Asphalt mixture performance and testing

Fatigue Performance and Pavement Design Studies of Hot Mix Asphalt modified with Hydrated Lime

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Abstract

Among other advantages, hydrated lime as filler substitute in hot mix asphalt (HMA) is supposed to increase fatigue resistance and thus, the design life of pavement structures. In this study, the stiffness and fatigue resistance of four reference mixtures without hydrated lime were compared to mixtures with comparable volumetric composition and addition of hydrated lime as partial filler substitute. The mixtures consisted of two surfaces layers, namely SMA 11 and SMA 16, one binder layer, AC 22 and one base layer, AC 32. 4-point-bending (4PB) tests according to EN 12697-26 and EN 12697-24 were carried out to determine stiffness and fatigue resistance. In addition, a recently developed test method for the assessment of the fatigue resistance on the mastic level was also employed in this study to compare mastic from all mixtures. The data from stiffness and fatigue testing on mix level were used as input data for pavement design studies in which pavement structures with reference and hydrated lime modified mixtures were compared. The results show that a balanced mix designed keeps stiffness levels of reference and hydrated lime modified mixtures within the same range and that hydrated lime does have the potential to increase fatigue performance. These findings are also reflected by the outcome of the pavement design studies, where an increased design life could be realized with the addition of hydrated lime modified mixtures. Mastic fatigue testing showed similar trends as asphalt mix fatigue testing.

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1. INTRODUCTION

Road pavements are an important part of a modern transport infrastructure. In recent years, road engineers have been facing a number of challenges: Increasing total weights of heavy goods vehicles (HGV), an increasing share of HGVs, more extreme weather patterns with higher average temperatures and severe short-term precipitation events [1] meet shrinking public budgets and increasing expected design lives. Recent updates in pavement design guides for bituminous bound pavements tend to ask for 30 years of design life compared to former 20 years [2].
To face these challenges, a change in paradigm in road engineering is seen in both, material characterization and mix design optimization on the one hand and pavement design on the other hand.
With regards to material characterization, empirical test methods like the Marshall mix design and recipe based mix design guidelines are eventually replaced by performance based (PB) test methods [3]. These PB test methods aim at simulating the situation in the field under traffic and climate loading in a more realistic way and take into account temperature- and loading-rate dependent viscoelastic material reactions of bituminous bound materials [4]. The European asphalt mix testing standards (EN 12697-xx) and product specifications (EN 13108-xx) include PB test methods and requirements for low temperature cracking resistance (TSRST), high temperature permanent deformation resistance (TCCT), stiffness and fatigue resistance (4PB).
With regards to pavement design guidelines, a shift from purely empirical guidelines to so called mechanical-empirical pavement design guidelines (MEPDG) can be observed. While older versions of pavement design guidelines were often based on material data from a model asphalt for calculation of design tables leading to uneconomic pavement designs, current versions take into account a more realistic traffic loading distribution, temperature profiles and input data based on PB testing of asphalt mix designs used specifically for a certain project. With this possibility, a more realistic and efficient pavement design is possible. In addition, this generation of pavement design guidelines give incentive for innovation, since improved material performance is taken into account for pavement design. The design result could serve as input to e.g. life-cycle costs analysis and, hence, enables to reveal economic benefits [5].
In the presented study, performance based lab testing was combined with a new version of the national pavement design method for the first time. Reference mixtures and hydrated lime (HL) modified mixtures were tested and the obtained data was used for comparative pavement design studies.
Hydrated lime has been used as a filler substitute and asphalt mix modifier for the last decades [6]. Studies have shown that hydrated lime modified asphalt mixtures can improve the moisture resistance [7-9], as well as improve stability due to higher stiffness [10]. In some cases, improved resistance to oxidative ageing was observed [11].
The objectives of the presented study were to show in a case study, how PB lab testing can be combined with modern pavement design methods to compare different asphalt mixtures in terms of their effect on design lifetimes. The study comprises of the following steps:

- Material selection and mix design
- PB laboratory testing for stiffness and fatigue
- Pavement design studies with input data from lab testing

2. MATERIALS AND METHODS

2.1. Mix Designs

For the presented study, two surface layer mixes (SMA 11 PmB 45/80-65 and SMA 16 PmB 45/80-65), one binder layer mix (AC 22 bin PmB 45/80-65) and one base layer mix (AC 32 base 70/100) were taken into account. The surface layers were produced with porphyritic mineral aggregates, the binder and base layer mixtures with limestone. For the reference mixtures, a limestone filler was used. For the HL modified mixtures, parts of the limestone filler were substituted by hydrated lime.
Table 1 and Table 2 contain basic information on the binder content, content of hydrated lime and air void content. The binder content was increased by 0.1 M% for the mixtures with hydrated lime to take into account higher binder absorption by the hydrated lime. Figure 1 shows the grading curves for the four mixtures.

Table 1. Selected mix design parameters for surface layer mixtures

	SMA 11	SMA 11 HL	SMA 16	SMA 16 HL
Binder content [M%]	5.4	5.5	5.2	5.3
Hydrated lime content [%]*)	0	30	0	30
Air void content [V%]	6.0	6.9	4.3	4.9

*) The hydrated lime content is given in % of the total 0.063 mm content

Table 2. Selected mix design parameters for binder and base layer mixtures

	AC 22	AC 22 HL	AC 32	AC 32 HL
Binder content [M%]	4.5	4.6	4.3	4.4
Hydrated lime content [%]*)	0	28	0	29
Air void content [V%]	4.0	3.9	5.6	5.3

*) The hydrated lime content is given in % of the total 0.063 mm content

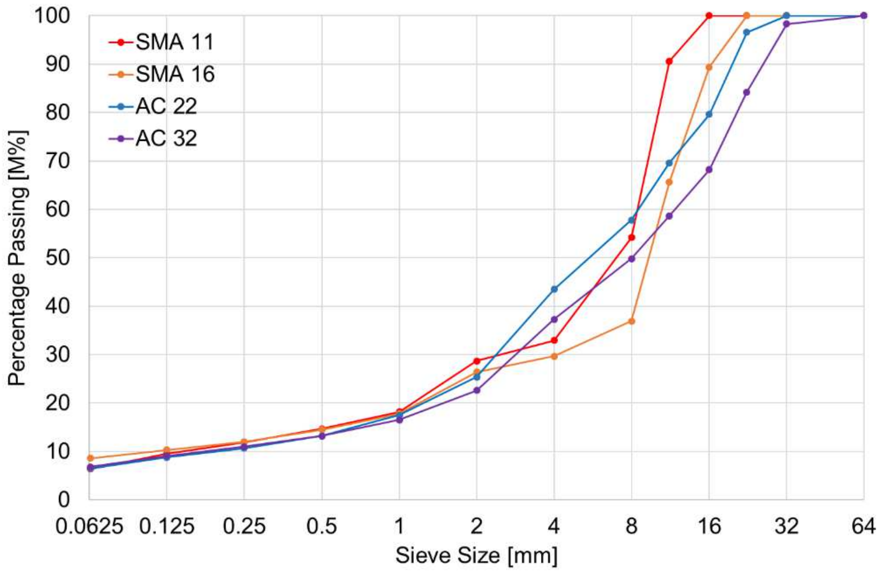

Figure 1. Grading curve of asphalt mixtures

2.2. Specimen Production

Aggregates and bitumen were preheated in a non-ventilated oven to target mixing temperature. Filler, fine and coarse aggregates were blended in a laboratory mixer for 30 sec to ensure homogeneous mix of aggregates. Bitumen was added and mixed for 5 min according to EN 12697-35. The mix was transferred to a steel roller segment compactor and slabs were compacted according to EN 12697-33. After the slabs were cooled down to room temperature, prismatic specimens were cut from the slabs and bulk density and dimensions were determined.

2.3. Test Methods

Since the pavement design method is based on the fatigue criterion, material testing included stiffness testing according to EN 12697-26 and fatigue testing according to EN 12697-24. For both, stiffness and fatigue, 4PB tests were carried out. Specimens with a nominal dimension of 60x60x500 mm were used for testing.
Stiffness testing was run at a temperature of +20°C and frequencies ranging from 0.1 Hz to 40 Hz. The strain amplitude on the bottom of the specimen was set to 50 µm/m to prevent any damage. For each mixture, 18 specimens were tested. Dynamic modulus |E*| and phase angle δ were derived from the recorded data.
For assessing the fatigue resistance, 4PB tests were carried out at a temperature of +20°C and a frequency of 30 Hz. A fatigue resistance assessment consists of tests at three different strain amplitudes with six replicates at each strain amplitude. Thus, a total of 18 specimens is needed for each asphalt mix. Fatigue resistance was only obtained for binder and base layer mixtures. The classic fatigue criterion was used; i.e. the state of fatigue is reached at the load cycle, at which the material stiffness has dropped to half its initial stiffness. The initial stiffness is derived after 100 load cycles.
Recently, a new test method for assessment of fatigue resistance of asphalt mastic has been developed [12]. With this method, small sample quantities of mastic are tested in the dynamic shear rheometer (DSR) in an oscillatory way until the sample fails due to fatigue. A specific specimen shape (hyperboloid) ensures stress concentration in the centre of the specimen, see Figure 2. Thus, problems with interface failure between mastic and load plates can be prevented. Details on the method are discussed in Hospodka et al. [12]. In the test method, samples are loaded at +10°C and 30 Hz at three different shear stress amplitudes. At each stress amplitude, three single specimens are tested. A fatigue function, similar to the function derived from 4PB on asphalt mixtures can be derived.
For this study, mastic from AC 32 base and AC 22 bin was taken into account. To prepare mastic specimens, all mineral aggregates, filler, fine and coarse aggregates, were manually mixed and then sieved on a 125 µm sieve to derive all fine aggregates below 125 µm. These aggregates were then mixed with hot bitumen in the same ratio of bitumen and filler as in the mixtures.

Figure 2. Mastic specimen shape for DSR fatigue testing (left) and sample after fatigue failure (right)

2.4. Pavement Design

The results from lab testing were used as input to pavement design studies using a recently developed mechanistic-empirical design method according to the Austrian standard RVS 03.08.68 [5, 13]. Within this approach, design levels for relevant parameters (traffic load, asphalt stiffness and fatigue behaviour) are introduced, which allow for the consideration of actual details on a project level. With increasing detail, also the experimental effort related to the identification increases but necessary reserves decrease allowing for more economic constructions. This allows for modern, performance related and economic design of bituminous pavements.

Depending on the availability of data regarding traffic volume of heavy goods vehicles (HGVs), probability of appearance of HGV types, distribution of HGV gross weights as well as distribution of HGV axle loads, representative distributions or measured data can be considered. Besides the volumetric composition of the mix, the viscoelastic behaviour of one of two model bitumen (paving grade or polymer-modified) can be applied to a Hirsch-type material model [14], which was adapted to fit stiffness test results of common asphalt types (standard level), to consider for realistic stiffness behaviour of the bituminous layers. Additionally, the stiffness behaviour can be determined using the performance-based material parameter S_{min} according to European standard EN 13108-1 (performance-based level) by multiplying the Hirsch-type model by a factor of the form

$$F_S = \frac{S_{min} @ 20°C}{S_{mix,p}} \tag{1}$$

with $S_{mix,p}$ as a statistically verified stiffness. To take a performance-related description of the fatigue behaviour into account, a factor $F(\varepsilon_6)$ was introduced to the fatigue criterion

$$N_{ijk} = \frac{k_1(T)}{F(\varepsilon_6)} \cdot \left(\frac{S_{mix,k}(T,f)}{\sigma_{e,ijk}} \right)^{k_2(T)} \tag{2}$$

with temperature-dependent parameters $k_1(T)$ and $k_2(T)$, the stiffness of the bituminous mix $S_{mix}(T,f)$ and the maximum stress due to traffic load $\sigma_{e,ijk}$. The fatigue parameter ε_6 is specified either from performance-based requirements according to European standard EN 13108-1 related to the bituminous base course (standard level) or can be obtained in four-point bending tests according to EN 12697-24 (performance-based level).

In the current study, performance-based levels are applied to account for the obtained test results for the mixtures described above. Besides the volumetric composition (bitumen and air void content as well as density of the mix) the stiffness parameter S_{min} according to EN 13108-1 obtained at 20 °C and 8 Hz as well as the fatigue parameter ε_6 obtained at 20 °C and 30 Hz according to EN 12697-24 are considered.

3. RESULTS AND DISCUSSION

3.1. Asphalt Mix Test Results

As mentioned above, one relevant input parameter for the pavement design method is the material stiffness (dynamic modulus $|G^*|$) at a temperature of +20°C and 8 Hz, the results are shown in Figure 3. For each mixture, the mean value and the 95% exceedance probability based on mean value and standard deviation is given. For mixtures with polymer modified binders, the mean values (larger values) are similar when reference and HL modified mixtures are compared. This shows that the stiffening effect due to addition of hydrated lime was compensated by increasing the

binder content by 0.1 M%. The 95% exceedance probability is comparable in all cases but the SMA 11, where the reference mix shows lower stiffness than the modified mixture.
For the base layer mixture, AC 32 base, which was designed with 70/100 bitumen, the HL modified mixtures exhibits a 20% higher mean stiffness and the 95% probability value is about 5% higher than the reference mixture. For non-modified bitumen, the stiffening effect of hydrated lime addition seems to be more pronounced than for the mixtures with polymer-modified binder. In addition, the scattering is higher for the AC 32 mixtures. This is because the large maximum aggregate size of 32 mm is not optimal for the specimen cross section of 60x60 mm.

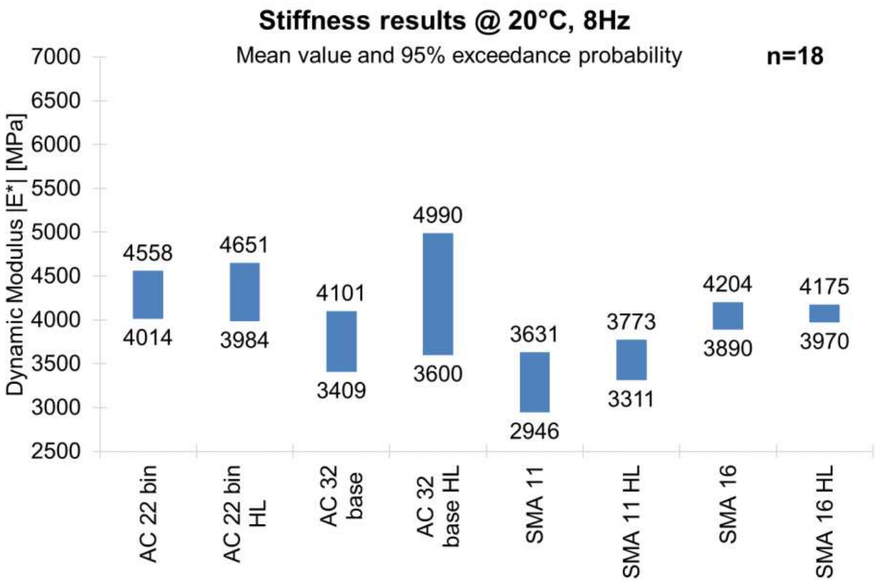

Figure 3. Results of stiffness testing

Figure 4 presents the results of fatigue testing on asphalt mixtures. Each diagrams contains results of 18 single fatigue tests by linking the applied strain amplitude on the bottom of the specimen to the load cycle at which the specimen is subject to fatigue. The single results are combined by the fatigue function (solid line) with the respective equation and coefficient of determination. As for the stiffness results, the 95% exceedance probability function is also given. At 10^6 load cycles, the mean $\varepsilon_{6,MV}$ value and the 95% probability $\varepsilon_{6,95}$ value are stated in each diagram.
For the AC 22 bin mixtures (top row), the HL modified mixtures exhibits a 10% higher $\varepsilon_{6,MV}$ value and a 15% higher $\varepsilon_{6,95}$ value compared to the reference mixtures. In both cases, the fatigue resistance can be described as very high, since the $\varepsilon_{6,MV}$ are clearly above 250 µm/m.
The AC 32 base mixtures (lower row) exhibit a much lower fatigue resistance, which can be explained by the use of non-modified binder, the larger nominal aggregate size and partly due to a rather low binder content. $\varepsilon_{6,MV}$ for the reference mixtures is 115 µm/m, whereas it is 120 µm/m for the modified mixture. The 95% exceeding probability comes to 88 µm/m and 86 µm/m, respectively. Thus, the modified mixture is slightly (4%) more fatigue resistant when looking at the mean values and slightly (4%) less fatigue resistant when looking at $\varepsilon_{6,95}$. In case of AC 32 base, the higher stiffness of the modified mixtures compensates for any improvement in fatigue resistance.

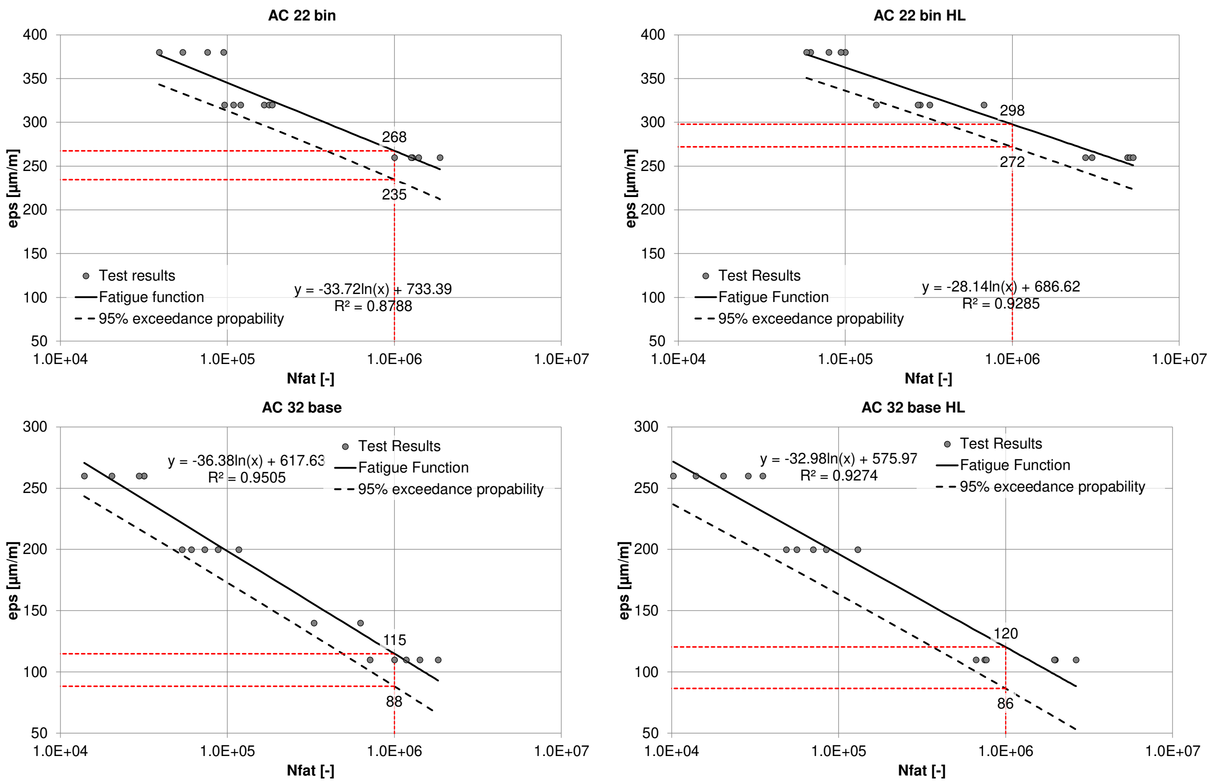

Figure 4. Results of fatigue testing on asphalt mixtures

3.2. Mastic Test Results

Results of the mastic fatigue tests are presented in Figure 5. The diagrams show the number of load cycles until fatigue for a single shear stress amplitude of 400 kPa. The left diagram contains data of the AC 22 mastic (PmB 45/80-65) and the right diagram the AC 32 mastic (70/100).

By direct comparison of AC 22 and AC 32 mastic, it becomes evident, that the PmB mastic exhibits a 6 to 10 times higher fatigue resistance. Also, the AC 32 mastic with non-modified binder brings a much smaller scattering than the AC 22 mastic with PmB. This can be linked to the impact of the more complex system of polymer (SBS), filler and bitumen.

Comparing reference to HL modified mastic, the AC 22 HL mastic brings a 16% higher fatigue resistance. This is in line with the results from asphalt mix fatigue testing. For the AC 32 mastic, the impact of the hydrated lime is much larger – an increase of 44% in fatigue resistance can be observed. While mastic and asphalt mix show the same trends, mastic testing with plain binder produced a stronger influence of the hydrated lime. When on asphalt mix leve, the hydrated lime content is about 1 % of total mass, it is more than 10 % of the total mass on the mastic level.

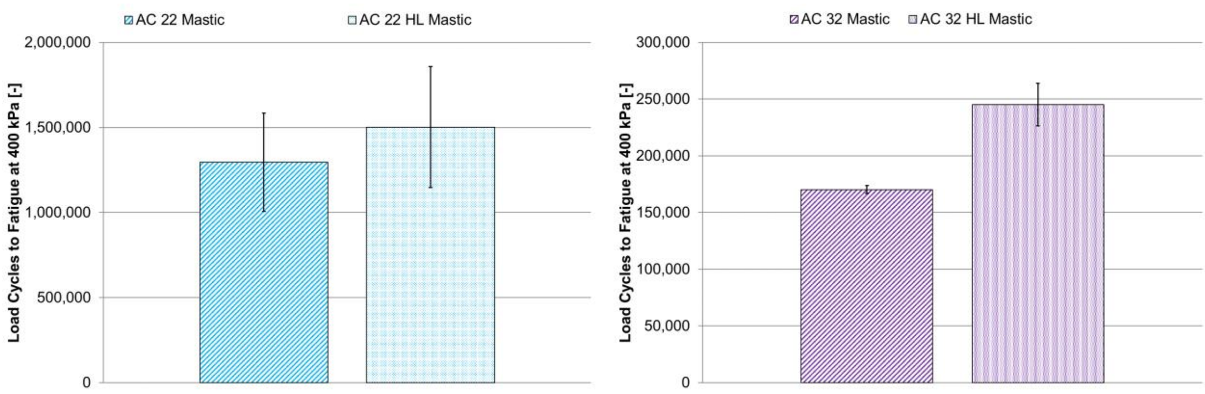

Figure 5. Results of mastic fatigue testing

3.3. Pavement Design Case Studies

The pavement design case studies were carried out according to the new national pavement design method as stated in RVS 03.08.68. Five different cross sections were analysed, as presented in Table 3 and Table 4. Three cross

sections (HW) are common pavement structures for the Austrian highway network. HW1 is current standard practice, HW2 is an alternative for which the AC 32 base was substituted by an AC 22 bin due to its higher fatigue resistance. HW3 is another alternative where the surface layer is an SMA 16 instead of an SMA 11. The unbound base layers are the same for all cross sections according to national regulations.
For the rural road (RR) network, two cross sections are compared. RR1 would be common practice, RR2 is an alternative similar to HW2, for which the AC 32 base was substituted by a fatigue resistant AC22 bin.
In the design studies, each cross section was calculated with reference mixtures and HL modified mixtures.

Table 3. Pavement design studies for highway (HW) cross sections

Layer	Pavement HW1		Pavement HW2		Pavement HW3	
Surface	3 cm	SMA 11	3 cm	SMA 11	5 cm	SMA 16
Binder	9 cm	AC 22 bin	9 cm	AC 22 bin	8 cm	AC 22 bin
Base	13 cm	AC 32 base	13 cm	AC 22 bin	12 cm	AC 32 base
Upper unbound base	20 cm	$E_{v1} \geq 90$ MN/m²	20 cm	$E_{v1} \geq 90$ MN/m²	20 cm	$E_{v1} \geq 90$ MN/m²
Lower unbound base	30 cm	$E_{v1} \geq 72$ MN/m²	30 cm	$E_{v1} \geq 72$ MN/m²	30 cm	$E_{v1} \geq 72$ MN/m²

Table 4. Pavement design studies for rural road (RR) cross sections

Layer	Pavement RR1		Pavement RR2	
Surface	3 cm	SMA 11	3 cm	SMA 11
Binder	---	---		---
Base	13 cm	AC 32 base	13 cm	AC 22 bin
Upper unbound base	20 cm	$E_{v1} \geq 90$ MN/m²	20 cm	$E_{v1} \geq 90$ MN/m²
Lower unbound base	30 cm	$E_{v1} \geq 60$ MN/m²	30 cm	$E_{v1} \geq 60$ MN/m²

The traffic load distribution considered for the design studies can be seen in Table 5. The method takes into account different HGV classes distinguished by the number of axles. For each class a conversion factor transfers the axle load distribution to an equivalent single axle load (ESAL). The traffic load distribution chosen for this study is representative of the actual traffic load on Austrian highways derived from traffic count stations across the network.

Table 5. Traffic load distribution for pavement design

Vehicle Class	Occurrence
2 axles	16.0%
3 axles	12.5%
4+ axles	71.5%

The necessary volumetric mix design parameters are presented in Table 6, the mechanical material parameters used for the design studies are shown in Table 7. All data is based on parameters derived from the tested mixtures. The binder content (B) is the target binder content, the air void content V_{air} represents the mean air void content of all specimens. The same is true for the maximum density of the mix. The binder density was set to 1.0 Mg/m³.
The mechanical material parameters are 95% probability values from stiffness and fatigue testing.

Table 6. Volumetric mix design parameters for asphalt mixtures

	Reference mixtures				HL modified mixtures			
	B [M%]	V_{air} [V%]	ρ_{mix} [Mg/m³]	ρ_{bit} [Mg/m³]	B [M%]	V_{air} [V%]	ρ_{mix} [Mg/m³]	ρ_{bit} [Mg/m³]
SMA11	5.4	6.0	2.40	1.00	5.5	6.9	2.41	1.00
SMA16	5.2	4.3	2.48	1.00	5.3	4.9	2.41	1.00
AC22 bin	4.5	4.0	2.50	1.00	4.6	3.9	2.48	1.00
AC32 base	4.3	5.6	2.45	1.00	4.4	5.3	2.45	1.00

Table 7. Mechanical material parameters for asphalt mixtures

	Reference mixtures		HL modified mixtures	
	S_{min} [N/mm^2]	ε_6 [µm/m]	S_{min} [N/mm^2]	ε_6 [µm/m]
SMA11	2800	-	2800	-
SMA16	3600	-	3600	-
AC22 bin	3600	235	3600	272
AC32 base	2800	88	3600	86

The results of the comparative design study are given in Table 8 and Figure 6. The table shows the admissible load cycles in million ESALs. Comparing the highway cross sections (HW), it can be seen that the change from AC 32 as base layer to AC 22 strongly increases the design life. This is because the AC 22 bin shows a significantly higher fatigue resistance than the AC 32 base. Substituting the surface layer from an SMA 11 to an SMA 16 does bring a slight increase in design life, which can be attributed to the higher stiffness of SMA 16. The rural road (RR) cross sections exhibit much lower design lives, which was expected. However, even here, the change from AC 32 base to AC 22 base almost doubles the lifetime.
Looking at the difference between reference and modified mixtures, high increases in design life occur when the base layer is an AC 22 bin. Again, the higher fatigue resistance of the AC 22 bin HL compared to the reference AC 22 bin can explain this. Small increases in the lifetime also happen for the AC 32 base due to higher stiffness of the AC 32 base HL.

Table 8. Admissible load cycles according to pavement design (in million ESALs)

	Reference	HL modified	Relative difference
HW 1	10.4	10.6	2%
HW 2	20.7	23.9	15%
HW 3	11.4	11.4	0%
RR 1	0.44	0.45	1%
RR 2	0.73	0.84	15%

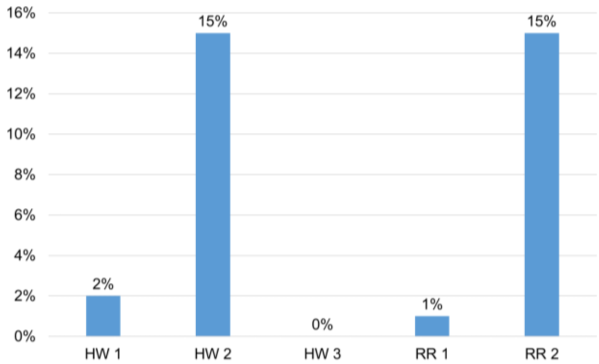

Figure 6. Change in pavement lifetime due to hydrate lime modification

4. SUMMARY AND CONCLUSIONS

This study presents a combination of performance based testing of asphalt mixtures and asphalt mastic on the one hand and modern, mechanistic pavement design on the other hand. The pavement design method can take actual volumetric asphalt mix design data and mechanical parameters (stiffness, fatigue resistance) as input for more realistic and efficient pavement design into account. Within the presented study, four reference and hydrated lime modified mixtures were tested and used in different cross sections for pavement design calculations.
Regarding the correlation between asphalt mastic and asphalt mix fatigue, both test methods show same trends. However, mastic fatigue testing tends to show a stronger impact of hydrated lime modification. This is because hydrated lime modification has a higher share in the mastic than in the complete mix.
In one case (AC 22 bin PmB 45/80-65) the hydrated lime modification showed significant increase of the fatigue resistance on the mix level (+15%), while for the other case (AC 32 base 70/100) no change in fatigue resistance was observed. However, for the AC 32 base, an increase in stiffness was measured due to hydrated lime modification.
The pavement design studies showed that the increased fatigue resistance for the AC 22 bin HL is a benefit for pavement structures if the base layer is also an AC 22 bin. The increased stiffness of AC 32 base due to modification did not results in significant increases of pavement design life.

In summary, the combination of performance based testing and modern pavement design methods can bring incentives to involve innovative materials into road construction since the benefit on design life can be shown.

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