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Original Research Paper

Ageing and performance of warm mix asphalt pavements

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HIGHLIGHTS

- Long term ageing of energy reduced pavements was tested using different heating and watering cycles.
- Rutting behaviour revealed controversial results with most of the energy reduce pavements showing an increase in rut depth.
- Fatigue resistance was improved resulting in an increase of fatigue life for aged mixtures due to increasing binder stiffness.

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ABSTRACT

This paper presents results from investigating the ageing behaviour and performance of different warm mix asphalt (WMA) pavement mixtures also called energy reduced pavements. The mixtures were either prepared in the laboratory or taken directly from a mixing plant. The study compared the rutting and fatigue behaviours of unaged material in comparison to long term laboratory aged material. In order to conduct the long term ageing, a special laboratory ageing protocol with different heating, cooling and watering cycles had been developed. The investigation revealed a quite controversial rutting behavior which could not be explained with the available data. While most aged energy reduced pavements showed increased rutting for other mixtures, lower rut depths could be found. As opposed to this finding, fatigue and stiffness of all aged energy reduced pavement samples compared to unaged samples improved significantly. The overall results led to the conclusion that the ageing of energy reduced pavement simulated in the laboratory is not very critical regarding their mechanical performance. Therefore, it was confirmed that the application of this type of pavement provides a good solution for saving on CO_2 emissions. Another advantage is that by using energy reduced pavements the road construction season can be significantly prolonged.

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1. Introduction

Since nowadays pavement construction is expected to be more energy efficient and road pavements are expected to be more environmentally and socially friendly, different concepts have been developed and put into practice. One concept is the use of warm or semi warm pavements allowing to lower the installation temperature significantly in order to save CO_2 emissions (D'Angelo et al., 2008; EAPA, 2010; Kheradmand et al., 2014; Martin et al., 2014).

Bituminous road pavements generally are constructed at temperatures between 150 °C and 160 °C. Nevertheless, for several years the asphalt industry has been under pressure to reduce production and construction temperatures. By reducing the temperatures, on the one hand CO_2 emissions from energy needed for the heating of the asphalt components and on the other hand hydrocarbon emissions from the manufacture and construction of asphalt pavements can be reduced.

As a result during recent years the amount of production methods of warm mix asphalt (WMA) has increased tremendously, making it more and more difficult for contracting authorities to differentiate between products and to select the optimum warm mix asphalt (WMA) concerning mechanical and energetical properties (EAPA, 2010). For the assessment of different concepts not only the energy balance is of importance but durability and lifespan have to be considered. Here, the influence of ageing on long term performance plays an important role.

Although first experiences with energy reduced pavement concepts show promising results, the long term resistance of these pavements compared with hot mix asphalt (HMA) remains largely unknown (Hasan et al., 2013; Safaei et al., 2014). Mostly only short to medium term performance data are available and the durability and long term resistance has still to be established (Bower et al., 2016; Raab et al., 2016; Raab and Partl, 2016).

In this context the Swiss Federal Office of Transport (FOT), has established a road research program under the title of "sustainable transport" in order to investigate energy reduced pavements, warm or semi warm pavements concepts allowing to significantly reduce the installation temperature in order to save CO_2 emissions. In the course of that program a research package consisting of seven different research projects has been launched as to investigate WMA pavements and their behaviour both in the laboratory and the field (Bueche et al., 2009).

This paper presents the results and findings of one of these research projects investigating the ageing characteristics of different types of energy reduced pavements (Raab et al., 2016).

2. Materials

For the investigation seven different warm or semi warm mixture types for a typical Swiss binder layer as shown in Table 1 were compared to a classic hot mix asphalt concrete binder AC B 16. The grading curve for all mixtures is shown in Fig. 1. The binder consisted of a 50/70 penetration grade binder, the binders for the foam mixtures are given in Table 1. The binder content was 4.6%, all binder characteristics are summarized in Table 2. All mixtures were prepared in the laboratory, while some mixtures as indicated in Table 1 additionally came from a mixing plant.

3. Preparation of laboratory mixtures

The laboratory mixtures were produced in the EMPA laboratory mixer putting together the delivered mineral aggregate fractions and binders including the additives (Fig. 2). All components were heated and produced at the temperatures given in Table 3. In this table the compaction temperature in laboratory are shown as well.

For the foam mixtures (FR-WATER and FR-WATER + RAP) the bitumen was foamed in the depicted foam bitumen mixer as shown in Fig. 3. For distinguishing between mixtures from the plant and the laboratory, laboratory mixtures will be called mixture_lab.

4. Ageing

In order to investigate ageing properties of energy reduced mixtures, a special ageing procedure as shown in Figs. 4 and 5 was developed. This ageing procedure should simulate long-

Table 1 – Mixture types.

Product group	Name	Product	Dosage	Bitumen
Warm-chemical additive	FR-PACK**	Cecabase	0.4%/binder	50/70
Warm-water containing zeolite	FR-ZEO**	Advera	0.25%/mix	50/70
Warm-wax	FR-WAX	Sasobit	3%/binder	50/70
Warm-foam bitumen	FR-WATER**	WAM-Foam	–	250/330, 35/50*
Warm-foam bitumen +50% RAP	FR-WATER + RAP	WAM-Foam + RAP	–	50/330, 50/70*
Half warm-cutback bitumen	PA-HWAM	LEA	0.3%/binder	250/330, 50/70*
Warm-chemical additive	PA-PACK	Greenseal	1%/binder	50/70
Hot-classic hot mix	REF-HOT**	AC B 16 S		50/70

Note: "*" means addition is as foam bitumen; "**" means mixtures are from plant and laboratory.

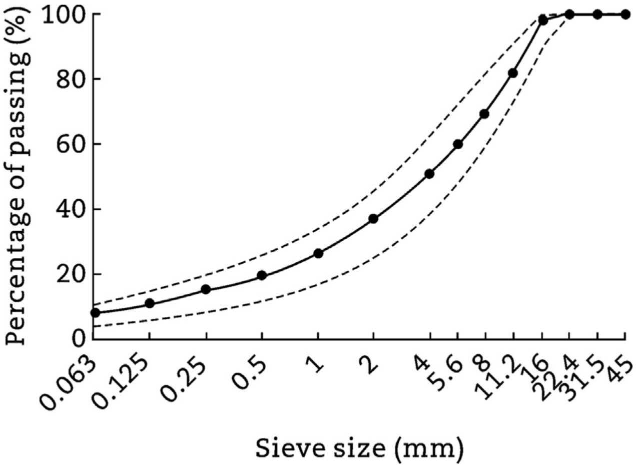

Fig. 1 – Grading curve of asphalt concrete binder course AC B 16.

Fig. 2 – EMPA laboratory mixer (content ca. 150 kg).

Table 2 – Binder characteristics, binder 50/70.

Binder characteristic	Value
Penetration (25 °C) (1/10 mm)	59
Softening point R & B (°C)	50.2
Breaking point (Fraass) (°C)	−19

term ageing and should be comparable to the in situ situation. Therefore, long term oven ageing procedure according to the literature with oven ageing of 85 °C was adapted and the procedure was per-formed on compacted specimens (AASHTO, 2002).

For this project generally Marshall specimens were taken, in case of rutting test ageing was done for the roller compacted slabs. According to the developed ageing procedure specimens were heated at 85 °C and after that emerged in cold water (starting temperature 20 °C) for 6 h as to simulate the effect of precipitation as a cause of heavy thunder showers. The complete ageing cycle is shown in Fig. 5.

5. Testing

Testing was conducted as shown in Table 4. For both laboratory and plant mixtures, fatigue test was conducted, for the plant mixture no rutting test was done.

5.1. *Rutting test*

Permanent deformation or rut formation was assessed using the large device wheel tracking test (Fig. 6) in accordance to the European Standard EN 12697-22 (CEN, 2004). In this test, the susceptibility of bituminous materials to deform is assessed by the rut formed by repeated passes of a loaded wheel at constant temperature of 60 °C.

Rutting tests are conducted on laboratory compacted specimens (Fig. 6). Testing is performed on 2 specimens with the dimension of 500 mm × 180 mm × 100 mm at a temperature of 60 °C. After a zero measurement the relative rut depth, e.g., the absolute rut depth as a percentage of the specimen height, is determined at different time intervals. For a binder mix AC B 16 S according to the Swiss standard the rut depth after 10,000 passings (one passing includes one forth and back) is relevant.

5.2. *Fatigue test*

The fatigue behaviour was investigated using the Marshall specimen and employing the German standard AL-Sp-Asphalt 09 (FGSV, 2009), which has been included in the European Standard EN 12697-24 (CEN, 2012) with the difference that a continuous sinusoidal function instead of a haversine impulse with rest periods is applied. The set-up is therefore the same as the indirect tensile test IT-CY shown in Fig. 7.

The loading frequency of 10 Hz and a temperature of 20 °C were used. As required by the standard, three loading amplitudes are implemented allowing the loading cycles to reach the fatigue criterion. A total of nine specimens were tested, three at each of three strain levels. The smallest loading amplitude is chosen in that way that the specimen fails after 1 million cycles and the largest amplitude so that the specimen withstands at least 1000 cycles. Through the vertical load a state of stress is produced in the middle of the specimen that leads to its eventual failure.

According to the German standard, the maximum of the so-called energy ratio (ER), as the product of number of cycles and stiffness modulus, is taken (Eq. (1) and Fig. 8). The fatigue behaviour is defined through the number of cycles designated as N_{Makro}, where micro cracks begin to form and where ER(N) reaches its maximum value, dropping after posterior cycles. The fatigue line is constructed using the Eq. (2). The advantage of this method is that the starting point of the curve is well defined since it starts at the zero point. The curve can therefore be approximated using a polymer function to the power of 4 and the maximum can be

Table 3 – Production and compaction temperatures.

Mixture type	Production	Production temp. (°C)		Compaction temp. (°C)
		Plant	Laboratory	
REF-HOT	Plant/lab	165	160	150
FR-PACK	Plant/lab	165	120	120
FR-ZEO	Plant/lab	130	130	120
FR-WAX	Lab	–	130	120
FR-WATER	Plant/lab	115	105	120
FR-WATER + RAP	Plant/lab	115	105	105
PA-HWAM	Lab	–	100	100
PA-PACK	Lab	–	120	120

(a) (b)

Fig. 3 – Bitumen foaming. (a) EMPA laboratory foam mixer. (b) Foaming process.

determined. Details can be found in the German standard AL-Sp-Asphalt 09 (FGSV, 2009).

$$ER(N) = |E(N)|N \quad (1)$$

where E(N) is the stiffness modulus at the particular cycle N.

$$N_{Makro} = C_1 \epsilon_{el,anf}{}^{C_2} \quad (2)$$

where $\epsilon_{el,anf}$ is elastic horizontal strain in the middle of the sample at the beginning of the experiment as defined in Eq. (1) (‰), C_1 and C_2 are material specific parameters that are determined using a regression analysis.

For the evaluation of the fatigue behaviour the initial elastic deformation at 1,000,000 cycles is taken as a characteristic value.

6. Test results

6.1. *Rutting behaviour*

Fig. 9 depicts the rutting test result for all unaged and aged (columns with dashed lines) laboratory mixtures. The

(a) (b)

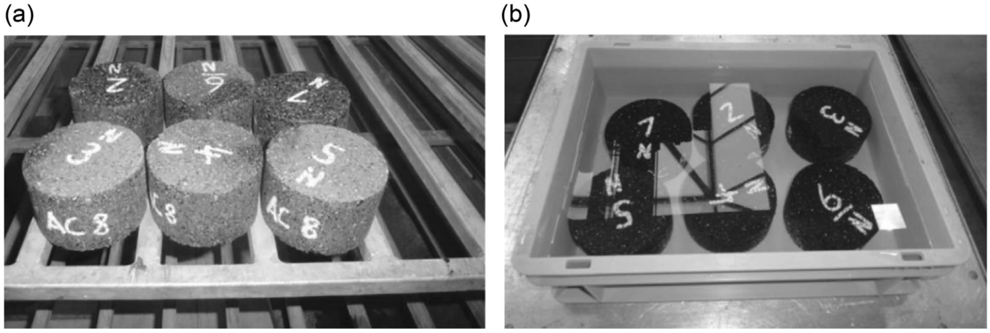

Fig. 4 – Ageing procedure. (a) Specimens in the oven. (b) Specimens in the water.

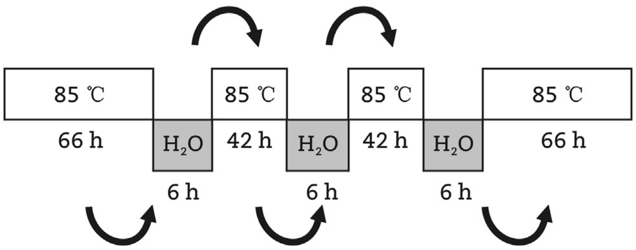

Fig. 5 – Ageing procedure.

Table 4 – Testing program.

Mixture group	Rutting test	Fatigue test
Laboratory	x	x
Plant	–	x

evaluation of the rutting behaviour shows for nearly all WMA mixtures an increase of the rut depth after ageing as opposed to the reference hot mix which performs-as expected-stiffer after ageing leading to a reduced rut depth. The mixture PA-HWAM also shows a decrease in rut depth with ageing, although this mixture shows the largest permanent deformation (>14%) of all investigated mixtures in the unaged state. Only for the wax modified mixture the increase in rut depth is negligible. For this kind of modification the phenomena of stiffening as a result of crystallization of the wax molecules is well known. Extremely high rut depths between 15% and 17% are visible for the aged mixtures of FR_PACK and FR_WATER.

6.2. *Fatigue behaviour*

Fig. 10 depicts the comparison of initial elastic deformation at 1,000,000 cycles for all laboratory mixtures in the unaged and aged states. Here, all WMA pavements show the same behaviour as the reference hot mixture resulting in an increase of fatigue life for the aged mixtures.

As shown in Fig. 11 the above mentioned results are confirmed by the fatigue behaviour of the mixtures directly taken from the mixing plant. In general the fatigue lives of

Fig. 6 – Rutting tester, specimen in the device.

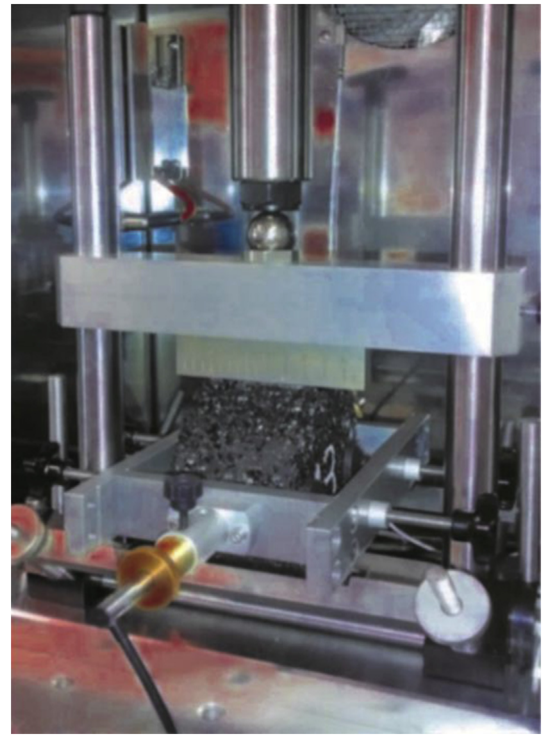

Fig. 7 – Test set-up for the indirect tensile test IT-CY at EMPA.

these mixtures are even higher than these of the laboratory fabricated ones, which could be an indication of the difficulty of re-producing energy reduced pavements in the laboratory.

7. Discussion

Comparing the results with findings from other studies there are differences and common findings.

According to the literature the rutting performance of WMA appears to be inconsistent when compared to that of HMA, which are due to the discrepancy in the test method (wheel tracking device, flow number, accelerated pavement analyser, etc.), test condition (wet or dry), composition (with RAP or without RAP) and WMA types (Bower et al., 2016; Copeland et al., 2010; Middleton and Forfylow, 2009; Mogawer et al., 2012; Prowell et al., 2013; Xiao et al., 2010). The inconsistency of rutting resistance found in the present study mainly appears to depend on the kind of warm mix additive or method used, although a clear influence of warm mix method or temperature could not be evaluated.

Researchers who investigated the rutting resistance of WMA mixtures containing high RAP content and conventional method using wheel tracking, found that the addition of high RAP content improved the rutting resistance of WMA mixtures (Doyle and Howard, 2013), a finding that could be confirmed by the test results (FR-WATER compared with FR-WATER + RAP).

Results of the present study further support findings that the fatigue performance of WMA compared with HMA was

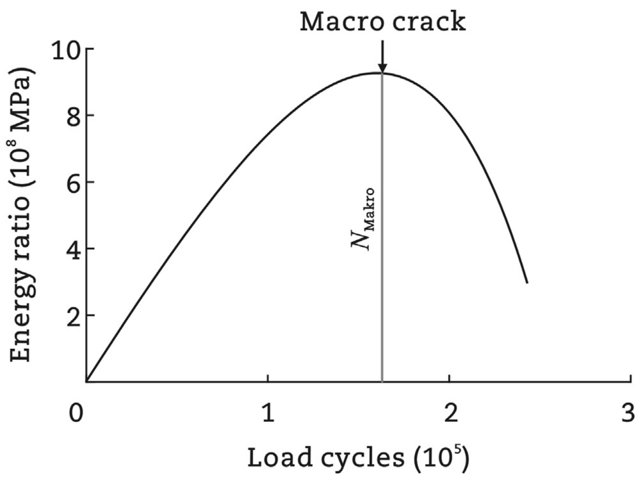

Fig. 8 – Schematic example for the determination of number of load cycles until N_{Makro}.

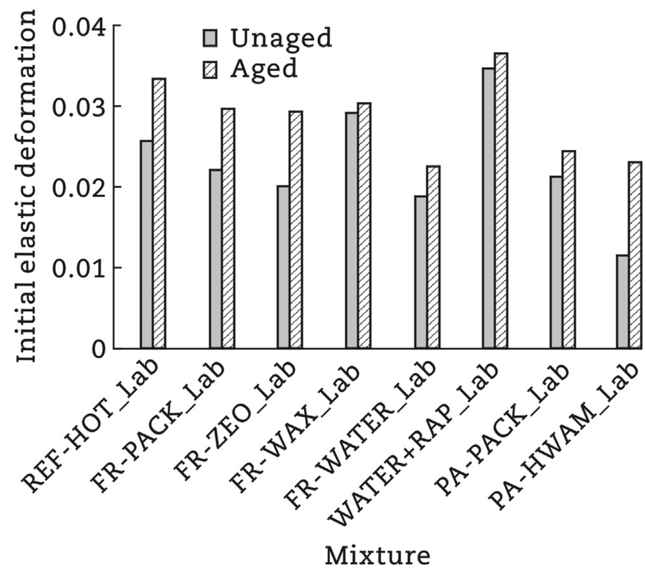

Fig. 10 – Initial elastic deformation at 1,000,000 cycles for all unaged and aged laboratory mixtures.

found equal or even improved according to the type of additive or the WMA method used. Further, it was found that ageing resulted in stiffer mixtures and improved fatigue behaviour (D'Angelo et al., 2008; Hasan et al., 2013; Kvasnak et al., 2010; Safaei et al., 2014).

Nevertheless, when looking at the rutting performance of aged WMA it cannot be fully clarified why the stiffening caused by ageing for nearly all WMA results in a reduction of rutting resistance. Here, a fact worth considering is temperature. While fatigue results are determined at a temperature of 20 °C, rutting tests are conducted at 60 °C. This finding leads to a twofold question: do high testing temperatures have a significant effect on the test results of aged material and should fatigue test be done at other temperatures than 20 °C?

8. Conclusions

For the investigation and simulation of the long term ageing behaviour of different energy reduced pavement mixtures a special laboratory ageing protocol with different heating and watering cycles was developed. With this method it was possible to see differences in the behaviour of aged and unaged mixtures when investigating the rutting and fatigue properties.

As for the rutting behaviour the study reveals quite controversial results with most of the energy reduce pavements showing an increase in rut depth. Especially the warm

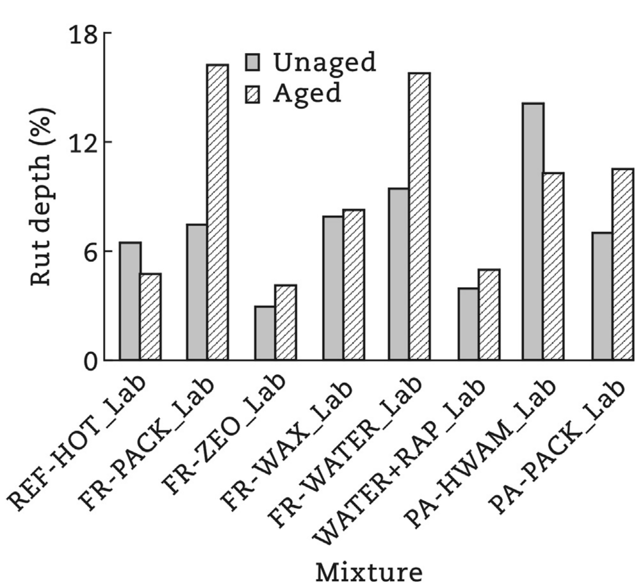

Fig. 9 – Rut depth for all unaged and aged laboratory mixtures.

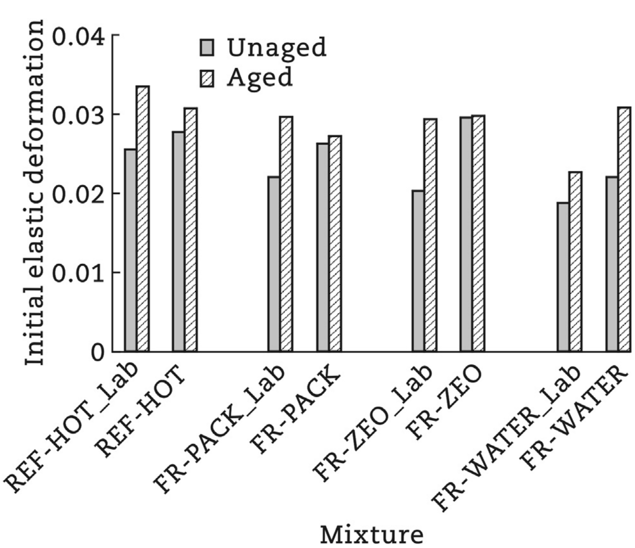

Fig. 11 – Initial elastic deformation at 1,000,000 cycles for plant and lab mixtures.

mixture with chemical additive FR_PACK and the foam asphalt mixture FR_WATER depict extremely high rut depth values of >15%. While in case of the foam asphalt mixture with reclaimed asphalt (RAP), the RAP seems to lead to stiffening and therefore increased resistance against permanent deformation already for the unaged mixture. The only energy reduced mixture PA-HWAM showing a decrease in rut depth with ageing, has already in the unaged state low resistance against permanent deformation with a rut depth >14%. The results indicate that for WMA the resistance against permanent deformation could become critical.

As opposed to this finding, fatigue resistance of all aged energy reduced mixtures compared to unaged mixtures improved significantly resulting in an increase of fatigue life for the aged mixtures as expected due to increasing binder stiffness.

Although, attention has to be paid to the rutting behaviour, overall findings lead to the conclusion that the ageing of energy reduced pavement concepts is not very critical and that the application of such pavements therefore provides a good solution for saving CO_2 emissions and prolonging the installation season. Nevertheless, all findings have to be validated by long term investigations and field trials, where especially the resistance against deformation requires increased attention.

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