.26
4.83	47.27	43.39	48.13	55.19	61.92	67.9	73.52	78.54
6.16	48.47	43.5	47.74	54.69	61.42	67.34	72.67	77.98
7.85	49.93	43.69	47.39	54.21	60.92	66.77	72.11	77.5
10	51.4	43.97	47.07	53.73	60.43	66.25	71.87	76.88

Bitumen blend HMA-30%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	2.96E+06	4.91E+05	5.64E+04	6.89E+03	1.10E+03	2.27E+02	5.68E+01	1.88E+01
0.127	3.45E+06	5.86E+05	6.88E+04	8.57E+03	1.37E+03	2.87E+02	7.29E+01	2.30E+01
0.162	4.04E+06	7.00E+05	8.42E+04	1.07E+04	1.72E+03	3.64E+02	9.30E+01	2.88E+01
0.207	4.70E+06	8.36E+05	1.03E+05	1.34E+04	2.18E+03	4.63E+02	1.16E+02	3.66E+01
0.264	5.46E+06	9.94E+05	1.25E+05	1.67E+04	2.75E+03	5.88E+02	1.50E+02	4.79E+01
0.336	6.30E+06	1.18E+06	1.52E+05	2.08E+04	3.43E+03	7.42E+02	1.90E+02	5.92E+01
0.428	7.26E+06	1.39E+06	1.84E+05	2.61E+04	4.33E+03	9.36E+02	2.40E+02	7.76E+01
0.546	8.35E+06	1.65E+06	2.24E+05	3.22E+04	5.37E+03	1.19E+03	3.06E+02	9.58E+01
0.695	9.56E+06	1.94E+06	2.70E+05	3.97E+04	6.73E+03	1.49E+03	3.89E+02	1.23E+02
0.886	1.09E+07	2.28E+06	3.26E+05	4.89E+04	8.41E+03	1.89E+03	4.94E+02	1.59E+02
1.13	1.25E+07	2.67E+06	3.94E+05	6.01E+04	1.05E+04	2.38E+03	6.27E+02	2.00E+02
1.59	1.50E+07	3.33E+06	5.10E+05	8.02E+04	1.42E+04	3.29E+03	8.68E+02	2.82E+02
1.83	1.62E+07	3.64E+06	5.68E+05	9.02E+04	1.62E+04	3.75E+03	1.00E+03	3.20E+02
2.34	1.84E+07	4.25E+06	6.82E+05	1.11E+05	2.03E+04	4.73E+03	1.27E+03	4.11E+02
2.98	2.08E+07	4.93E+06	8.15E+05	1.35E+05	2.54E+04	5.92E+03	1.59E+03	5.20E+02
3.79	2.36E+07	5.71E+06	9.72E+05	1.65E+05	3.14E+04	7.42E+03	2.01E+03	6.59E+02
4.83	2.67E+07	6.61E+06	1.16E+06	2.01E+05	3.89E+04	9.28E+03	2.54E+03	8.39E+02
6.16	3.02E+07	7.63E+06	1.38E+06	2.44E+05	4.81E+04	1.16E+04	3.20E+03	1.07E+03
7.85	3.40E+07	8.79E+06	1.64E+06	2.97E+05	5.94E+04	1.44E+04	4.04E+03	1.34E+03
10	3.84E+07	1.01E+07	1.94E+06	3.60E+05	7.32E+04	1.80E+04	5.09E+03	1.71E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	57.26	66.62	75.08	81.86	86.12	88.65	89.82	90
0.127	56.26	65.79	74.49	81.21	85.65	88.21	89.04	87.87
0.162	55.46	65.03	73.84	80.74	85.24	88	90	89.16
0.207	54.54	64.29	73.25	79.99	84.87	87.63	89.27	88.21
0.264	53.76	63.54	72.63	79.48	84.31	87.41	88.89	89.54
0.336	52.98	62.74	72.02	79.02	84.4	87.06	88.89	89.9
0.428	52.26	61.96	71.4	78.49	83.62	86.9	88.74	89.08
0.546	51.57	61.16	70.76	77.96	83.07	86.37	88.24	90
0.695	50.93	60.38	70.13	77.4	82.76	86.08	88.4	89.07
0.886	50.34	59.6	69.48	76.86	82.18	85.8	87.49	90
1.13	49.8	58.83	68.83	76.32	81.6	85.39	87.29	88.49
1.59	49.21	57.77	67.88	75.55	81.31	84.72	86.87	90
1.83	49	57.33	67.48	75.23	80.67	84.5	86.9	89.62
2.34	48.67	56.62	66.8	74.66	80.05	84	86.28	89.58
2.98	48.46	55.94	66.09	74.1	79.8	83.64	86.08	89.04
3.79	48.36	55.3	65.4	73.56	79.29	83.24	85.28	89.11
4.83	48.35	54.68	64.67	73	78.77	82.78	85.07	89.61
6.16	48.43	54.11	63.96	72.42	78.27	82.32	84.48	89.92
7.85	48.65	53.6	63.24	71.83	77.77	81.73	83.86	90
10	48.97	53.15	62.54	71.25	77.24	81.02	83.21	90

Bitumen blend HMA-60%

Complex modulus (Pa)									80°C
Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	80
0.1	4.47E+06	2.61E+06	4.43E+05	5.96E+04	8.25E+03	1.38E+03	2.86E+02	7.02E+01	2.06E+01
0.127	1.08E+07	2.99E+06	5.19E+05	7.15E+04	1.02E+04	1.72E+03	3.63E+02	8.80E+01	2.46E+01
0.162	1.23E+07	3.41E+06	6.08E+05	8.58E+04	1.25E+04	2.15E+03	4.58E+02	1.12E+02	3.22E+01
0.207	1.37E+07	3.90E+06	7.12E+05	1.03E+05	1.54E+04	2.67E+03	5.76E+02	1.44E+02	4.22E+01
0.264	1.54E+07	4.43E+06	8.31E+05	1.23E+05	1.90E+04	3.32E+03	7.26E+02	1.81E+02	5.29E+01
0.336	1.72E+07	5.03E+06	9.67E+05	1.47E+05	2.31E+04	4.12E+03	9.13E+02	2.30E+02	6.75E+01
0.428	1.91E+07	5.70E+06	1.12E+06	1.75E+05	2.85E+04	5.14E+03	1.15E+03	2.91E+02	8.61E+01
0.546	2.13E+07	6.47E+06	1.30E+06	2.08E+05	3.46E+04	6.35E+03	1.43E+03	3.69E+02	1.08E+02
0.695	2.36E+07	7.31E+06	1.51E+06	2.47E+05	4.19E+04	7.87E+03	1.80E+03	4.68E+02	1.40E+02
0.886	2.62E+07	8.26E+06	1.75E+06	2.93E+05	5.07E+04	9.69E+03	2.25E+03	5.84E+02	1.77E+02
1.13	2.91E+07	9.32E+06	2.02E+06	3.46E+05	6.13E+04	1.19E+04	2.80E+03	7.39E+02	2.23E+02
1.59	3.36E+07	1.10E+07	2.46E+06	4.38E+05	7.98E+04	1.59E+04	3.82E+03	1.02E+03	3.12E+02
1.83	3.56E+07	1.18E+07	2.67E+06	4.82E+05	8.89E+04	1.79E+04	4.34E+03	1.17E+03	3.57E+02
2.34	3.94E+07	1.32E+07	3.07E+06	5.70E+05	1.07E+05	2.20E+04	5.40E+03	1.47E+03	4.56E+02
2.98	4.36E+07	1.48E+07	3.51E+06	6.69E+05	1.29E+05	2.73E+04	6.70E+03	1.84E+03	5.76E+02
3.79	4.82E+07	1.66E+07	4.01E+06	7.85E+05	1.54E+05	3.32E+04	8.28E+03	2.30E+03	7.25E+02
4.83	5.33E+07	1.86E+07	4.58E+06	9.21E+05	1.85E+05	4.05E+04	1.02E+04	2.87E+03	9.15E+02
6.16	5.91E+07	2.08E+07	5.23E+06	1.08E+06	2.21E+05	4.93E+04	1.26E+04	3.60E+03	1.15E+03
7.85	6.55E+07	2.32E+07	5.95E+06	1.26E+06	2.64E+05	5.99E+04	1.55E+04	4.48E+03	1.45E+03
10	7.28E+07	2.59E+07	6.76E+06	1.47E+06	3.15E+05	7.27E+04	1.90E+04	5.57E+03	1.83E+03

Phase angle (°)									
Temperature /Frequency	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C	80
0.1	5.91	50.41	59.55	68.37	76.61	83.36	86.4	89.25	88.31
0.127	43.12	49.7	58.85	67.77	75.56	82.18	86.15	88.09	88.36
0.162	42.11	49.07	58.17	67.15	74.91	81.76	85.99	88.26	87.91
0.207	41.76	48.38	57.52	66.49	74.28	80.76	85.44	88.31	88.07
0.264	41.17	47.66	56.84	65.87	73.85	80.72	84.84	87.88	88
0.336	40.78	47.05	56.16	65.26	73.07	79.69	84.54	87.62	89.36
0.428	40.35	46.43	55.5	64.65	72.46	79.12	83.92	87.26	88.88
0.546	39.99	45.87	54.83	64.04	71.84	78.55	83.54	86.69	87.93
0.695	39.59	45.28	54.18	63.46	71.23	77.72	82.84	86.41	89.12
0.886	39.3	44.78	53.51	62.86	70.64	77.53	82.45	85.72	88.68
1.13	39.01	44.3	52.86	62.27	70.05	76.82	81.8	85.54	87.48
1.59	38.72	43.64	51.95	61.44	69.26	75.79	81	85.16	87.71
1.83	38.63	43.39	51.59	61.1	68.96	75.34	80.81	84.78	86.62
2.34	38.55	42.99	50.95	60.5	68.37	75.14	80.2	84.44	85.98
2.98	38.51	42.65	50.35	59.92	67.83	74.38	79.67	84.1	85.77
3.79	38.56	42.34	49.76	59.32	67.29	73.82	79.15	83.64	85.28
4.83	38.71	42.08	49.17	58.73	66.77	73.31	78.74	83.37	85.1
6.16	38.97	41.87	48.61	58.13	66.23	72.79	78.09	83.05	84.06
7.85	39.43	41.71	48.05	57.53	65.71	72.26	77.45	82.7	83.12
10	40.12	41.61	47.54	56.93	65.17	71.77	76.77	82.63	82.8

Bitumen blend Chem1a-60%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	2.21E+06	4.52E+05	6.51E+04	9.10E+03	1.47E+03	3.02E+02	7.15E+01	2.16E+01
0.127	2.54E+06	5.28E+05	7.78E+04	1.12E+04	1.84E+03	3.82E+02	9.10E+01	2.65E+01
0.162	2.92E+06	6.18E+05	9.30E+04	1.37E+04	2.29E+03	4.82E+02	1.16E+02	3.39E+01
0.207	3.35E+06	7.22E+05	1.11E+05	1.69E+04	2.87E+03	6.07E+02	1.49E+02	4.35E+01
0.264	3.83E+06	8.42E+05	1.33E+05	2.08E+04	3.56E+03	7.64E+02	1.88E+02	5.55E+01
0.336	4.36E+06	9.78E+05	1.58E+05	2.54E+04	4.42E+03	9.58E+02	2.37E+02	7.02E+01
0.428	4.96E+06	1.13E+06	1.87E+05	3.09E+04	5.44E+03	1.20E+03	3.00E+02	9.05E+01
0.546	5.63E+06	1.32E+06	2.22E+05	3.74E+04	6.74E+03	1.50E+03	3.80E+02	1.13E+02
0.695	6.38E+06	1.52E+06	2.63E+05	4.52E+04	8.27E+03	1.88E+03	4.79E+02	1.44E+02
0.886	7.22E+06	1.76E+06	3.11E+05	5.45E+04	1.02E+04	2.35E+03	6.03E+02	1.83E+02
1.13	8.17E+06	2.03E+06	3.67E+05	6.57E+04	1.25E+04	2.93E+03	7.62E+02	2.31E+02
1.59	9.69E+06	2.47E+06	4.62E+05	8.52E+04	1.68E+04	3.98E+03	1.06E+03	3.26E+02
1.83	1.04E+07	2.67E+06	5.07E+05	9.47E+04	1.87E+04	4.51E+03	1.20E+03	3.77E+02
2.34	1.17E+07	3.08E+06	5.98E+05	1.14E+05	2.32E+04	5.62E+03	1.51E+03	4.68E+02
2.98	1.32E+07	3.52E+06	7.01E+05	1.36E+05	2.85E+04	6.95E+03	1.89E+03	5.96E+02
3.79	1.48E+07	4.03E+06	8.20E+05	1.63E+05	3.47E+04	8.58E+03	2.36E+03	7.49E+02
4.83	1.67E+07	4.60E+06	9.59E+05	1.94E+05	4.22E+04	1.06E+04	2.96E+03	9.48E+02
6.16	1.88E+07	5.26E+06	1.12E+06	2.32E+05	5.12E+04	1.31E+04	3.69E+03	1.19E+03
7.85	2.11E+07	6.00E+06	1.31E+06	2.76E+05	6.21E+04	1.60E+04	4.60E+03	1.50E+03
10	2.37E+07	6.83E+06	1.52E+06	3.28E+05	7.51E+04	1.96E+04	5.73E+03	1.89E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	51.0	58.8	67.3	75.5	82.4	86.6	88.2	88.5
0.127	50.4	58.2	66.6	74.8	81.4	85.8	88.6	88.9
0.162	49.7	57.5	66.0	74.0	80.7	85.5	87.7	88.4
0.207	49.1	56.9	65.4	73.4	80.4	85.0	87.8	88.9
0.264	48.6	56.3	64.7	72.7	79.4	84.4	87.3	88.7
0.336	48.1	55.7	64.2	72.0	79.2	84.0	87.2	89.4
0.428	47.6	55.1	63.6	71.4	78.2	83.5	86.7	88.2
0.546	47.2	54.5	63.0	70.8	77.9	83.0	86.4	89.1
0.695	46.8	53.9	62.4	70.1	77.1	82.5	86.0	88.4
0.886	46.5	53.3	61.8	69.6	76.5	81.9	85.6	88.0
1.13	46.2	52.8	61.2	69.0	75.8	81.4	85.0	87.9
1.59	46.0	52.0	60.5	68.2	74.9	80.5	84.5	87.0
1.83	45.9	51.8	60.1	67.9	74.7	80.2	84.2	86.8
2.34	45.9	51.3	59.6	67.3	74.1	79.6	83.5	86.5
2.98	45.9	50.8	59.0	66.8	73.5	79.0	83.2	86.4
3.79	46.0	50.4	58.5	66.3	73.0	78.5	82.5	85.8
4.83	46.2	50.1	58.0	65.7	72.4	78.0	82.0	85.3
6.16	46.5	49.7	57.4	65.2	71.9	77.4	81.5	85.0
7.85	46.9	49.5	56.9	64.7	71.3	76.7	80.9	84.7
10	47.5	49.3	56.4	64.2	70.8	76.2	80.4	84.4

Bitumen blend Chem1b-60%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	2.21E+06	4.52E+05	6.51E+04	9.10E+03	1.47E+03	3.02E+02	7.15E+01	2.16E+01
0.127	2.54E+06	5.28E+05	7.78E+04	1.12E+04	1.84E+03	3.82E+02	9.10E+01	2.65E+01
0.162	2.92E+06	6.18E+05	9.30E+04	1.37E+04	2.29E+03	4.82E+02	1.16E+02	3.39E+01
0.207	3.35E+06	7.22E+05	1.11E+05	1.69E+04	2.87E+03	6.07E+02	1.49E+02	4.35E+01
0.264	3.83E+06	8.42E+05	1.33E+05	2.08E+04	3.56E+03	7.64E+02	1.88E+02	5.55E+01
0.336	4.36E+06	9.78E+05	1.58E+05	2.54E+04	4.42E+03	9.58E+02	2.37E+02	7.02E+01
0.428	4.96E+06	1.13E+06	1.87E+05	3.09E+04	5.44E+03	1.20E+03	3.00E+02	9.05E+01
0.546	5.63E+06	1.32E+06	2.22E+05	3.74E+04	6.74E+03	1.50E+03	3.80E+02	1.13E+02
0.695	6.38E+06	1.52E+06	2.63E+05	4.52E+04	8.27E+03	1.88E+03	4.79E+02	1.44E+02
0.886	7.22E+06	1.76E+06	3.11E+05	5.45E+04	1.02E+04	2.35E+03	6.03E+02	1.83E+02
1.13	8.17E+06	2.03E+06	3.67E+05	6.57E+04	1.25E+04	2.93E+03	7.62E+02	2.31E+02
1.59	9.69E+06	2.47E+06	4.62E+05	8.52E+04	1.68E+04	3.98E+03	1.06E+03	3.26E+02
1.83	1.04E+07	2.67E+06	5.07E+05	9.47E+04	1.87E+04	4.51E+03	1.20E+03	3.77E+02
2.34	1.17E+07	3.08E+06	5.98E+05	1.14E+05	2.32E+04	5.62E+03	1.51E+03	4.68E+02
2.98	1.32E+07	3.52E+06	7.01E+05	1.36E+05	2.85E+04	6.95E+03	1.89E+03	5.96E+02
3.79	1.48E+07	4.03E+06	8.20E+05	1.63E+05	3.47E+04	8.58E+03	2.36E+03	7.49E+02
4.83	1.67E+07	4.60E+06	9.59E+05	1.94E+05	4.22E+04	1.06E+04	2.96E+03	9.48E+02
6.16	1.88E+07	5.26E+06	1.12E+06	2.32E+05	5.12E+04	1.31E+04	3.69E+03	1.19E+03
7.85	2.11E+07	6.00E+06	1.31E+06	2.76E+05	6.21E+04	1.60E+04	4.60E+03	1.50E+03
10	2.37E+07	6.83E+06	1.52E+06	3.28E+05	7.51E+04	1.96E+04	5.73E+03	1.89E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	52.52	62.54	74.05	81.61	85.89	88.71	89.53	88.02
0.127	51.53	61.64	73.27	81.2	85.35	88.67	89.6	89.19
0.162	51.1	60.47	72.48	80.79	86.37	88.36	89.31	90
0.207	50.45	59.49	71.69	80.28	85.19	88.15	89.4	88.84
0.264	49.99	58.77	70.84	79.82	85.19	87.77	89.18	89.57
0.336	49.84	57.77	69.98	79.27	84.66	87.59	89.02	89.54
0.428	49.62	57.06	69.11	78.74	84.46	87.3	88.93	89.61
0.546	49.69	56.17	68.2	78.16	83.85	87.06	88.73	89.64
0.695	49.93	55.44	67.29	77.57	83.84	86.89	88.5	89.77
0.886	50.36	54.74	66.36	76.98	83.29	86.64	88.47	89.55
1.13	51.05	54.13	65.45	76.35	82.72	86.27	88.19	89.79
1.59	52.37	53.42	64.15	75.42	82.08	85.82	87.96	88.95
1.83	53.1	53.17	63.63	75.01	81.82	85.66	87.87	88.93
2.34	54.47	52.87	62.72	74.31	81.36	85.31	87.56	88.76
2.98	56.03	52.7	61.87	73.57	80.88	85.09	87.35	88.58
3.79	57.77	52.68	61.05	72.82	80.38	84.54	87.16	88.36
4.83	59.65	52.85	60.25	72.06	79.88	84.17	86.93	88.26
6.16	61.86	53.17	59.52	71.27	79.33	83.66	86.77	87.88
7.85	64.23	53.67	58.85	70.45	78.79	83.41	86.57	87.38
10	66.74	54.36	58.24	69.64	78.24	82.96	86.37	86.99

Bitumen blend Chem2-60%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	1.66E+06	3.62E+05	5.09E+04	7.04E+03	1.15E+03	2.42E+02	5.82E+01	1.69E+01
0.127	1.92E+06	4.26E+05	6.11E+04	8.63E+03	1.45E+03	3.04E+02	7.43E+01	2.21E+01
0.162	2.21E+06	5.01E+05	7.35E+04	1.07E+04	1.82E+03	3.85E+02	9.43E+01	2.89E+01
0.207	2.55E+06	5.88E+05	8.83E+04	1.31E+04	2.25E+03	4.86E+02	1.21E+02	3.66E+01
0.264	2.93E+06	6.89E+05	1.06E+05	1.61E+04	2.83E+03	6.14E+02	1.52E+02	4.69E+01
0.336	3.35E+06	8.04E+05	1.26E+05	1.99E+04	3.50E+03	7.71E+02	1.93E+02	5.76E+01
0.428	3.83E+06	9.38E+05	1.51E+05	2.43E+04	4.39E+03	9.69E+02	2.45E+02	7.42E+01
0.546	4.38E+06	1.09E+06	1.80E+05	2.98E+04	5.39E+03	1.22E+03	3.10E+02	9.78E+01
0.695	4.99E+06	1.27E+06	2.14E+05	3.61E+04	6.66E+03	1.53E+03	3.91E+02	1.20E+02
0.886	5.68E+06	1.47E+06	2.54E+05	4.38E+04	8.23E+03	1.91E+03	4.91E+02	1.54E+02
1.13	6.45E+06	1.71E+06	3.01E+05	5.31E+04	1.01E+04	2.38E+03	6.25E+02	1.94E+02
1.59	7.70E+06	2.09E+06	3.82E+05	6.92E+04	1.35E+04	3.26E+03	8.59E+02	2.72E+02
1.83	8.28E+06	2.27E+06	4.20E+05	7.71E+04	1.52E+04	3.70E+03	9.89E+02	3.09E+02
2.34	9.39E+06	2.63E+06	4.97E+05	9.31E+04	1.87E+04	4.61E+03	1.24E+03	3.95E+02
2.98	1.06E+07	3.02E+06	5.86E+05	1.12E+05	2.30E+04	5.73E+03	1.56E+03	5.06E+02
3.79	1.20E+07	3.47E+06	6.88E+05	1.34E+05	2.83E+04	7.08E+03	1.95E+03	6.39E+02
4.83	1.35E+07	3.97E+06	8.09E+05	1.61E+05	3.46E+04	8.78E+03	2.44E+03	8.02E+02
6.16	1.52E+07	4.56E+06	9.49E+05	1.93E+05	4.21E+04	1.08E+04	3.05E+03	1.01E+03
7.85	1.72E+07	5.21E+06	1.11E+06	2.31E+05	5.13E+04	1.33E+04	3.82E+03	1.27E+03
10	1.94E+07	5.96E+06	1.30E+06	2.76E+05	6.23E+04	1.63E+04	4.77E+03	1.62E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	53.4	60.72	69.04	76.9	83.45	86.95	89.1	89.19
0.127	52.73	60.05	68.38	76.07	82.59	86.41	88.05	87.74
0.162	52.1	59.4	67.76	75.55	82.34	86.24	88.67	90
0.207	51.47	58.76	67.12	74.82	81.21	85.68	88.21	88.07
0.264	50.91	58.12	66.5	74.5	81.02	85.43	87.61	89.98
0.336	50.33	57.49	65.9	73.53	80.61	84.49	87.36	88.11
0.428	49.83	56.88	65.31	73.23	79.89	84.43	87.51	88.57
0.546	49.33	56.29	64.72	72.37	79.22	83.94	86.99	87.88
0.695	48.9	55.69	64.14	71.77	78.8	83.23	86.59	88.92
0.886	48.5	55.09	63.56	71.17	77.57	82.86	86.33	87.49
1.13	48.14	54.52	62.98	70.59	77	82.31	85.73	87.64
1.59	47.73	53.75	62.2	69.79	76.48	81.69	84.83	87.36
1.83	47.59	53.46	61.87	69.46	75.94	81.22	84.7	86.78
2.34	47.4	52.95	61.32	68.92	75.51	80.71	84.36	87.29
2.98	47.27	52.5	60.76	68.37	74.83	80.26	83.6	86.64
3.79	47.22	52.06	60.21	67.84	74.36	79.73	83.21	86.09
4.83	47.25	51.65	59.66	67.34	73.83	79.21	82.5	85.6
6.16	47.37	51.29	59.14	66.81	73.27	78.77	81.79	85.36
7.85	47.61	50.98	58.59	66.32	72.78	78.27	81.17	84.91
10	47.99	50.71	58.09	65.82	72.29	77.6	80.46	84.5

Bitumen blend Chem3-60%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	1.65E+06	3.43E+05	4.80E+04	6.73E+03	1.12E+03	2.36E+02	5.83E+01	1.81E+01
0.127	1.90E+06	4.03E+05	5.77E+04	8.25E+03	1.41E+03	2.94E+02	7.46E+01	2.15E+01
0.162	2.19E+06	4.75E+05	6.95E+04	1.02E+04	1.76E+03	3.72E+02	9.51E+01	2.70E+01
0.207	2.52E+06	5.58E+05	8.35E+04	1.25E+04	2.21E+03	4.70E+02	1.19E+02	3.46E+01
0.264	2.89E+06	6.54E+05	1.00E+05	1.55E+04	2.78E+03	5.94E+02	1.51E+02	4.63E+01
0.336	3.31E+06	7.64E+05	1.20E+05	1.90E+04	3.42E+03	7.47E+02	1.93E+02	5.78E+01
0.428	3.78E+06	8.92E+05	1.43E+05	2.32E+04	4.25E+03	9.38E+02	2.45E+02	7.24E+01
0.546	4.32E+06	1.04E+06	1.70E+05	2.85E+04	5.29E+03	1.18E+03	3.11E+02	9.33E+01
0.695	4.92E+06	1.21E+06	2.03E+05	3.46E+04	6.50E+03	1.47E+03	3.87E+02	1.19E+02
0.886	5.60E+06	1.40E+06	2.41E+05	4.20E+04	8.02E+03	1.85E+03	4.93E+02	1.52E+02
1.13	6.36E+06	1.62E+06	2.86E+05	5.09E+04	9.87E+03	2.32E+03	6.23E+02	1.89E+02
1.59	7.60E+06	1.99E+06	3.63E+05	6.64E+04	1.32E+04	3.16E+03	8.65E+02	2.66E+02
1.83	8.17E+06	2.16E+06	4.00E+05	7.41E+04	1.49E+04	3.60E+03	9.88E+02	3.06E+02
2.34	9.26E+06	2.50E+06	4.73E+05	8.95E+04	1.83E+04	4.49E+03	1.24E+03	3.81E+02
2.98	1.05E+07	2.87E+06	5.58E+05	1.08E+05	2.25E+04	5.57E+03	1.55E+03	4.86E+02
3.79	1.18E+07	3.30E+06	6.55E+05	1.29E+05	2.78E+04	6.90E+03	1.94E+03	6.20E+02
4.83	1.33E+07	3.78E+06	7.71E+05	1.55E+05	3.40E+04	8.55E+03	2.43E+03	7.90E+02
6.16	1.51E+07	4.33E+06	9.05E+05	1.86E+05	4.14E+04	1.06E+04	3.04E+03	9.92E+02
7.85	1.70E+07	4.96E+06	1.06E+06	2.23E+05	5.04E+04	1.30E+04	3.81E+03	1.25E+03
10	1.91E+07	5.66E+06	1.24E+06	2.66E+05	6.12E+04	1.60E+04	4.75E+03	1.57E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	53.33	60.9	69.3	77.14	83.2	86.86	90	88.14
0.127	52.76	60.25	68.66	76.33	82.56	86.76	89.02	90
0.162	51.99	59.55	68.01	75.94	82.26	86.21	88.46	88.6
0.207	51.34	58.89	67.38	75.12	81.92	85.77	88.21	89.47
0.264	50.69	58.23	66.75	74.36	80.9	85.32	87.73	89.8
0.336	50.13	57.59	66.14	73.95	80.48	84.9	87.39	89.38
0.428	49.55	56.93	65.53	73.29	79.68	84.32	87.46	87.52
0.546	49.04	56.3	64.93	72.64	79.58	83.99	87.04	88.23
0.695	48.58	55.65	64.34	72.02	78.71	83.62	86.35	87.78
0.886	48.11	55.02	63.76	71.42	77.99	82.99	86.6	87.83
1.13	47.73	54.41	63.15	70.83	77.61	82.53	85.85	88.56
1.59	47.27	53.58	62.33	70.02	76.71	81.74	85.39	86.81
1.83	47.09	53.23	62.01	69.7	76.16	81.34	85.24	87.48
2.34	46.88	52.66	61.4	69.13	76.04	80.9	84.94	86.29
2.98	46.72	52.11	60.83	68.59	75.23	80.35	84.59	85.44
3.79	46.65	51.61	60.26	68.04	74.59	79.82	84.15	85.16
4.83	46.65	51.11	59.68	67.52	74.03	79.25	83.99	84.27
6.16	46.75	50.65	59.09	66.99	73.51	78.81	83.74	83.5
7.85	46.96	50.24	58.53	66.47	73	78.35	83.73	82.96
10	47.28	49.87	57.97	65.93	72.48	77.66	83.72	81.45

Bitumen blend Chem4-60%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	1.48E+06	2.97E+05	4.17E+04	5.70E+03	9.69E+02	1.99E+02	5.13E+01	1.59E+01
0.127	1.71E+06	3.50E+05	5.02E+04	7.05E+03	1.22E+03	2.54E+02	6.54E+01	1.95E+01
0.162	1.98E+06	4.13E+05	6.06E+04	8.70E+03	1.52E+03	3.19E+02	8.40E+01	2.59E+01
0.207	2.29E+06	4.87E+05	7.30E+04	1.08E+04	1.91E+03	4.05E+02	1.05E+02	3.25E+01
0.264	2.64E+06	5.73E+05	8.77E+04	1.33E+04	2.38E+03	5.14E+02	1.36E+02	4.29E+01
0.336	3.03E+06	6.71E+05	1.05E+05	1.63E+04	2.97E+03	6.43E+02	1.71E+02	5.36E+01
0.428	3.48E+06	7.85E+05	1.26E+05	2.00E+04	3.68E+03	8.08E+02	2.17E+02	6.80E+01
0.546	3.99E+06	9.18E+05	1.50E+05	2.46E+04	4.59E+03	1.02E+03	2.75E+02	8.62E+01
0.695	4.55E+06	1.07E+06	1.79E+05	3.01E+04	5.66E+03	1.27E+03	3.48E+02	1.11E+02
0.886	5.19E+06	1.25E+06	2.13E+05	3.65E+04	6.99E+03	1.60E+03	4.39E+02	1.39E+02
1.13	5.92E+06	1.45E+06	2.54E+05	4.44E+04	8.57E+03	2.00E+03	5.56E+02	1.80E+02
1.59	7.09E+06	1.78E+06	3.23E+05	5.81E+04	1.15E+04	2.74E+03	7.72E+02	2.42E+02
1.83	7.64E+06	1.94E+06	3.57E+05	6.48E+04	1.30E+04	3.12E+03	8.75E+02	2.81E+02
2.34	8.68E+06	2.25E+06	4.24E+05	7.86E+04	1.61E+04	3.89E+03	1.11E+03	3.52E+02
2.98	9.83E+06	2.60E+06	5.01E+05	9.46E+04	1.96E+04	4.85E+03	1.39E+03	4.58E+02
3.79	1.11E+07	2.99E+06	5.90E+05	1.14E+05	2.42E+04	6.01E+03	1.75E+03	5.74E+02
4.83	1.26E+07	3.44E+06	6.95E+05	1.37E+05	2.97E+04	7.45E+03	2.19E+03	7.23E+02
6.16	1.42E+07	3.96E+06	8.19E+05	1.64E+05	3.63E+04	9.24E+03	2.73E+03	9.09E+02
7.85	1.60E+07	4.54E+06	9.62E+05	1.97E+05	4.43E+04	1.14E+04	3.43E+03	1.15E+03
10	1.81E+07	5.21E+06	1.13E+06	2.36E+05	5.39E+04	1.40E+04	4.26E+03	1.44E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	54.46	61.93	70.15	77.71	83.75	87.36	89.39	90
0.127	53.61	61.39	69.49	77.14	83.28	86.99	89.71	88.09
0.162	52.99	60.69	68.86	76.32	82.65	86.48	88.35	88.08
0.207	52.33	60.05	68.24	75.77	82.18	86.11	88.5	90
0.264	51.68	59.4	67.62	75.06	81.47	85.57	87.83	89.07
0.336	51.08	58.78	67.02	74.46	81.07	85.24	87.72	88.46
0.428	50.53	58.09	66.42	74.05	80.3	84.66	87.76	89.05
0.546	50.02	57.5	65.84	73.35	79.78	84.33	87.51	89.13
0.695	49.53	56.88	65.25	72.73	79.18	83.81	86.96	89.55
0.886	49.07	56.27	64.68	72.15	78.58	83.18	86.62	88.51
1.13	48.67	55.66	64.11	71.57	77.97	82.74	85.94	89.2
1.59	48.2	54.84	63.32	70.76	77.14	81.96	85.51	88.38
1.83	48.02	54.5	62.98	70.46	76.71	81.69	85.42	88.41
2.34	47.78	53.96	62.42	69.9	76.17	81.17	85.05	88.15
2.98	47.62	53.44	61.87	69.36	75.47	80.58	84.14	87.26
3.79	47.51	52.93	61.31	68.83	74.97	80	83.89	87.05
4.83	47.49	52.47	60.76	68.32	74.63	79.53	83.72	86.99
6.16	47.55	52.04	60.21	67.81	74.1	78.87	83.29	87.4
7.85	47.72	51.65	59.65	67.28	73.58	78.26	82.88	87.09
10	48	51.3	59.13	66.78	73.08	77.5	82.29	87.76

Bitumen blend Wax-60%

Complex modulus (Pa)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	3.81E+06	9.08E+05	1.53E+05	2.70E+04	5.16E+03	1.31E+03	3.85E+02	1.04E+02
0.127	4.32E+06	1.05E+06	1.80E+05	3.20E+04	6.15E+03	1.55E+03	4.58E+02	1.24E+02
0.162	4.90E+06	1.21E+06	2.11E+05	3.81E+04	7.46E+03	1.86E+03	5.41E+02	1.46E+02
0.207	5.53E+06	1.39E+06	2.48E+05	4.53E+04	8.93E+03	2.23E+03	6.46E+02	1.75E+02
0.264	6.24E+06	1.60E+06	2.91E+05	5.38E+04	1.07E+04	2.67E+03	7.65E+02	2.09E+02
0.336	7.02E+06	1.83E+06	3.40E+05	6.38E+04	1.28E+04	3.19E+03	9.17E+02	2.47E+02
0.428	7.88E+06	2.10E+06	3.98E+05	7.56E+04	1.54E+04	3.85E+03	1.09E+03	2.98E+02
0.546	8.85E+06	2.40E+06	4.65E+05	8.96E+04	1.86E+04	4.59E+03	1.31E+03	3.56E+02
0.695	9.91E+06	2.74E+06	5.42E+05	1.06E+05	2.22E+04	5.52E+03	1.56E+03	4.27E+02
0.886	1.11E+07	3.13E+06	6.32E+05	1.26E+05	2.70E+04	6.60E+03	1.88E+03	5.16E+02
1.13	1.24E+07	3.56E+06	7.36E+05	1.49E+05	3.23E+04	7.96E+03	2.25E+03	6.23E+02
1.59	1.45E+07	4.26E+06	9.08E+05	1.88E+05	4.15E+04	1.03E+04	2.93E+03	8.16E+02
1.83	1.54E+07	4.58E+06	9.90E+05	2.07E+05	4.60E+04	1.14E+04	3.27E+03	9.04E+02
2.34	1.73E+07	5.20E+06	1.15E+06	2.45E+05	5.52E+04	1.38E+04	3.96E+03	1.11E+03
2.98	1.93E+07	5.88E+06	1.33E+06	2.89E+05	6.59E+04	1.66E+04	4.77E+03	1.34E+03
3.79	2.15E+07	6.64E+06	1.54E+06	3.39E+05	7.86E+04	1.99E+04	5.76E+03	1.64E+03
4.83	2.40E+07	7.49E+06	1.77E+06	3.99E+05	9.38E+04	2.41E+04	7.00E+03	2.00E+03
6.16	2.69E+07	8.45E+06	2.05E+06	4.70E+05	1.12E+05	2.93E+04	8.48E+03	2.45E+03
7.85	3.00E+07	9.53E+06	2.35E+06	5.52E+05	1.34E+05	3.53E+04	1.03E+04	3.00E+03
10	3.34E+07	1.07E+07	2.70E+06	6.47E+05	1.59E+05	4.24E+04	1.24E+04	3.66E+03

Phase angle (°)

Frequency (Hz)	10°C	20°C	30°C	40°C	50°C	60°C	70°C	80°C
0.1	46.16	53.47	59.94	63.74	65.29	64.85	62.9	62.76
0.127	45.87	52.95	59.57	63.63	65.55	65.26	63.5	63.47
0.162	45.23	52.3	59.29	63.52	66.01	65.6	63.94	64.06
0.207	44.79	51.72	58.9	63.43	65.95	65.8	64.16	64.33
0.264	44.26	51.21	58.46	63.3	65.99	66.51	64.74	65.26
0.336	43.95	50.65	58.09	63.12	66.1	66.31	65.29	66.3
0.428	43.63	50.15	57.66	62.95	66.27	66.97	65.82	66.71
0.546	43.34	49.59	57.25	62.76	66.25	67.34	66.53	67.55
0.695	43.13	49.07	56.81	62.52	66.19	67.63	66.96	68.59
0.886	42.98	48.6	56.37	62.29	66.3	67.72	67.72	69.04
1.13	42.88	48.1	55.91	62.03	66.26	67.9	68.43	69.85
1.59	42.9	47.48	55.26	61.65	66.19	68.58	69.16	70.77
1.83	42.93	47.24	54.98	61.48	66.11	68.28	69.45	71.35
2.34	43.13	46.84	54.5	61.17	66.05	68.52	69.95	72.03
2.98	43.47	46.51	54.03	60.85	65.87	68.59	70.37	72.52
3.79	43.9	46.21	53.55	60.5	65.74	68.66	70.68	73.05
4.83	44.48	45.96	53.06	60.15	65.55	68.71	71.13	73.45
6.16	45.22	45.78	52.59	59.78	65.35	68.79	71.49	74.08
7.85	46.12	45.66	52.12	59.39	65.13	68.77	71.74	74.29
10	47.18	45.62	51.66	58.99	64.88	68.7	71.94	75.1

Mastic results

BTSV results

Mastic testing	BTSV T	Std. dev.	BTSV δ	Std. dev.
	°C	°C	°	°
RAP	**80.7**	0.10	**80.3**	0.13
HMA 60%	**64.2**	0.00	**81.6**	0.02
WMA-Chem1 60%	**65.4**	0.05	**81.5**	0.03
WMA-Chem2 60%	**63.6**	0.06	**81.6**	0.05
WMA-Chem3 60%	**62.3**	0.23	**83.0**	0.10
WMA-Chem4 60%	**62.9**	0.03	**82.0**	0.01
WMA-Wax 60%	**67.9**	0.29	**79.9**	0.24
WMA-Kombi 60%	**66.3**	0.05	**80.7**	0.15

Results of temperature frequency sweeps

RAP mastic

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	4.00E+06	8.14E+05	1.38E+05	2.75E+04	5.82E+03	1.44E+03	4.26E+02	1.48E+02
1.27E-01	4.54E+06	9.42E+05	1.66E+05	3.34E+04	7.30E+03	1.81E+03	5.31E+02	1.84E+02
1.62E-01	5.17E+06	1.09E+06	1.99E+05	4.09E+04	8.98E+03	2.24E+03	6.71E+02	2.31E+02
2.07E-01	5.87E+06	1.27E+06	2.37E+05	4.99E+04	1.13E+04	2.83E+03	8.47E+02	2.90E+02
2.64E-01	6.66E+06	1.48E+06	2.83E+05	6.08E+04	1.40E+04	3.54E+03	1.06E+03	3.66E+02
3.36E-01	7.54E+06	1.71E+06	3.38E+05	7.38E+04	1.74E+04	4.46E+03	1.34E+03	4.61E+02
4.28E-01	8.53E+06	1.97E+06	4.01E+05	8.92E+04	2.16E+04	5.56E+03	1.68E+03	5.81E+02
5.46E-01	9.61E+06	2.28E+06	4.76E+05	1.07E+05	2.68E+04	6.92E+03	2.11E+03	7.34E+02
6.95E-01	1.08E+07	2.63E+06	5.62E+05	1.30E+05	3.27E+04	8.54E+03	2.65E+03	9.25E+02
8.86E-01	1.21E+07	3.03E+06	6.65E+05	1.56E+05	4.01E+04	1.07E+04	3.33E+03	1.16E+03
1.13E+00	1.35E+07	3.49E+06	7.86E+05	1.88E+05	4.91E+04	1.32E+04	4.17E+03	1.47E+03
1.59E+00	1.57E+07	4.25E+06	9.90E+05	2.43E+05	6.49E+04	1.80E+04	5.69E+03	2.03E+03
1.83E+00	1.67E+07	4.61E+06	1.09E+06	2.70E+05	7.26E+04	2.04E+04	6.48E+03	2.32E+03
2.34E+00	1.85E+07	5.29E+06	1.28E+06	3.23E+05	8.88E+04	2.54E+04	8.07E+03	2.92E+03
2.98E+00	2.04E+07	6.06E+06	1.50E+06	3.86E+05	1.08E+05	3.15E+04	1.00E+04	3.67E+03
3.79E+00	2.25E+07	6.91E+06	1.76E+06	4.59E+05	1.30E+05	3.87E+04	1.24E+04	4.57E+03
4.83E+00	2.46E+07	7.90E+06	2.06E+06	5.48E+05	1.57E+05	4.75E+04	1.54E+04	5.72E+03
6.16E+00	2.69E+07	8.99E+06	2.41E+06	6.51E+05	1.90E+05	5.84E+04	1.90E+04	7.12E+03
7.85E+00	2.92E+07	1.02E+07	2.81E+06	7.74E+05	2.30E+05	7.12E+04	2.34E+04	8.85E+03
1.00E+01	3.17E+07	1.15E+07	3.27E+06	9.17E+05	2.76E+05	8.70E+04	2.88E+04	1.10E+04

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	51.4	58.8	68.1	75.2	80.2	84.5	86.2	85.0
0.127	50.7	58.5	67.7	74.7	79.6	83.2	86.4	85.5
0.162	50.0	57.8	67.0	73.9	79.2	83.6	86.4	86.0
0.207	49.4	57.4	66.3	73.3	78.5	83.5	86.2	86.3
0.264	48.7	56.9	65.7	72.6	78.1	82.7	86.1	86.5
0.336	47.9	56.5	64.9	71.8	77.7	82.2	86.0	86.6
0.428	47.2	55.9	64.3	71.2	77.1	81.5	85.7	86.7
0.546	46.5	55.4	63.7	70.5	76.4	81.6	85.4	86.7
0.695	45.7	54.8	63.1	69.8	75.9	81.0	85.0	86.6
0.886	44.8	54.4	62.5	69.1	75.2	80.4	84.6	86.4
1.13	43.9	53.8	61.9	68.5	74.6	80.0	84.1	86.2
1.59	42.7	52.9	61.1	67.6	73.7	79.0	83.4	85.8
1.83	42.1	52.6	60.7	67.2	73.4	78.8	83.1	85.7
2.34	41.1	51.9	60.1	66.6	72.7	78.2	82.6	85.3
2.98	40.1	51.2	59.6	66.0	72.0	77.4	82.1	84.9
3.79	39.1	50.5	59.0	65.5	71.4	76.8	81.5	84.5
4.83	38.1	49.8	58.4	64.9	70.8	76.2	81.0	84.1
6.16	37.0	49.1	57.8	64.4	70.3	75.5	80.4	83.6
7.85	36.0	48.3	57.2	63.8	69.7	74.9	79.8	83.1
10	35.0	47.5	56.6	63.3	69.1	74.3	79.2	82.7

Mastic blend HMA-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	5.39E+05	7.59E+04	1.26E+04	2.33E+03	5.93E+02	1.83E+02	6.10E+01	2.63E+01
0.127	6.29E+05	9.22E+04	1.56E+04	2.89E+03	7.43E+02	2.25E+02	7.59E+01	3.26E+01
0.162	7.36E+05	1.11E+05	1.95E+04	3.63E+03	9.31E+02	2.83E+02	9.55E+01	4.07E+01
0.207	8.62E+05	1.35E+05	2.43E+04	4.57E+03	1.17E+03	3.57E+02	1.21E+02	5.13E+01
0.264	1.01E+06	1.63E+05	3.00E+04	5.69E+03	1.47E+03	4.49E+02	1.53E+02	6.46E+01
0.336	1.18E+06	1.97E+05	3.69E+04	7.20E+03	1.84E+03	5.68E+02	1.93E+02	8.14E+01
0.428	1.38E+06	2.37E+05	4.52E+04	8.95E+03	2.32E+03	7.15E+02	2.44E+02	1.03E+02
0.546	1.61E+06	2.85E+05	5.55E+04	1.12E+04	2.90E+03	9.03E+02	3.09E+02	1.30E+02
0.695	1.87E+06	3.42E+05	6.78E+04	1.40E+04	3.63E+03	1.13E+03	3.91E+02	1.65E+02
0.886	2.18E+06	4.10E+05	8.29E+04	1.74E+04	4.56E+03	1.43E+03	4.96E+02	2.08E+02
1.13	2.55E+06	4.91E+05	1.01E+05	2.17E+04	5.70E+03	1.81E+03	6.29E+02	2.64E+02
1.59	3.16E+06	6.31E+05	1.33E+05	2.97E+04	7.81E+03	2.51E+03	8.78E+02	3.69E+02
1.83	3.44E+06	6.99E+05	1.49E+05	3.36E+04	8.90E+03	2.86E+03	1.00E+03	4.23E+02
2.34	4.01E+06	8.35E+05	1.82E+05	4.15E+04	1.11E+04	3.61E+03	1.28E+03	5.37E+02
2.98	4.66E+06	9.95E+05	2.20E+05	5.11E+04	1.38E+04	4.54E+03	1.60E+03	6.80E+02
3.79	5.39E+06	1.18E+06	2.66E+05	6.27E+04	1.71E+04	5.67E+03	2.03E+03	8.59E+02
4.83	6.24E+06	1.40E+06	3.22E+05	7.71E+04	2.13E+04	7.13E+03	2.54E+03	1.09E+03
6.16	7.21E+06	1.66E+06	3.89E+05	9.44E+04	2.66E+04	8.94E+03	3.21E+03	1.38E+03
7.85	8.32E+06	1.97E+06	4.69E+05	1.16E+05	3.30E+04	1.12E+04	4.03E+03	1.73E+03
10	9.57E+06	2.33E+06	5.64E+05	1.42E+05	4.09E+04	1.40E+04	5.04E+03	2.19E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	62.9	72.7	79.3	83.7	84.4	84.6	86.6	85.0
0.127	62.4	72.3	78.8	83.8	84.6	85.4	87.2	85.8
0.162	61.9	71.6	78.2	82.7	84.5	85.3	87.5	86.3
0.207	61.6	71.0	77.6	82.6	84.6	85.7	87.7	86.8
0.264	61.2	70.3	77.0	81.9	84.6	85.7	87.9	87.1
0.336	60.8	69.8	76.5	81.6	84.3	85.9	88.0	87.4
0.428	60.4	69.3	76.0	81.8	84.2	86.0	88.1	87.6
0.546	60.0	68.7	75.4	80.7	84.1	86.1	88.1	87.8
0.695	59.6	68.1	74.8	80.4	83.7	85.8	88.1	88.0
0.886	59.2	67.6	74.2	80.0	83.5	85.7	88.0	88.1
1.13	58.7	67.0	73.7	79.6	83.1	85.5	87.9	88.2
1.59	58.1	66.3	72.9	78.6	82.6	85.0	87.7	88.2
1.83	57.8	66.0	72.6	78.4	82.4	85.0	87.6	88.3
2.34	57.3	65.5	72.0	77.8	81.8	84.8	87.4	88.3
2.98	56.8	64.9	71.5	77.2	81.6	84.4	87.2	88.2
3.79	56.3	64.4	71.0	76.7	81.0	84.1	86.9	88.1
4.83	55.8	63.9	70.5	76.2	80.5	83.7	86.7	88.0
6.16	55.3	63.4	69.9	75.7	80.1	83.3	86.3	87.9
7.85	54.7	62.8	69.4	75.2	79.6	82.9	86.0	87.8
10	54.2	62.3	69.0	74.6	79.1	82.3	85.7	87.6

Mastic blend Chem1-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	3.89E+05	5.62E+04	9.28E+03	1.82E+03	4.93E+02	1.58E+02	5.20E+01	2.23E+01
1.27E-01	4.56E+05	6.83E+04	1.15E+04	2.27E+03	6.10E+02	1.94E+02	6.45E+01	2.77E+01
1.62E-01	5.35E+05	8.31E+04	1.44E+04	2.88E+03	7.60E+02	2.44E+02	8.14E+01	3.48E+01
2.07E-01	6.31E+05	1.01E+05	1.80E+04	3.64E+03	9.63E+02	3.04E+02	1.03E+02	4.40E+01
2.64E-01	7.43E+05	1.23E+05	2.25E+04	4.54E+03	1.21E+03	3.80E+02	1.30E+02	5.55E+01
3.36E-01	8.72E+05	1.49E+05	2.79E+04	5.71E+03	1.52E+03	4.83E+02	1.65E+02	7.00E+01
4.28E-01	1.03E+06	1.81E+05	3.44E+04	7.10E+03	1.92E+03	6.05E+02	2.09E+02	8.85E+01
5.46E-01	1.20E+06	2.18E+05	4.23E+04	8.94E+03	2.41E+03	7.63E+02	2.65E+02	1.12E+02
6.95E-01	1.41E+06	2.63E+05	5.19E+04	1.12E+04	3.03E+03	9.56E+02	3.35E+02	1.42E+02
8.86E-01	1.66E+06	3.17E+05	6.37E+04	1.39E+04	3.80E+03	1.21E+03	4.24E+02	1.80E+02
1.13E+00	1.95E+06	3.81E+05	7.80E+04	1.73E+04	4.77E+03	1.53E+03	5.40E+02	2.30E+02
1.59E+00	2.44E+06	4.93E+05	1.04E+05	2.38E+04	6.55E+03	2.12E+03	7.54E+02	3.21E+02
1.83E+00	2.67E+06	5.47E+05	1.16E+05	2.71E+04	7.48E+03	2.43E+03	8.62E+02	3.68E+02
2.34E+00	3.13E+06	6.57E+05	1.42E+05	3.36E+04	9.37E+03	3.07E+03	1.10E+03	4.69E+02
2.98E+00	3.66E+06	7.85E+05	1.73E+05	4.15E+04	1.17E+04	3.86E+03	1.38E+03	5.93E+02
3.79E+00	4.27E+06	9.37E+05	2.09E+05	5.12E+04	1.45E+04	4.84E+03	1.75E+03	7.52E+02
4.83E+00	4.98E+06	1.12E+06	2.54E+05	6.30E+04	1.81E+04	6.09E+03	2.20E+03	9.51E+02
6.16E+00	5.81E+06	1.33E+06	3.08E+05	7.77E+04	2.26E+04	7.64E+03	2.78E+03	1.20E+03
7.85E+00	6.75E+06	1.58E+06	3.72E+05	9.54E+04	2.82E+04	9.58E+03	3.50E+03	1.53E+03
1.00E+01	7.83E+06	1.88E+06	4.50E+05	1.17E+05	3.50E+04	1.20E+04	4.39E+03	1.92E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	64.6	74.4	80.4	84.6	85.0	83.7	86.9	85.9
0.127	64.1	73.7	80.0	84.2	85.6	84.8	87.6	86.6
0.162	63.8	73.2	79.5	84.1	85.7	85.0	87.8	87.0
0.207	63.4	72.4	78.9	83.5	85.5	85.6	88.1	87.4
0.264	63.1	72.0	78.4	83.5	85.6	85.9	88.2	87.7
0.336	62.7	71.3	77.8	83.5	85.6	86.0	88.3	88.0
0.428	62.4	70.8	77.3	82.2	85.3	86.3	88.4	88.2
0.546	62.0	70.3	76.8	82.0	85.1	86.5	88.4	88.4
0.695	61.6	69.7	76.2	81.6	84.8	86.4	88.4	88.5
0.886	61.2	69.1	75.6	81.0	84.5	86.3	88.3	88.5
1.13	60.8	68.6	75.1	80.6	84.1	86.1	88.3	88.5
1.59	60.2	67.9	74.3	79.9	83.8	85.8	88.1	88.5
1.83	59.9	67.6	74.0	79.5	83.4	85.6	88.0	88.6
2.34	59.5	67.0	73.4	79.0	82.9	85.4	87.8	88.5
2.98	59.0	66.5	72.9	78.5	82.7	85.1	87.6	88.4
3.79	58.6	66.0	72.3	78.0	82.0	84.8	87.3	88.3
4.83	58.1	65.5	71.8	77.5	81.7	84.4	87.1	88.2
6.16	57.6	65.0	71.3	76.9	81.0	84.1	86.8	88.0
7.85	57.1	64.5	70.8	76.4	80.8	83.8	86.4	87.8
10	56.6	64.0	70.3	75.9	80.4	83.2	86.1	87.5

Mastic blend Chem2-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	4.80E+05	6.82E+04	1.14E+04	2.16E+03	6.17E+02	1.95E+02	6.33E+01	2.63E+01
1.27E-01	5.61E+05	8.30E+04	1.40E+04	2.67E+03	7.60E+02	2.40E+02	7.79E+01	3.22E+01
1.62E-01	6.56E+05	1.00E+05	1.75E+04	3.37E+03	9.45E+02	2.98E+02	9.73E+01	4.00E+01
2.07E-01	7.72E+05	1.22E+05	2.18E+04	4.32E+03	1.19E+03	3.77E+02	1.22E+02	5.03E+01
2.64E-01	9.04E+05	1.48E+05	2.72E+04	5.35E+03	1.50E+03	4.67E+02	1.54E+02	6.32E+01
3.36E-01	1.06E+06	1.79E+05	3.35E+04	6.63E+03	1.87E+03	5.85E+02	1.92E+02	7.96E+01
4.28E-01	1.24E+06	2.16E+05	4.11E+04	8.34E+03	2.34E+03	7.29E+02	2.43E+02	1.00E+02
5.46E-01	1.46E+06	2.60E+05	5.05E+04	1.04E+04	2.93E+03	9.12E+02	3.07E+02	1.27E+02
6.95E-01	1.70E+06	3.13E+05	6.18E+04	1.30E+04	3.66E+03	1.15E+03	3.87E+02	1.60E+02
8.86E-01	1.99E+06	3.76E+05	7.57E+04	1.63E+04	4.59E+03	1.44E+03	4.89E+02	2.02E+02
1.13E+00	2.33E+06	4.50E+05	9.26E+04	2.04E+04	5.74E+03	1.81E+03	6.18E+02	2.57E+02
1.59E+00	2.90E+06	5.81E+05	1.22E+05	2.78E+04	7.83E+03	2.50E+03	8.61E+02	3.57E+02
1.83E+00	3.18E+06	6.44E+05	1.37E+05	3.14E+04	8.91E+03	2.85E+03	9.85E+02	4.09E+02
2.34E+00	3.71E+06	7.71E+05	1.67E+05	3.90E+04	1.11E+04	3.59E+03	1.25E+03	5.21E+02
2.98E+00	4.33E+06	9.19E+05	2.03E+05	4.80E+04	1.38E+04	4.50E+03	1.58E+03	6.56E+02
3.79E+00	5.03E+06	1.09E+06	2.45E+05	5.90E+04	1.70E+04	5.64E+03	1.98E+03	8.32E+02
4.83E+00	5.85E+06	1.30E+06	2.97E+05	7.25E+04	2.13E+04	7.08E+03	2.49E+03	1.05E+03
6.16E+00	6.79E+06	1.55E+06	3.59E+05	8.90E+04	2.66E+04	8.85E+03	3.15E+03	1.33E+03
7.85E+00	7.87E+06	1.83E+06	4.34E+05	1.09E+05	3.31E+04	1.11E+04	3.94E+03	1.68E+03
1.00E+01	9.10E+06	2.17E+06	5.23E+05	1.33E+05	4.09E+04	1.38E+04	4.94E+03	2.12E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	63.7	73.6	79.6	82.5	83.3	81.9	84.6	84.3
0.127	63.2	72.8	79.3	82.4	84.0	82.2	85.4	85.3
0.162	62.9	72.1	78.7	82.6	83.7	83.2	86.0	85.8
0.207	62.5	71.6	78.1	81.5	84.1	83.2	86.3	86.4
0.264	62.1	71.0	77.6	82.1	83.8	83.8	86.7	86.8
0.336	61.7	70.5	77.1	81.7	83.9	84.3	86.9	87.1
0.428	61.4	69.9	76.5	81.3	83.7	84.4	87.1	87.2
0.546	61.0	69.3	75.9	81.3	83.6	84.4	87.2	87.5
0.695	60.6	68.7	75.4	80.1	83.5	84.5	87.4	87.6
0.886	60.2	68.2	74.8	79.7	83.1	84.7	87.4	87.8
1.13	59.8	67.7	74.2	79.7	82.9	84.8	87.4	87.9
1.59	59.2	66.9	73.4	78.9	82.4	84.5	87.3	88.0
1.83	59.0	66.6	73.1	78.6	82.3	84.4	87.3	88.0
2.34	58.5	66.1	72.6	78.1	81.9	84.3	87.2	88.0
2.98	58.1	65.6	72.0	77.6	81.7	84.0	87.0	87.8
3.79	57.6	65.1	71.5	77.1	81.1	83.7	86.8	87.9
4.83	57.2	64.5	71.0	76.6	80.6	83.5	86.5	87.9
6.16	56.7	64.0	70.5	76.1	80.3	83.1	86.2	87.8
7.85	56.3	63.5	70.0	75.5	79.9	82.7	86.0	87.6
10	55.8	63.0	69.5	75.0	79.5	82.4	85.6	87.5

Mastic blend Chem3-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	5.27E+05	6.25E+04	9.87E+03	1.96E+03	5.89E+02	2.27E+02	6.38E+01	3.02E+01
1.27E-01	6.07E+05	7.55E+04	1.23E+04	2.47E+03	7.11E+02	2.55E+02	7.70E+01	3.62E+01
1.62E-01	7.03E+05	9.22E+04	1.54E+04	3.08E+03	8.80E+02	3.16E+02	9.61E+01	4.43E+01
2.07E-01	8.17E+05	1.12E+05	1.92E+04	3.82E+03	1.10E+03	3.87E+02	1.21E+02	5.50E+01
2.64E-01	9.50E+05	1.36E+05	2.39E+04	4.82E+03	1.37E+03	4.79E+02	1.52E+02	6.86E+01
3.36E-01	1.11E+06	1.66E+05	2.99E+04	6.01E+03	1.71E+03	5.94E+02	1.91E+02	8.57E+01
4.28E-01	1.29E+06	2.00E+05	3.68E+04	7.52E+03	2.15E+03	7.39E+02	2.40E+02	1.07E+02
5.46E-01	1.50E+06	2.43E+05	4.54E+04	9.50E+03	2.68E+03	9.14E+02	3.04E+02	1.35E+02
6.95E-01	1.75E+06	2.93E+05	5.59E+04	1.18E+04	3.36E+03	1.14E+03	3.83E+02	1.70E+02
8.86E-01	2.05E+06	3.54E+05	6.87E+04	1.49E+04	4.21E+03	1.43E+03	4.83E+02	2.14E+02
1.13E+00	2.39E+06	4.27E+05	8.45E+04	1.85E+04	5.27E+03	1.79E+03	6.11E+02	2.71E+02
1.59E+00	2.98E+06	5.55E+05	1.13E+05	2.54E+04	7.27E+03	2.46E+03	8.53E+02	3.76E+02
1.83E+00	3.25E+06	6.18E+05	1.26E+05	2.91E+04	8.25E+03	2.80E+03	9.74E+02	4.29E+02
2.34E+00	3.81E+06	7.44E+05	1.55E+05	3.62E+04	1.04E+04	3.51E+03	1.24E+03	5.46E+02
2.98E+00	4.44E+06	8.92E+05	1.89E+05	4.49E+04	1.30E+04	4.42E+03	1.56E+03	6.88E+02
3.79E+00	5.17E+06	1.07E+06	2.30E+05	5.54E+04	1.61E+04	5.54E+03	1.97E+03	8.68E+02
4.83E+00	6.02E+06	1.28E+06	2.81E+05	6.86E+04	2.00E+04	6.93E+03	2.48E+03	1.10E+03
6.16E+00	7.00E+06	1.53E+06	3.42E+05	8.46E+04	2.51E+04	8.71E+03	3.13E+03	1.39E+03
7.85E+00	8.12E+06	1.82E+06	4.15E+05	1.04E+05	3.14E+04	1.09E+04	3.93E+03	1.75E+03
1.00E+01	9.40E+06	2.17E+06	5.03E+05	1.29E+05	3.90E+04	1.37E+04	4.93E+03	2.20E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	62.1	74.6	80.4	83.9	81.4	77.7	84.4	81.4
0.127	61.8	74.2	80.2	83.0	83.3	79.9	85.8	82.9
0.162	61.8	73.6	79.6	84.4	83.4	81.8	86.4	84.0
0.207	61.5	73.1	79.4	83.4	83.8	81.7	86.8	84.8
0.264	61.4	72.7	79.0	83.3	84.1	81.9	87.2	85.4
0.336	61.4	72.2	78.5	82.9	84.2	82.7	87.5	86.0
0.428	61.2	71.8	78.2	82.9	84.0	83.2	87.7	86.5
0.546	61.1	71.3	77.7	81.7	84.3	83.5	87.9	86.9
0.695	60.9	70.8	77.2	82.0	83.9	83.9	88.0	87.2
0.886	60.7	70.3	76.7	81.7	84.1	84.1	88.0	87.5
1.13	60.4	69.8	76.2	81.5	84.0	84.5	88.1	87.7
1.59	60.0	69.1	75.6	80.7	83.5	84.5	88.1	87.9
1.83	59.9	68.8	75.3	80.5	83.5	84.5	88.0	88.0
2.34	59.5	68.3	74.8	80.0	83.2	84.5	88.0	88.0
2.98	59.1	67.8	74.3	79.6	82.8	84.6	87.8	88.0
3.79	58.6	67.3	73.7	79.1	82.6	84.3	87.7	88.1
4.83	58.2	66.8	73.2	78.6	82.0	84.2	87.5	88.1
6.16	57.6	66.3	72.7	78.2	81.6	84.1	87.3	88.0
7.85	57.1	65.7	72.2	77.7	81.5	83.7	87.1	87.9
10	56.5	65.2	71.7	77.2	81.1	83.5	86.9	87.8

Mastic blend Chem4-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	3.89E+05	5.62E+04	9.28E+03	1.82E+03	4.93E+02	1.58E+02	5.20E+01	2.23E+01
1.27E-01	4.56E+05	6.83E+04	1.15E+04	2.27E+03	6.10E+02	1.94E+02	6.45E+01	2.77E+01
1.62E-01	5.35E+05	8.31E+04	1.44E+04	2.88E+03	7.60E+02	2.44E+02	8.14E+01	3.48E+01
2.07E-01	6.31E+05	1.01E+05	1.80E+04	3.64E+03	9.63E+02	3.04E+02	1.03E+02	4.40E+01
2.64E-01	7.43E+05	1.23E+05	2.25E+04	4.54E+03	1.21E+03	3.80E+02	1.30E+02	5.55E+01
3.36E-01	8.72E+05	1.49E+05	2.79E+04	5.71E+03	1.52E+03	4.83E+02	1.65E+02	7.00E+01
4.28E-01	1.03E+06	1.81E+05	3.44E+04	7.10E+03	1.92E+03	6.05E+02	2.09E+02	8.85E+01
5.46E-01	1.20E+06	2.18E+05	4.23E+04	8.94E+03	2.41E+03	7.63E+02	2.65E+02	1.12E+02
6.95E-01	1.41E+06	2.63E+05	5.19E+04	1.12E+04	3.03E+03	9.56E+02	3.35E+02	1.42E+02
8.86E-01	1.66E+06	3.17E+05	6.37E+04	1.39E+04	3.80E+03	1.21E+03	4.24E+02	1.80E+02
1.13E+00	1.95E+06	3.81E+05	7.80E+04	1.73E+04	4.77E+03	1.53E+03	5.40E+02	2.30E+02
1.59E+00	2.44E+06	4.93E+05	1.04E+05	2.38E+04	6.55E+03	2.12E+03	7.54E+02	3.21E+02
1.83E+00	2.67E+06	5.47E+05	1.16E+05	2.71E+04	7.48E+03	2.43E+03	8.62E+02	3.68E+02
2.34E+00	3.13E+06	6.57E+05	1.42E+05	3.36E+04	9.37E+03	3.07E+03	1.10E+03	4.69E+02
2.98E+00	3.66E+06	7.85E+05	1.73E+05	4.15E+04	1.17E+04	3.86E+03	1.38E+03	5.93E+02
3.79E+00	4.27E+06	9.37E+05	2.09E+05	5.12E+04	1.45E+04	4.84E+03	1.75E+03	7.52E+02
4.83E+00	4.98E+06	1.12E+06	2.54E+05	6.30E+04	1.81E+04	6.09E+03	2.20E+03	9.51E+02
6.16E+00	5.81E+06	1.33E+06	3.08E+05	7.77E+04	2.26E+04	7.64E+03	2.78E+03	1.20E+03
7.85E+00	6.75E+06	1.58E+06	3.72E+05	9.54E+04	2.82E+04	9.58E+03	3.50E+03	1.53E+03
1.00E+01	7.83E+06	1.88E+06	4.50E+05	1.17E+05	3.50E+04	1.20E+04	4.39E+03	1.92E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	64.6	74.4	80.4	84.6	85.0	83.7	86.9	85.9
0.127	64.1	73.7	80.0	84.2	85.6	84.8	87.6	86.6
0.162	63.8	73.2	79.5	84.1	85.7	85.0	87.8	87.0
0.207	63.4	72.4	78.9	83.5	85.5	85.6	88.1	87.4
0.264	63.1	72.0	78.4	83.5	85.6	85.9	88.2	87.7
0.336	62.7	71.3	77.8	83.5	85.6	86.0	88.3	88.0
0.428	62.4	70.8	77.3	82.2	85.3	86.3	88.4	88.2
0.546	62.0	70.3	76.8	82.0	85.1	86.5	88.4	88.4
0.695	61.6	69.7	76.2	81.6	84.8	86.4	88.4	88.5
0.886	61.2	69.1	75.6	81.0	84.5	86.3	88.3	88.5
1.13	60.8	68.6	75.1	80.6	84.1	86.1	88.3	88.5
1.59	60.2	67.9	74.3	79.9	83.8	85.8	88.1	88.5
1.83	59.9	67.6	74.0	79.5	83.4	85.6	88.0	88.6
2.34	59.5	67.0	73.4	79.0	82.9	85.4	87.8	88.5
2.98	59.0	66.5	72.9	78.5	82.7	85.1	87.6	88.4
3.79	58.6	66.0	72.3	78.0	82.0	84.8	87.3	88.3
4.83	58.1	65.5	71.8	77.5	81.7	84.4	87.1	88.2
6.16	57.6	65.0	71.3	76.9	81.0	84.1	86.8	88.0
7.85	57.1	64.5	70.8	76.4	80.8	83.8	86.4	87.8
10	56.6	64.0	70.3	75.9	80.4	83.2	86.1	87.5

Mastic blend Kombi-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	9.71E+05	1.47E+05	2.51E+04	4.91E+03	1.27E+03	3.82E+02	1.04E+02	3.60E+01
1.27E-01	1.11E+06	1.73E+05	3.04E+04	6.06E+03	1.55E+03	4.69E+02	1.24E+02	4.27E+01
1.62E-01	1.28E+06	2.05E+05	3.64E+04	7.35E+03	1.90E+03	5.65E+02	1.51E+02	5.19E+01
2.07E-01	1.47E+06	2.44E+05	4.41E+04	9.09E+03	2.31E+03	6.94E+02	1.87E+02	6.40E+01
2.64E-01	1.69E+06	2.88E+05	5.31E+04	1.11E+04	2.83E+03	8.49E+02	2.31E+02	7.93E+01
3.36E-01	1.94E+06	3.40E+05	6.37E+04	1.34E+04	3.46E+03	1.05E+03	2.85E+02	9.84E+01
4.28E-01	2.24E+06	4.02E+05	7.66E+04	1.64E+04	4.24E+03	1.27E+03	3.55E+02	1.23E+02
5.46E-01	2.57E+06	4.76E+05	9.22E+04	2.01E+04	5.17E+03	1.56E+03	4.43E+02	1.53E+02
6.95E-01	2.95E+06	5.61E+05	1.11E+05	2.45E+04	6.32E+03	1.92E+03	5.52E+02	1.92E+02
8.86E-01	3.40E+06	6.62E+05	1.33E+05	3.00E+04	7.80E+03	2.36E+03	6.89E+02	2.41E+02
1.13E+00	3.90E+06	7.81E+05	1.60E+05	3.64E+04	9.61E+03	2.91E+03	8.60E+02	3.03E+02
1.59E+00	4.75E+06	9.85E+05	2.07E+05	4.79E+04	1.27E+04	3.93E+03	1.18E+03	4.19E+02
1.83E+00	5.14E+06	1.08E+06	2.29E+05	5.36E+04	1.42E+04	4.44E+03	1.34E+03	4.76E+02
2.34E+00	5.91E+06	1.28E+06	2.76E+05	6.50E+04	1.76E+04	5.49E+03	1.68E+03	6.03E+02
2.98E+00	6.77E+06	1.50E+06	3.30E+05	7.90E+04	2.17E+04	6.79E+03	2.11E+03	7.57E+02
3.79E+00	7.75E+06	1.76E+06	3.94E+05	9.55E+04	2.68E+04	8.38E+03	2.63E+03	9.53E+02
4.83E+00	8.86E+06	2.07E+06	4.71E+05	1.16E+05	3.28E+04	1.04E+04	3.27E+03	1.20E+03
6.16E+00	1.01E+07	2.43E+06	5.63E+05	1.40E+05	4.02E+04	1.27E+04	4.10E+03	1.51E+03
7.85E+00	1.15E+07	2.84E+06	6.71E+05	1.70E+05	4.91E+04	1.57E+04	5.09E+03	1.89E+03
1.00E+01	1.31E+07	3.33E+06	8.00E+05	2.06E+05	6.02E+04	1.93E+04	6.33E+03	2.37E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	56.6	65.0	70.8	74.9	75.2	74.1	78.3	79.0
0.127	56.3	64.8	70.7	74.3	75.5	73.7	79.8	80.8
0.162	56.1	64.7	70.7	74.2	75.3	74.9	80.8	81.8
0.207	55.8	64.2	70.3	74.2	76.1	75.5	81.6	82.7
0.264	55.7	64.1	70.3	74.1	76.3	76.1	82.2	83.4
0.336	55.4	63.9	70.1	74.3	76.8	76.4	82.8	84.0
0.428	55.2	63.6	69.9	74.2	76.9	77.6	83.2	84.5
0.546	54.9	63.3	69.7	74.1	76.5	77.8	83.6	85.0
0.695	54.7	63.1	69.4	74.0	76.6	78.1	83.9	85.3
0.886	54.4	62.8	69.1	73.8	76.6	78.4	84.1	85.7
1.13	54.1	62.4	68.8	73.6	76.6	78.6	84.2	85.9
1.59	53.7	62.0	68.4	73.3	76.5	78.9	84.3	86.1
1.83	53.5	61.8	68.2	73.2	76.8	78.9	84.3	86.2
2.34	53.1	61.5	67.9	73.0	76.4	79.1	84.3	86.3
2.98	52.7	61.1	67.5	72.7	76.3	79.1	84.3	86.3
3.79	52.3	60.7	67.2	72.5	76.2	79.1	84.1	86.3
4.83	51.9	60.3	66.8	72.2	76.1	78.9	84.0	86.3
6.16	51.4	59.9	66.5	71.9	75.9	79.0	83.8	86.2
7.85	50.9	59.5	66.1	71.6	75.7	78.7	83.6	86.1
10	50.4	59.1	65.7	71.3	75.5	78.4	83.4	85.9

Mastic blend Wax-60%

Complex modulus (Pa)

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
1.00E-01	1.61E+06	3.38E+05	5.82E+04	1.08E+04	2.41E+03	8.08E+02	1.68E+02	4.61E+01
1.27E-01	1.82E+06	3.83E+05	6.70E+04	1.27E+04	2.86E+03	9.27E+02	1.94E+02	5.52E+01
1.62E-01	2.05E+06	4.39E+05	7.86E+04	1.52E+04	3.45E+03	1.06E+03	2.31E+02	6.68E+01
2.07E-01	2.33E+06	5.01E+05	9.15E+04	1.80E+04	4.16E+03	1.24E+03	2.77E+02	8.11E+01
2.64E-01	2.65E+06	5.75E+05	1.07E+05	2.15E+04	4.96E+03	1.46E+03	3.33E+02	1.00E+02
3.36E-01	3.00E+06	6.59E+05	1.25E+05	2.55E+04	5.95E+03	1.73E+03	4.01E+02	1.23E+02
4.28E-01	3.41E+06	7.57E+05	1.45E+05	3.05E+04	7.08E+03	2.08E+03	4.86E+02	1.50E+02
5.46E-01	3.86E+06	8.68E+05	1.71E+05	3.62E+04	8.50E+03	2.49E+03	5.92E+02	1.86E+02
6.95E-01	4.38E+06	9.97E+05	2.00E+05	4.29E+04	1.03E+04	3.01E+03	7.23E+02	2.30E+02
8.86E-01	4.97E+06	1.15E+06	2.34E+05	5.09E+04	1.22E+04	3.61E+03	8.84E+02	2.85E+02
1.13E+00	5.64E+06	1.32E+06	2.75E+05	6.05E+04	1.48E+04	4.38E+03	1.09E+03	3.53E+02
1.59E+00	6.72E+06	1.61E+06	3.44E+05	7.73E+04	1.94E+04	5.70E+03	1.46E+03	4.79E+02
1.83E+00	7.21E+06	1.75E+06	3.78E+05	8.54E+04	2.16E+04	6.35E+03	1.64E+03	5.46E+02
2.34E+00	8.17E+06	2.02E+06	4.44E+05	1.02E+05	2.63E+04	7.73E+03	2.03E+03	6.80E+02
2.98E+00	9.22E+06	2.33E+06	5.22E+05	1.21E+05	3.16E+04	9.32E+03	2.50E+03	8.48E+02
3.79E+00	1.04E+07	2.68E+06	6.13E+05	1.44E+05	3.79E+04	1.13E+04	3.09E+03	1.06E+03
4.83E+00	1.17E+07	3.09E+06	7.20E+05	1.72E+05	4.56E+04	1.36E+04	3.81E+03	1.32E+03
6.16E+00	1.31E+07	3.57E+06	8.47E+05	2.05E+05	5.50E+04	1.66E+04	4.72E+03	1.65E+03
7.85E+00	1.47E+07	4.11E+06	9.95E+05	2.44E+05	6.61E+04	2.02E+04	5.83E+03	2.06E+03
1.00E+01	1.64E+07	4.74E+06	1.17E+06	2.91E+05	7.97E+04	2.44E+04	7.18E+03	2.58E+03

Phase angle

Frequency (Hz)	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0.1	51.2	54.7	60.0	63.8	66.1	61.3	70.4	74.8
0.127	51.1	54.7	60.4	64.5	66.7	62.3	72.0	76.1
0.162	50.9	55.2	60.6	64.6	66.6	64.3	73.3	77.2
0.207	50.8	55.2	60.9	65.2	66.9	65.6	74.2	78.2
0.264	50.6	55.3	61.1	65.7	67.4	66.8	75.2	78.9
0.336	50.4	55.3	61.4	65.9	68.1	67.9	76.1	79.7
0.428	50.3	55.5	61.6	66.2	68.1	68.7	76.9	80.4
0.546	50.1	55.5	61.7	66.3	68.8	69.3	77.7	81.1
0.695	50.0	55.6	61.8	66.6	68.9	70.1	78.3	81.6
0.886	49.8	55.6	61.9	66.7	69.0	70.8	78.9	82.1
1.13	49.6	55.6	62.0	66.8	69.8	71.4	79.5	82.6
1.59	49.3	55.6	62.0	66.9	70.3	72.0	80.1	83.1
1.83	49.1	55.6	62.0	67.0	69.8	72.4	80.3	83.3
2.34	48.9	55.5	62.0	67.0	70.4	72.7	80.7	83.5
2.98	48.6	55.3	61.9	67.0	70.5	73.2	81.0	83.7
3.79	48.3	55.2	61.8	67.0	70.7	73.3	81.1	83.9
4.83	48.0	55.0	61.7	67.0	70.7	73.5	81.3	84.0
6.16	47.6	54.9	61.6	67.0	70.8	73.8	81.3	84.0
7.85	47.2	54.6	61.4	66.9	70.8	74.0	81.3	84.0
10	46.8	54.4	61.2	66.8	70.8	74.0	81.3	83.9

Mixture results - recovered binder

BTSV results

Recovered binder	BTSV T	Std. dev.	BTSV δ	Std. dev.
	°C	°C	°	°
L-HMA 30%	**55.4**	0.15	**79.1**	0.15
L-HMA 60%	**54.2**	0.15	**76.0**	0.15
F-HMA 50%	**56.0**	0.12	**75.8**	0.04
L-WMA-Chem1 30%	**54.2**	0.15	**80.1**	0.15
L-WMA-Chem1 60%	**53.6**	0.15	**76.2**	0.15
F-WMA-Chem1 60%	**56.2**	0.15	**72.8**	0.15
L-WMA-Chem2 30%	**53.0**	0.15	**80.2**	0.15
L-WMA-Chem2 60%	**52.5**	0.15	**76.5**	0.15
L-WMA-Kombi 30%	**53.7**	0.15	**77.7**	0.15
L-WMA-Kombi 60%	**57.2**	0.01	**74.6**	0.13
F-WMA-Kombi 60%	**59.7**	0.15	**73.5**	0.15
F-WMA-Foam 60%	**55.4**	0.06	**75.1**	0.04

Conventional tests (Penetration, Softening Point & Fraass) results

Specimen	Avg. Softening Point (°C)	Std. Dev.	Avg. Penetration (25°C)	Std. Dev.	Avg. Fraass (°C)	Std. Dev.
L-HMA (30%)	50.85	0.07	47.6	0.55	-10.71	1.60
L-HMA (60%)	53.10	0.24	45.2	0.75	-13.68	0.74
L-WMA-Chem1 (30%)	51.27	0.15	50.0	0.63	-9.83	0.41
L-WMA-Chem1 (60%)	52.05	0.19	50.5	0.84	-13.25	0.50
L-WMA-Chem2 (30%)	50.23	0.13	55.0	1.26	-10.5	0.55
L-WMA-Chem2 (60%)	51.40	0.22	62.3	1.50	-13.38	2.56
L-WMA-Kombi (30%)	54.45	0.19	47.2	0.84	-10.0	1.07
L-WMA-Kombi (60%)	56.30	0.14	50.8	0.41	-14.33	1.21
F-WMA-Kombi (60%)	59.20	0.14	40.5	0.55	-14.3	0.96
F-WMA-Foam (60%)	54.45	0.35	49.17	0.41	-14.5	0.58
F-WMA-Chem1 (60%)	53.40	0.14	49.5	0.55	-14.0	0.96
F-HMA-Ref (50%)	56.00	0.14	37.0	0.00	-12.0	0.82

Table A3: Conventional binder results of recovered binder (BFH)

Thermal stress restrained specimen test (TSRST)

	TSRST Critical Stress (MPa)		TSRST Critical Temperatur (°C)	
	Average	Std.dev.	Average	Std.dev.
L-HMA 30%	**3.8**	0.14	**-37.0**	0.35
L-HMA 60%	**3.5**	0.14	**-34.7**	1.53
F-HMA 50%	**3.4**	0.11	**-33.1**	2.99
L-WMA-Chem1 30%	**3.9**	0.20	**-33.5**	1.90
L-WMA-Chem1 60%	**3.7**	0.22	**-35.8**	1.26
F-WMA-Chem1 60%	**3.3**	0.05	**-36.9**	0.59
L-WMA-Chem2 30%	**4.0**	0.01	**-37.8**	0.36
L-WMA-Chem2 60%	**3.7**	0.23	**-37.2**	1.13
L-WMA-Kombi 30%	**3.8**	0.10	**-36.4**	0.33
L-WMA-Kombi 60%	**4.0**	0.30	**-35.7**	0.66
F-WMA-Kombi 60%	**3.6**	0.24	**-37.1**	0.62
F-WMA-Foam 60%	**3.5**	0.16	**-34.2**	1.24

Asphalt mixture volumetrics

Specimen	Air Voids (%)	VMA	VFB	Flow
L-HMA 30%	3.60	14.90	75.40	3.10
L-HMA 60%	3.20	14.30	77.80	3.10
L-WMA-Chem1 30%	4.82	15.40	68.72	3.20
L-WMA-Chem1 60%	3.75	14.80	74.36	3.70
L-WMA-Chem2 30%	4.55	15.60	71.09	3.30
L-WMA-Chem2 60%	3.26	14.60	77.92	3.60
L-WMA-Kombi 30%	5.22	15.60	66.84	3.70
L-WMA-Kombi 60%	4.79	15.40	69.12	3.70

Table A4: Mixture volumetrics results (BFH)

Marshall Stability (Laboratory mixtures)

Designation	d (mm)	h (mm)	m (g)	ρ (kg/m³)	S (kN)	F (mm)	FT (mm)	Ft (mm)	S/F (kN/mm)
L-HMA 30%	101.4	62.0	1199.5	2394.5	12.3	3.1	3.2	1.8	4.0
Std. Dev.	–	–	2.4	3.2	0.17	0.2	0.2	0.0	–
L-HMA 60%	101.3	62.2	1201.9	2397.5	11.7	3.1	3.1	1.8	3.7
Std. Dev.	–	–	1.4	2.5	0.58	0.06	0.06	0.0	–
L-WMA-Chem1 30%	101.3	63.0	1200.0	2364.6	11.7	3.2	3.2	1.6	3.7
Std. Dev.	–	–	0.8	14.2	0.88	0.15	0.15	0.0	–
L-WMA-Chem1 60%	101.3	62.4	4801.7	9526.2	10.4	3.7	3.7	1.9	2.8
Std. Dev.	–	–	6240.0	12360.3	0.79	0.4	0.4	0.1	–
L-WMA-Chem2 30%	101.4	63.5	1200.9	2343.2	7.6	3.3	3.2	1.7	2.3
Std. Dev.	–	–	0.4	14.1	0.35	0.17	0.17	0.1	–
L-WMA-Chem2 60%	101.4	62.1	1201.5	2397.3	9.8	3.6	3.6	2.2	2.7
Std. Dev.	–	–	0.4	9.5	0.16	0.15	0.15	0.2	–
L-WMA-Kombi 30%	101.3	63.6	1200.5	2343.2	10.7	3.7	3.7	1.9	2.9
Std. Dev.	–	–	0.7	8.9	0.2	0.2	0.2	0.2	–
L-WMA-Chem1 60%	101.4	63.7	1201.0	2336.0	9.4	3.7	3.6	2.0	2.5
Std. Dev.	–	–	1.5	11.1	1.26	0.15	0.15	0.2	–

Table A5: Marshall stability results of laboratory mixtures (BFH)

Marshall Stability (Laboratory mixtures) (after aging)

Designation	d (mm)	h (mm)	m (g)	ρ (kg/m³)	S (kN)	F (mm)	F T (mm)	F t (mm)	S/F (kN/mm)
L-HMA 30%	101.5	63.3	1199.2	2340.2	13.1	3.0	3.1	1.6	4.4
Std. Dev.	–	–	1.27	6.18	0.43	0.31	–	–	–
L-HMA 60%	101.5	62.5	1197.4	2369.1	14.7	3.2	3.2	1.7	4.7
Std. Dev.	–	–	0.55	2.39	0.20	0.36	–	–	–
L-WMA-Chem1 30%	101.4	64.0	1201.4	2324.3	10.3	3.2	3.2	1.6	3.3
Std. Dev.	–	–	1.04	5.52	0.45	0.26	–	–	–
L-WMA-Chem1 60%	101.5	62.6	1198.6	2367.7	11.7	4.0	4.0	1.8	3.0
Std. Dev.	–	–	0.83	10.65	0.47	0.72	–	–	–
L-WMA-Chem2 30%	101.5	63.4	1199.2	2337.7	11.5	3.4	3.4	1.8	3.4
Std. Dev.	–	–	0.53	4.67	0.50	0.40	–	–	–
L-WMA-Chem2 60%	101.5	62.8	1198.3	2359.5	12.1	3.4	3.4	1.8	3.5
Std. Dev.	–	–	0.72	3.93	0.29	0.17	–	–	–
L-WMA-Kombi 30%	101.5	63.2	1204.3	2355.1	11.9	2.9	2.9	1.6	4.1
Std. Dev.	–	–	1.85	9.32	0.33	0.06	–	–	–
L-WMA-Chem1 60%	101.4	63.4	1203.4	2351.8	11.3	3.9	3.8	1.9	2.9
Std. Dev.	–	–	2.90	11.35	0.17	0.46	–	–	–

Table A6: Marshall stability results of laboratory mixtures (after aging) (BFH)

Marshall stability (Field mixtures)

Designation	d (mm)	h (mm)	m (g)	ρ (kg/m³)	S (kN)	F (mm)	F T (mm)	F t (mm)	S/F (kN/mm)
WMA-KMB (60%) MIX R	101.5	62.8	1199.1	2361.7	11.9	4.2	4.2	2.1	2.9
Std. Dev.	–	–	0.42	1.98	0.66	0.78	–	–	–
WMA-SCH (60%) MIX J	101.5	62.7	1199.5	2364.5	11.0	4.0	4.0	2.2	2.8
Std. Dev.	–	–	0.49	7.21	0.55	0.79	–	–	–
WMA-CHE (60%) MIX P	101.5	63.3	1199.2	2341.3	10.7	3.0	3.0	1.7	3.5
Std. Dev.	–	–	0.66	5.38	0.53	0.26	–	–	–
HMA-Ref (50%) MIX Q	101.5	62.4	1197.1	2370.0	12.9	2.9	2.9	1.6	4.5
Std. Dev.	–	–	1.88	2.98	0.20	–	–	–	

Table A7: Marshall stability results of field mixtures (BFH)

Indirect tensile strength (ITS)

Designation	d (mm)	h (mm)	m (g)	ρ (kg/m³)	S (kN)	F (mm)	F T (mm)	F t (mm)	S/F (kN/mm)
L-HMA 30%									
1 nass	101.4	63.7	1200.0	2332.8	13.5	1.8	1.7	1.0	7.6
2 nass	101.4	63.8	1204.8	2338.5	13.6	1.7	1.7	1.1	8.0
3 nass	101.4	63.8	1200.0	2329.1	13.9	1.8	1.8	1.1	7.8
4 tocken	101.4	64.0	1201.2	2324.2	15.7	1.5	1.5	1.1	10.2
5 trocken	101.4	63.6	1201.2	2338.8	17.4	1.6	1.6	1.2	10.7
6 trocken	101.4	63.9	1206.0	2337.1	16.6	1.6	1.6	1.0	10.4
Mittelwert	101.4	63.8	1202.2	2333.4	15.1	1.7	1.6	1.1	9.1
Std. Abw.			2.56	5.87	1.69				
L-HMA 60%									
Nass 1	101.3	63.5	1202.6	2349.8	10.6	1.5	1.5	0.9	7.2
Nass 2	101.3	63.4	1201.9	2352.2	12.3	1.4	1.4	0.9	8.7
Nass 3	101.3	63.1	1203.1	2365.7	11.4	1.5	1.4	1.0	7.5
Trocken 4	101.3	63.4	1201.9	2352.2	12.4	1.4	1.4	1.0	8.6
Trocken 5	101.3	63.2	1202.6	2361.0	11.7	1.5	1.4	1.0	8.0
Trocken 6	101.3	63.2	1202.8	2361.4	12.3	1.4	1.3	1.0	8.8
Mittelwert	101.3	63.3	1202.5	2357.1	11.8	1.5	1.4	1.0	8.1
Std. Abw.			0.49	6.47	0.71				
L-WMA-Chem1 30%									
Nass 1	101.3	64.6	1202.7	2310.0	12.8	1.9	1.8	1.1	6.6
Nass 2	101.3	64.7	1201.3	2303.8	12.1	2.0	1.9	1.1	6.2
Nass 3	101.3	64.3	1198.3	2312.3	12.4	1.9	1.8	1.1	6.5
Trocken 4	101.3	64.0	1199.1	2324.7	14.6	1.6	1.6	1.0	9.2
Trocken 5	101.3	64.5	1201.8	2311.9	13.9	1.6	1.6	1.0	8.6
Trocken 6	101.3	64.6	1202.1	2308.9	14.1	1.8	1.8	1.3	7.8
Mittelwert	101.3	64.5	1200.9	2311.9	13.3	1.8	1.7	1.1	7.5
Std. Abw.			1.77	6.97	1.02				
L-WMA-Chem1 60%									
Nass 1	101.3	63.8	1201.0	2335.7	10.8	2.3	2.2	1.4	4.6
Nass 2	101.3	63.7	1201.3	2339.9	11.0	1.9	1.9	1.2	5.6
Nass 3	101.3	63.3	1199.4	2351.0	11.4	1.8	1.7	1.1	6.3
Trocken 4	101.3	63.7	1199.3	2336.0	12.1	1.6	1.6	1.0	7.4
Trocken 5	101.3	63.2	1200.0	2355.9	12.4	1.6	1.6	1.1	7.7
Trocken 6	101.3	63.6	1200.3	2341.7	12.8	1.5	1.5	1.0	8.3
Mittelwert	101.3	63.6	1200.2	2343.4	11.7	1.8	1.8	1.1	6.7
Std. Abw.			0.82	8.28	0.80				

Designation	d (mm)	h (mm)	m (g)	ρ (kg/m³)	S (kN)	F (mm)	F T (mm)	F t (mm)	S/F (kN/mm)
LWMA-Chem2 30%									
Nass 1	101.4	64.7	1201.2	2299.0	11.6	1.7	1.6	1.0	6.9
Nass 2	101.4	64.6	1200.4	2301.1	11.6	1.8	1.8	1.1	6.3
Nass 3	101.4	65.0	1202.8	2291.5	11.9	1.9	1.9	1.2	6.4
Trocken 4	101.4	65.2	1202.1	2283.1	12.1	1.8	1.8	1.1	6.7
Trocken 5	101.4	65.1	1202.3	2287.0	11.4	1.7	1.7	1.0	6.7
Trocken 6	101.4	65.6	1201.9	2268.8	12.5	1.9	1.9	1.4	6.5
Mittelwert	101.4	65.0	1201.8	2288.4	11.9	1.8	1.8	1.1	6.6
Std. Abw.			0.86	11.80	0.39				
L-WMA-Chem2 60%									
Nass 1	101.4	63.7	1201.7	2336.1	10.1	1.9	1.9	1.3	5.3
Nass 2	101.4	63.7	1202.3	2337.3	10.9	1.9	1.9	1.2	5.8
Nass 3	101.4	63.5	1201.5	2343.1	10.7	1.7	1.7	1.0	6.2
Trocken 4	101.4	63.3	1201.9	2351.3	11.7	1.8	1.7	1.1	6.7
Trocken 5	101.4	62.8	1200.7	2367.6	11.4	1.7	1.7	1.0	6.6
Trocken 6	101.4	62.5	1198.4	2374.4	11.9	1.6	1.5	1.1	7.5
Mittelwert	101.4	63.3	1201.1	2351.6	11.1	1.8	1.7	1.1	6.4
Std. Abw.			1.42	16.10	0.69				
L-WMA-Kombi 30%									
Nass 1	101.3	65.8	1200.3	2263.4	12.0	1.8	1.8	1.1	6.5
Nass 2	101.3	65.7	1200.6	2267.4	11.6	2.1	2.0	1.1	5.6
Nass 3	101.3	65.0	1201.3	2293.1	12.3	1.9	1.8	1.1	6.6
Trocken 4	101.3	65.7	1199.2	2264.7	12.5	1.4	1.4	1.0	8.7
Trocken 5	101.3	65.7	1199.2	2264.7	12.8	1.6	1.6	1.1	7.9
Trocken 6	101.3	64.7	1200.8	2302.8	13.9	1.6	1.5	1.0	8.9
Mittelwert	101.3	65.4	1200.2	2276.0	12.5	1.7	1.7	1.1	7.4
Std. Abw.			0.86	17.32	0.80				
L-WMA-Kombi 60%									
Nass 1	101.4	64.8	1202.1	2297.2	9.9	1.7	1.6	1.0	5.8
Nass 2	101.4	64.9	1201.3	2292.1	10.3	1.6	1.6	1.0	6.3
Nass 3	101.4	64.3	1202.2	2315.3	10.0	1.9	1.9	1.1	5.2
Trocken 4	101.4	64.6	1202.5	2305.1	11.6	1.3	1.3	0.9	8.6
Trocken 5	101.4	64.1	1205.8	2329.4	12.1	1.5	1.5	1.0	7.8
Trocken 6	101.4	63.9	1199.3	2324.1	12.7	1.5	1.5	1.0	8.3
Mittelwert	101.4	64.4	1202.2	2310.5	11.1	1.6	1.6	1.0	7.0
Std. Abw.			2.11	14.90	1.19				

Table A8: Indirect tensile strength of laboratory mixtures (BFH)

Indirect tensile strength ratio (ITSR)

Designation	d (mm)	h (mm)	m (g)	ρ (kg/m³)	ITSR (%)
L-HMA (30%)	101.4	63.8	1202.2	2333.4	82.5
Std. Dev.	–	–	2.56	5.87	–
L-HMA (60%)	101.3	63.3	1202.5	2357.1	94.2
Std. Dev.	–	–	0.49	6.47	–
L-WMA-Chem1 (30%)	101.3	64.5	1200.9	2311.9	87.6
Std. Dev.	–	–	1.77	6.97	–
L-WMA-Chem1 (60%)	101.3	63.6	1200.2	2343.4	89.0
Std. Dev.	–	–	0.82	8.28	–
L-WMA-Chem2 (30%)	101.4	65.0	1201.8	2288.4	97.5
Std. Dev.	–	–	0.86	11.80	–
L-WMA-Chem2 (60%)	101.4	63.3	1201.1	2351.6	90.6
Std. Dev.	–	–	1.42	16.10	–
L-WMA-Kombi (30%)	101.3	65.4	1200.2	2276.0	91.6
Std. Dev.	–	–	0.86	17.32	–
L-WMA-Kombi (60%)	101.4	64.4	1202.2	2310.5	83.0
Std. Dev.	–	–	2.11	14.90	–

Table A9: Indirect tensile strength raito (ITSR) of laboratory mixtures (BFH)

Semi circular bending (SCB)

Designation	n	F_{max} (kN)	Std. Dev. (kN)	$K_{I}c$ ($N \cdot mm^{-3/2}$)	Std. Dev. ($N \cdot mm^{-3/2}$)
L-HMA (30%)	6	9.1	1.21	32.9	4.58
L-HMA (60%)	5	10.6	1.24	37.6	3.93
L-WMA-Chem1 (30%)	5	8.2	0.78	28.7	2.91
L-WMA-Chem1 (60%)	2	10.3	0.59	36.9	2.16
L-WMA-Chem2 (30%)	6	8.6	0.66	31.3	2.52
L-WMA-Chem2 (60%)	3	10.3	1.00	38.2	3.80
L-WMA-Kombi (30%)	4	9.2	0.65	32.8	2.21
L-WMA-Kombi (60%)	4	10.0	0.73	36.2	—

Table A10: Semi circular bending (SCB) results of laboratory mixtures (BFH)

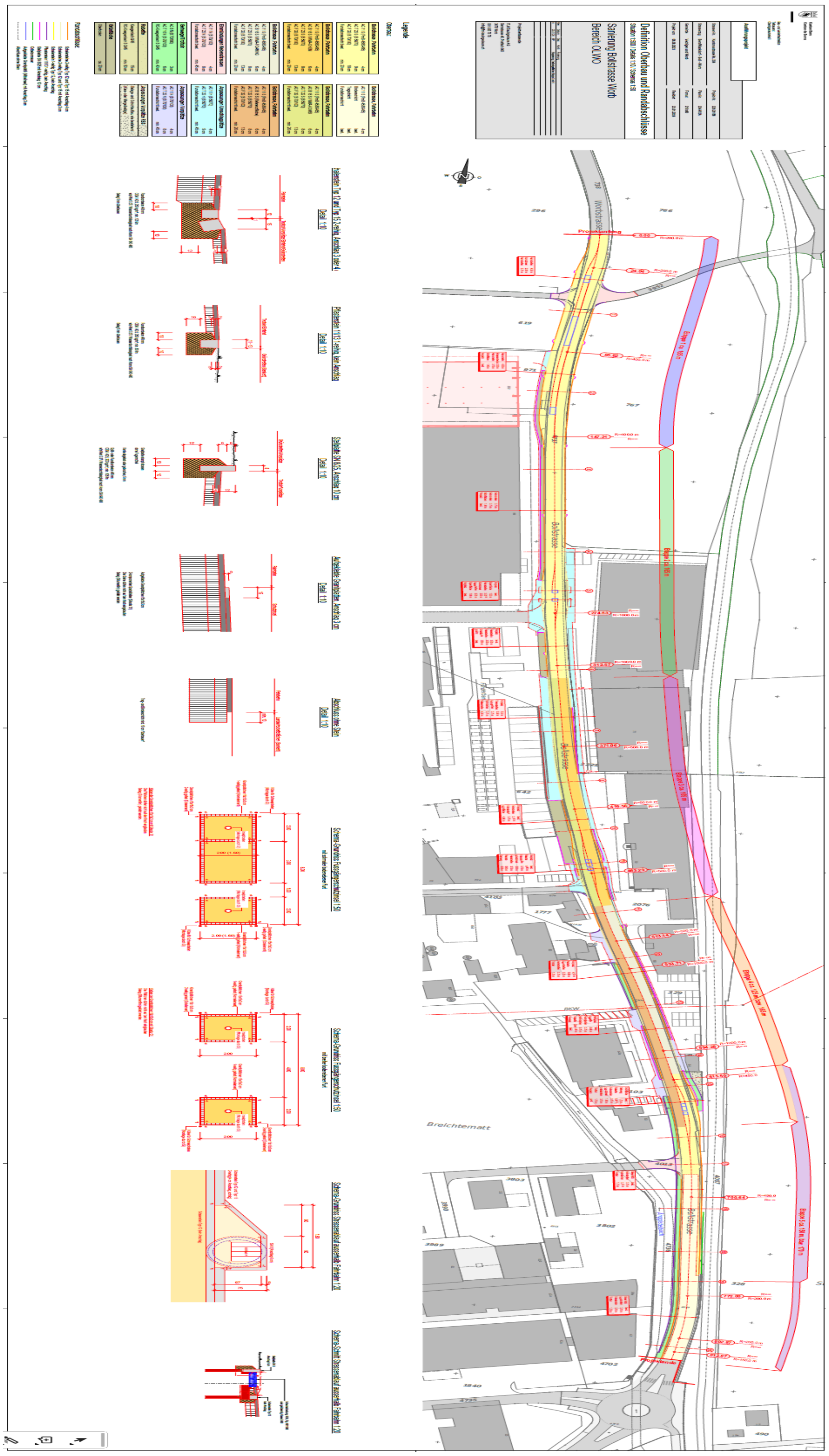

Figure A1: Details of test section layout plan

Figure A2: Extracted core (CW) taken out from Section Chem1 (inside wheel path)

Figure A3: Extracted core (FO) taken out from Section Foam (outside wheel path)

Figure A4: Extracted core (FW) taken out from Section Foam (Inside wheel path)

Figure A5: Extracted core (KO) taken out from Section Kombi (Outside wheel path)

Figure A6: Extracted core (KW) taken out from Section Kombi (Inside wheel path)

Figure A7: Extracted core (RO) taken out from Section Ref (Outside wheel path)

Figure A8: Extracted core (RW) taken out from Section Ref (Inside wheel path)

Projektabschluss

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FORSCHUNG IM STRASSENWESEN DES UVEK

Version vom 09.10.2013

Formular Nr. 3: Projektabschluss

erstellt / geändert am: 10.06.2025

Grunddaten

Projekt-Nr.:	TRU_20_01G_01
Projekttitel:	Optimierung von Warmasphalt unter Berücksichtigung von RAP-Zugabe (WMA-RAP)
Enddatum:	31.08.2025

Texte

Zusammenfassung der Projektresultate:

Das Forschungsprojekt befasst sich mit der Optimierung von Warmazphalt (WMA – Warm Mix Asphalt) unter Einbindung von Recyclingasphalt (RAP – Reclaimed Asphalt Pavement), mit dem Ziel, umweltfreundliche Strassenbaumaterialien zu entwickeln, ohne dabei die strukturelle oder mechanische Leistungsfähigkeit zu beeinträchtigen. Der Einsatz von RAP reduziert den Bedarf an Primärrohstoffen wie Gesteinskörnungen und Bitumen und trägt zur Senkung der Emissionen während der Asphaltproduktion bei – eine zentrale Strategie zur Förderung ressourceneffizienter Infrastrukturen. Ziel des Projekts ist es, WMA-RAP-Mischungen zu bestimmen, die hinsichtlich mechanischer Eigenschaften und Dauerhaftigkeit mit konventionellen Heißmischasphalten (HMA – Hot Mix Asphalt) vergleichbar oder ihnen sogar überlegen sind. Zu den spezifischen Zielen gehören die Bewertung verschiedener WMA-Technologien (Additive), die Leistungsbewertung von im Labor und in der Anlage produzierten WMA-RAP-Mischungen sowie die Ableitung von Empfehlungen zur Aktualisierung der Schweizer Asphaltmischgutnormen auf Grundlage der Untersuchungsergebnisse.
Die im Rahmen dieses Projekts angewandte Methodik war umfassend und strukturiert. Sie kombinierte umfangreiche Laboruntersuchungen mit der Validierung von in der Anlage produzierten Mischungen. Die Forschung war, wie in Abbildung 1 dargestellt, in fünf unterschiedliche Arbeitspakete (WPs) untergliedert wobei jedes Paket eine zentrale Phase der Studie bildet. WP1 beinhaltete eine umfassende Literaturrecherche und die Entwicklung von Hypothesen, in deren Rahmen globale und nationale Studien zu WMA und RAP analysiert wurden. WP2 konzentrierte sich auf die Auswahl geeigneter chemischer und organischer Additive durch Bindemittel- und Mastixprüfungen, um die Produkte zu identifizieren, die sich am besten für die WMA-Herstellung eignen. In WP3 wurden Laborprüfungen an Asphaltgütern mit unterschiedlichen RAP-Gehalten (30 % und 60 %) in Kombination mit verschiedenen WMA-Additiven durchgeführt, um deren mechanische und dauerhafte Eigenschaften zu bewerten. WP4 beinhaltete den Bau einer Versuchsstrecke mit Abschnitten aus WMA und HMA sowie die anschließende vergleichende Laboruntersuchung. Im WP5 werden die Projektergebnisse ausgewertet und praxisorientierte Empfehlungen für die Schweizer Asphaltnormen gegeben. Für alle Untersuchungen wurde ein einheitliches Referenzmischgut, AC B 16 S, verwendet – mit Ausnahme der im Werk hergestellten Mischungen (d. h. 50 % RAP) – wobei alle Materialien von Schweizer Lieferanten bezogen wurden, um die Anwendbarkeit und Relevanz der Ergebnisse für den nationalen Straßenbau sicherzustellen.

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Zielerreichung:

Basierend auf der Literaturauswertung und den Erfahrungen aus dem PLANET-Projekt konzentriert sich dieses Projekt auf die Anwendung von Warmasphalt (WMA) unter Zugabe von Recyclingasphalt (RAP), mit dem Hauptziel, nachzuweisen, dass WMA mit RAP eine geeignete Alternative zu herkömmlichem Heißasphalt (HMA) mit RAP darstellen kann.Zur Erreichung dieses Ziels und zur Weiterentwicklung von WMA als breit einsetzbare Mischgutsorte wurden folgende Teilziele definiert:Analyse verschiedener Herstellungsverfahren von WMA mit RAP und Herausstellung möglicher Unterschiede zwischen diesen Methoden.Untersuchung der Leistungsfähigkeit von WMA-Mischungen sowohl im Labor als auch im Feldversuch.Quantifizierung der mechanischen Eigenschaften von WMA mit RAP im Vergleich zu einem Referenz-HMA mit RAP.Ableitung von Schlussfolgerungen zur weiteren Anwendung von WMA.Beitrag zur Normung im Bereich WMA-Mischungen.

Folgerungen und Empfehlungen:

Die wesentliche Schlussfolgerung dieser Forschung ist eindeutig: Alle Warmasphaltmischungen zeigten ähnliche Ergebnisse wie der Referenz-Heißasphalt. Zwar gibt es kleinere Unterschiede in den Testergebnissen, diese sind jedoch meist nicht konsistent. Die folgenden Schlussfolgerungen basieren auf den projektspezifischen Ergebnissen und Analysen:
• Es gab keinen WMA-Prozess, der den anderen überlegen war. Da die Auswahl der Zusatzstoffe jedoch auf früheren Erfahrungen beruhte, ist nicht garantiert, dass alle auf dem Markt erhältlichen WMA-Zusätze geeignet sind.
• In einigen Prüfungen zeigen die 60 % RAP-Mischungen ein steiferes Verhalten (Erweichungspunkt Ring und Kugel), in anderen ist das Gegenteil der Fall (Steifigkeitsmodul bei -10 °C, Brechpunkt nach Fraass). Manchmal scheinen die Ergebnisse auch zufällig zu sein (Marshall-Stabilität, TSRST-Versagens-Temperatur). Dennoch kann der Unterschied in der Steifigkeit nicht auf den höheren RAP-Gehalt zurückgeführt werden, da die Steifigkeit durch die Art des zugesetzten Bindemittels angepasst wird.
• Es ist überraschend, dass Mischungen mit 30 % RAP und Bitumen 70/100 ein ähnliches Verhalten zeigen wie solche mit 60 % RAP und einem zugesetzten sehr weichen Bitumen 330/400, da keine Feinabstimmung vorgenommen wurde, um die kommerziellen Bindemittel anzupassen (z.B. Mischung zweier Frischbindemittel auf einen Zielwert).
• Die Ergebnisse des Spurbildungsprüfung waren nicht eindeutig und sollten durch weitere Prüfungen ergänzt werden, um die Hochtemperatur-Eigenschaften besser bestimmen zu können. In jedem Fall sollte den bleibenden Verformungen auf den Teststrecken in den kommenden Jahren besondere Aufmerksamkeit geschenkt werden.
• HMA-Mischungen, sowohl Labor als Feldmischungen, zeigen eine konstant hohe Marshall-Stabilität und bestätigen ihre starke Leistung selbst bei bis zu 60 % RAP.
• Verarbeitbarkeit und Verdichtbarkeit von WMA-Mischungen wurden durch die niedrigeren Produktions- und Verdichtungstemperaturen nicht negativ beeinflusst.
• Das Langzeitverhalten von WMA wurde in dieser Studie nicht untersucht, sollte aber in einem Folgeprojekt behandelt werden. Dabei sollte besonderes Augenmerk auf das Spurbildungsverhalten gelegt werden. Außerdem muss die Schichthaftung zwischen Bindemittel- und Deckschicht bestimmt werden. Eine US-Studie beobachtete, dass WMA-Mischungen eine niedrigere Anfangssteifigkeit besitzen und schneller altern, dass jedoch letztlich Steifigkeit und Spurbildungsverhalten mit HMA vergleichbar sind (NCHRP, 2015).
• Höhere RAP-Gehalte (bis zu 60 %) können sowohl in HMA- als auch in WMA-Mischungen erfolgreich eingesetzt werden, ohne die mechanischen Eigenschaften wesentlich zu beeinträchtigen. Die Studie sollte auf weitere Mischtypen und noch höhere RAP-Gehalte ausgeweitet werden.
Die Ergebnisse dieser Untersuchung deuten darauf hin, dass die WMA-Technologien, insbesondere diejenigen, die chemische Zusätze wie Chem1 und Kombi enthalten, eine vielversprechende nachhaltige Alternative zu herkömmlichen HMA darstellen, ohne die wichtigsten mechanischen Eigenschaften des Asphalts zu beeinträchtigen.

Publikationen:

Keine Publikationen

Der Projektleiter/die Projektleiterin:

Name: Öngel   Vorname: Aybike

Amt, Firma, Institut: Institut für Baustoffe und biobasierte Materialien IBBM, Berner Fachhochschule BFH

Unterschrift des Projektleiters/der Projektleiterin:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Eidgenössisches Departement für
Umwelt, Verkehr, Energie und Kommunikation UVEK
Bundesamt für Strassen ASTRA

FORSCHUNG IM STRASSENWESEN DES UVEK

Formular Nr. 3: Projektabschluss

Beurteilung der Begleitkommission:

Beurteilung:

Das Forschungsprojekt wurde gemäss Ausschreibung durchgeführt!
Projektbeschrieb, Umsetzung sowie Zielerreichung mit Folgerungen und Empfehlungen entsprechen dem Forschungsprojekt und bringen der Normen sowie der Praxis weitere Erkenntnisse. Welche umgesetzt werden können resp. bereits eingeflossen sind.

Umsetzung:

Es wurden Praxis (Feldversuche) und Theorie (Labor) zusammen mit Literaturauswertung und den Erfahrungen aus dem PLANET-Projekt berücksichtigt.
Dieses Projekt konzentriert auf die Anwendung von Warmasphalt (WMA).

weitergehender Forschungsbedarf:

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Einfluss auf Normenwerk:

Die Erhöhung des RAP-Anteils wurde bereits in der VSS Normen berücksichtigt und dem entsprechend angepasst.
Zusätzlich lässt die Norm über einen Vermerk offen, bei einer Absprache mit dem Bauherr die RAP-Anteile noch weiter zu erhöhen. Schlussendlich müssen die Norm-Anforderungen erfüllt werden.

Der Präsident/die Präsidentin der Begleitkommission:

Name: Bucheli Vorname: Hans Peter

Amt, Firma, Institut: Implenia Schweiz AG, BBP Belagsbautechnik und Produktion

Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:

HP. Bucheli