Mechanical properties and quality-control of warm asphalt

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ABSTRACT

The aim of the research project PLANET is to provide road experts with technical know-how for the production of bituminous mixtures and paving with low energy and environmental impacts. In this paper the objectives are to assess the methods of control that are usually applied to hot mixes and to make an in-depth study of the mechanical behaviour of the different warm-asphalt technologies in comparison with a similar hot mixed asphalt.
Five test fields with 4 different warm-asphalt technologies and one with hot mix-asphalt have been realised. The mixing and laying procedures has been fully documented and the methods of quality control that are usually used were applied. For this purpose a protocol of preparing the sample in the laboratory has been established.
A huge amount of samples and cores were tested by different test methods, such as interlayer bonding, rutting test, uni- and triaxial cyclic compression test, water sensitivity, fatigue, modulus of elasticity, and indirect tensile test at different temperatures. To assess the time-depended increase of the interlayer bonding a laboratory test-program has been run.
The results will be presented and discussed.

Keywords: Compatibility, Low-Temperature, Mechanical Properties, Warm Asphalt Mixture

1. INTRODUCTION

Warm mix asphalts (WMA) have become more and more used in the Swiss market. Until now, the wax modified bitumen and the foam-technology have mainly been used. To get more knowledge with other WMA-technologies and to be able to compare the different options for WMA, a research project called PLANET [1, 2, 3] has been started. The aim of research project PLANET is to provide road experts with technical know-how for the production of bituminous mixtures and paving with low energy and environmental impacts. The objectives of this paper are to assess the methods of control that are usually applied to hot mix asphalts (HMA) and to make an in-depth study of the mechanical behaviour of the different warm-asphalt technologies in comparison with an equivalent hot mixed asphalt.

2. TEST SECTIONS

A test site, located in Bern region (central part of Switzerland), was divided into five different tests sections of approximately 800 m^2 that were constructed in November 2012. Each test section has an approximate length of 130 m in which a total amount of 130 t of warm mix asphalt was laid. The traffic loading is 2,500 vehicle/day and the proportion of heavy vehicles were estimated at around 5%. The choice of the WMA techniques was made from consideration of the related experience, literature data (in particular [4, 5, 6, 7, 8, 9]), the availability for the Swiss market and the potential performances of the products [1]. The final choice permits the comparison of foaming techniques (2 bitumen), the uses of zeolite as well as a well-known chemical additive (tensio-active agent). The selected WMA techniques are summarised in Table 1 that also contains the production temperature at the plant and the dosage of the given additives, these two parameters being defined in accordance with the recommendations of the WMA suppliers.

Table 1: Selected WMA asphalt techniques for the test sections

Code	Type	T_{prod} [°C]	Bitumen (pen)	Technique
REF	HMA	165	50/70	
PACK	WMA	130	50/70	Chemical additive, dosage 0.4%/bit.
ZEO	WMA	130	50/70	Chemical zeolite, dosage 0.25%/agg.
WATER	WMA	115	250/330, 35/50	Foaming technique
WATER+RAP	WMA	115	250/330, 70/100	Foaming technique, 50% RAP

The structure of the road was determined by the local authorities, while the tested layer was the upper base layer:

Surface layer	AC 11	40 mm
Upper base layer	ACB 16	65 mm (with different warm asphalt mixtures)
Under base layer	ACT 22	95 mm
Foundation layer	ACF	120 mm

3. CONTROL OF THE REALISATION OF THE TEST SECTIONS

3.1 Controls on the compaction

The compaction applied directly behind the finisher is presented in Figure 1. Thereby the compaction is calculate in% of the reference density (Marshall density). The pre-compaction is similar for the mixtures REF, ZEO and WATER + RAP (85.5 % of the Marshall density); for the mixtures WATER it is lower (82.7 %) and for PACK higher (87.6 %). Unfortunately, it is not known if the setting of the finisher was changed between the test sections, but it can be assumed, that such changes have not be done due to the fact that all section where laid continuously on the same day. This assumption means that mixture PACK was better, and the mixture WATER worse, compacted than the mixtures REF, ZEO and WATER + RAP.

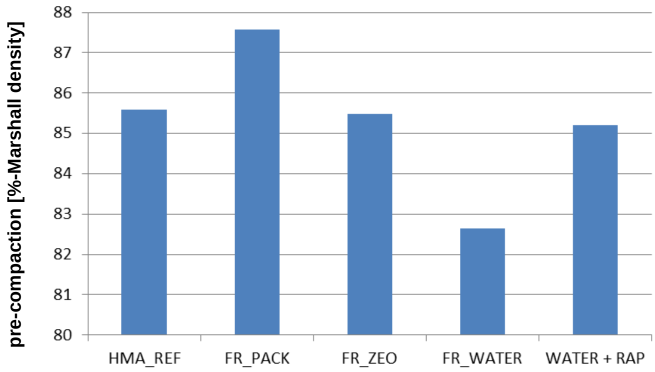

Figure 1: Compaction directly behind the finisher

Table 2: Estimated number of required roller passes to reach 99 % of Marshall reference-density

mixture	Number of passes to reach 99 % of Marshall density	Temperature at the beginning of compaction [°C]	Temperature at the end of compaction [°C]
REF	9.6	138	64
PACK	9.5	114	56
ZEO	8.3	113	65
WATER	12.1	103	56
WATER + RAP	13.0	101	55

The mixtures where compacted at the recommended temperatures for the single products. Based on the measured values with a nuclear density test, the increase of density was calculated using the mathematical model:

$$\rho = \rho_0 + (\rho_m - \rho_0)(1 - e^{-aN})$$

ρ_0: density behind the finisher
ρ_m maximum density (estimated value)
a: parameter to describe the increase of the density (estimated value)
N: number of roller passes

The formula was used to estimate the required number of roller passes to achieve a density corresponding to 99% of the Marshall density (Table 2).

Both mixtures with foam-technology (WATER and WATER+RAP) needed significant more roller passes to achieve the same degree of compaction, although it should be noted that the temperature of the mixtures WATER and WATER+RAP at the beginning of the compaction was lower. There is no correlation between the pre-compaction (directly behind the finisher) and the estimated required number of passes.

3.2 Testing on mixtures

3.2.1 Conditioning Method

Before testing the various WMA mixtures, it was necessary to determine the optimal laboratory procedure for asphalt mixture conditioning (i.e. choice of temperature and reheating method); the reheating temperature being highly dependent on the warm mix technique. The applied methodology was specifically based on the experience from [10, 11, 12]. Thus, the various WMA were first heated using a microwave and then stabilised in an oven at different target temperatures. The results for Marshall air voids contents are presented in Figure 2 where the target air voids content corresponds to the reference REF (blue line). Based on this analysis, a reheating temperature of 120 °C was set for the PACK and ZEO mixtures and 105 °C for the WATER+RAP and WATER (155 °C for REF). Note that these temperatures also accord with the compaction temperatures applied on the test site.

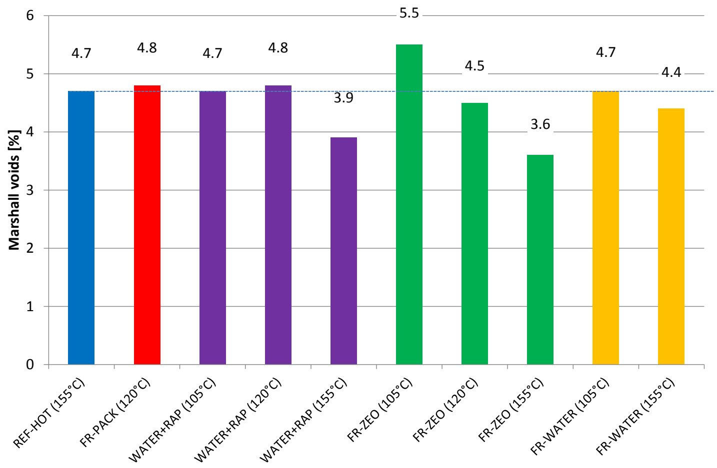

Figure 2: Marshall (50/50 blows) voids for different reheating temperatures in the laboratoy

3.2.2 Mixture controls

The grading curves of the different mixtures are represented in Figure 3 that also contains the target grading curve (grey). The different mixtures are comparable even though there is a variation in the filler point (between 6.8% for REF and 11.6% for WATER). The binder content varied between 4.50% (REF) and 5.05% (ZEO) with a target value of 4.60%. The water content of the asphalt mixtures containing “water” varied between 0.09% (ZEO) and 0.14% (WATER+RAP). As discussed in [1, 15], such a moisture content is not considered to have a significant impact on the performance of the mixtures.

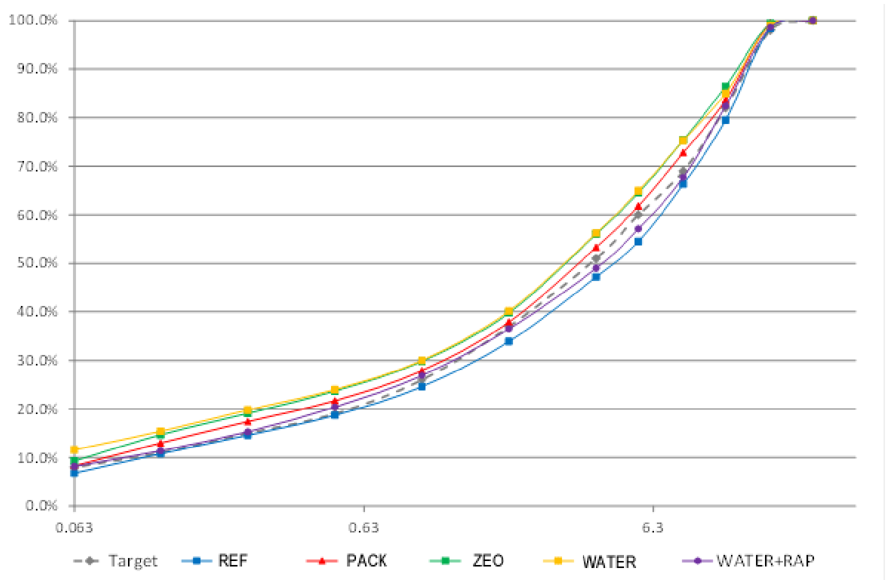

Figure 3: Grading curve of the various mixtures tested

Table 3: Binder- and void-content

	REF	PACK	ZEO	WATER	WATER+RAP
Binder content[mass-%]	4.50	4.89	5.05	5.00	4.65
Voids Marshall [vol.-%]	3.8	4.8	4.5	5.3	5.3

The analysis of the recovered binders (Table 4) indicates that the ageing of PACK and foaming techniques with RAP is comparable to the reference REF. On the other hand, ZEO and WATER have a slightly less aged binder because the recovered bitumen penetration is slightly higher and R&B lower than the reference. The different ageing has an influence on the mechanical properties and will be considered in the following section.

Table 4: Characteristics of recovered binders

	REF	PACK	ZEO	WATER	WATER+RAP
Pen @ 25°C [10^{-1} mm]	39	36	45	41	39
R&B [°C]	55.7	54.7	52.7	52.6	55.9

3.3 Testing on cores

On each test section 4 cores (Ø 150 mm) were taken and the layer of warm asphalt was analysed in the laboratory, by measuring the thickness, the density and the bonding to the layer below.

Table 5: Results of the tested cores

	REF	PACK	ZEO	WATER	WATER+RAP
Layer Thickness [mm]	62	66	71	70	75
Air voids content [vol.-%]	5.9	5.1	4.3	5.9	4.5
Compaction degree [%]	97.5	98.6	99.3	98.5	100
Bonding [kN]	8.3	-	8.1	12.4	-

The reference REF sample was thinner than the other test sections and also had the worse compaction; the value of 97.5 % not fulfilling the Swiss requirement of > 98%. The results of the bonding test according to EN 12697-48 show that no values could be determined for two sections (PACK and WATER+RAP). This means that the bond was so bad that the layer separated spontaneous. Only the section WATER fulfils the Swiss requirement of > 12 kN. The data in Table 5 do not establish whether the lower temperatures of the WMA technologies lead to any problems or not because the section with HMA (REF) also did not fulfil the requirement.

4. MECHANICAL PROPERTIES

The conditioning of the samples was done according to section 3.2.1. For all samples which were compacted, the temperatures listed in Table 6 were applied.

Table 6: temperature of compaction

Mixture	Temperature of compaction [°C]
REF	155
PACK	120
ZEO	120
WATER	105
WATER+RAP	105

4.1 Compactability

To assess the advantage of the WAM in term of reducing the required compaction-energy, gyratory-tests where run in accordance with EN 12697-31. The test-temperatures where defined from the suppliers' recommendations. PACK, ZEO and WATER show significant smaller numbers of required rotations than REF for the lower levels of compaction, while WATER+RAP required a slightly lower number than REF (see Figure 4).

Table 7: Number of required rotation in gyratory-test (EN 12697-31) to achieve a fixed void content

	Test temperature [°C]	Number of required rotation to achieve a void content of …		
Mixture		10 %	7.5 %	5 %
REF	155	18	33	62
PACK	120	12	20	41
ZEO	120	13	22	48
WATER	120	12	23	43
WATER+RAP	120	15	27	58

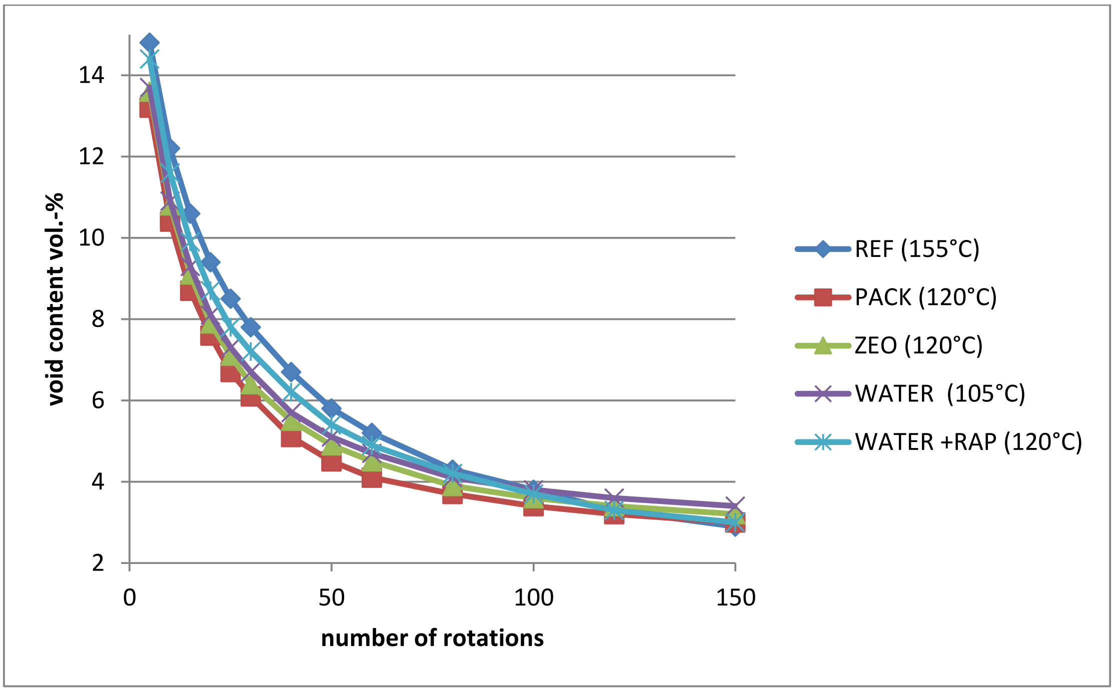

Figure 4: void content as a function of the number of rotations in the gyratory-test

When above 5 % air voids content, all WAM needed less energy to be compacted than the reference HMA. An air void content of 5 % corresponds to the value of compaction in the laboratory (Marshall compaction). Below 5 % voids, the differences between the mixtures become smaller and below 4 % they disappear.

The results of the mathematical model used in section 3.1 are contradictory to the results of the laboratory test. It may be assumed that the behaviour of the mixtures in a laboratory test is nearer to reality than a mathematic model. Therefore, the results of the gyratory test have been taken in account in the final evaluation.

4.2 Water sensitivity

Water sensitivity results (ITSR according to EN 12697-12) are summarised in Figure 5 where transparent colours correspond to dry samples (ITS_d) and solid colors to samples with water conditioning at 22 °C and the ITSR ratio being shown in black lines. Except for the WATER mixture, the various WMAs meet the requirements according to Swiss standards (ITSR ratio > 70%). According to the experience, an ITSR ratio below 80% could be considered as an indicator of a potential water sensitive mixture. A clear difference can also be observed in the measured stresses. Indeed, stresses in WMA samples without conditioning are between 11% (PACK) and 51% (WATER+RAP) lower than for the REF mixture. This measured stress difference varies between 34% (PACK) and 77% (WATER) for the wet samples. Considering the ITSR ratios and the stresses at samples failure, it is suspected that the WMAs tested are more sensitive than the reference HMA, particularly for the WATER mixture.

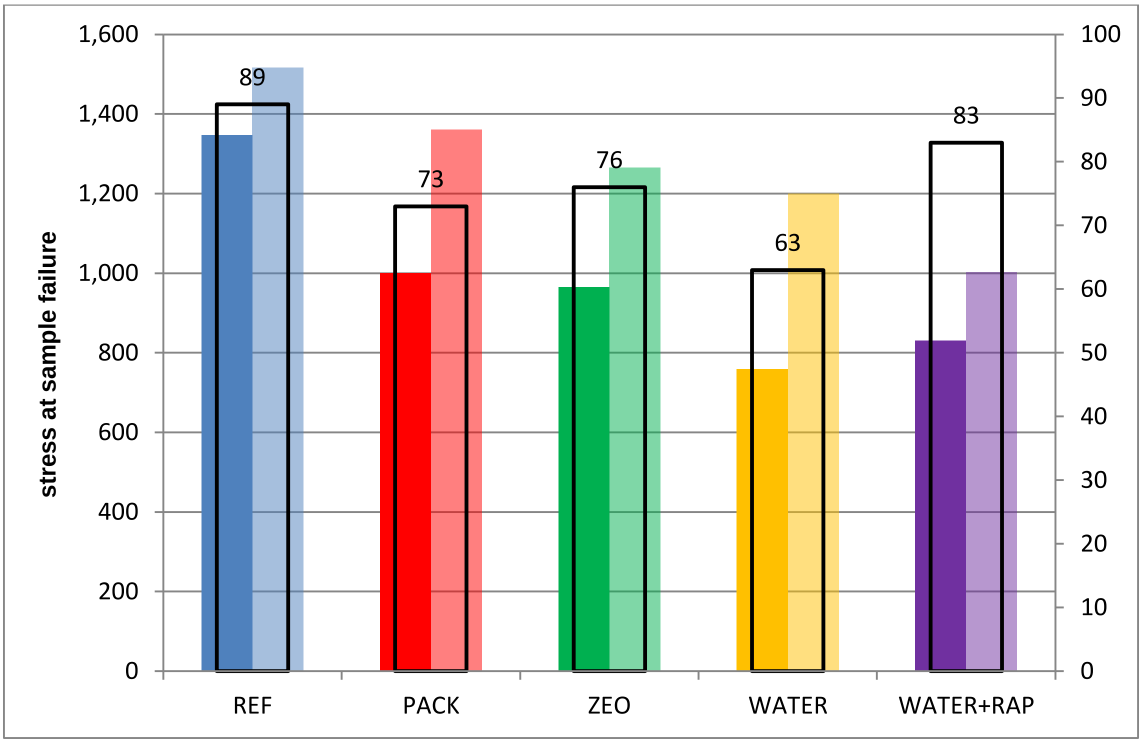

Figure 5: Water sensitivity tests according to EN 12697-12 (transparent colours for ITS_d / solid colours for ITS_w and black lines for ITSR ratio)

4.3 Bonding of the layers

After the tests on cores to control the laying of the asphalt, a suspicion arose that the bonding of the layers could be a problem because of the lower process temperatures of WAM mixtures. Therefore, cores where taken at intervals to get information on the bonding. In practise, it is well known that the bonding improves with time before the test takes place. As the test site was on a public road, it was not possible to take 4 cores for each section at each intended time interval (which would mean a total of 125 cores!) in addition to all the other cores taken. Unfortunately, the selection of sections and the reduction of the sampling led to less information. The results are summarised in Table 7 and show an increase in the spring/summer months for REF and PACK, a continuing satisfactory level for WATER+RAP and an apparent decrease for ZEO and WATER.

Table 8: Development of the layer-bonding in situ [kN] according to EN 12697-48

	1 day	2 days	4 days	5 month	9 month
REF			8.3	7.1	11.6
PACK				6.8	10.4
ZEO	5.1	5.1	8.1	4.3	
WATER	8.8	11.6	12.4	6.9*	5
WATER+ RAP				13.3	12.7
number of values	2	2	2	4	1
Calendar month of sampling	October	October	October	March	July

***Two samples without value**

The results in Table 8 were not satisfactory; therefore, a laboratory test programme was started in which a layer of WAM-Asphalt was compacted on an asphalt base layer using a smooth steel laboratory compactor according to EN 12697-33. The compaction was done at the temperature indicated by the supplier and cores were taken at intervals to run the bonding test according to prEN 12697-48 (Leutner-Test). The samples were stored between the sampling of the cores at a constant temperature of 22 °C. For the lower base layer a HMA AC 16 was used; the WAM mixtures REF, ZEO and PACK were laid as second layer. In addition to the mentioned WAM mixtures, a wax-modified WAM was laid as well, using 1.5 % wax (based on the bitumen). Cores were taking after 3, 21 and 90 days and tested in accordance with EN 12697-48. The development of shear bond resistance is presented in Figure 6.

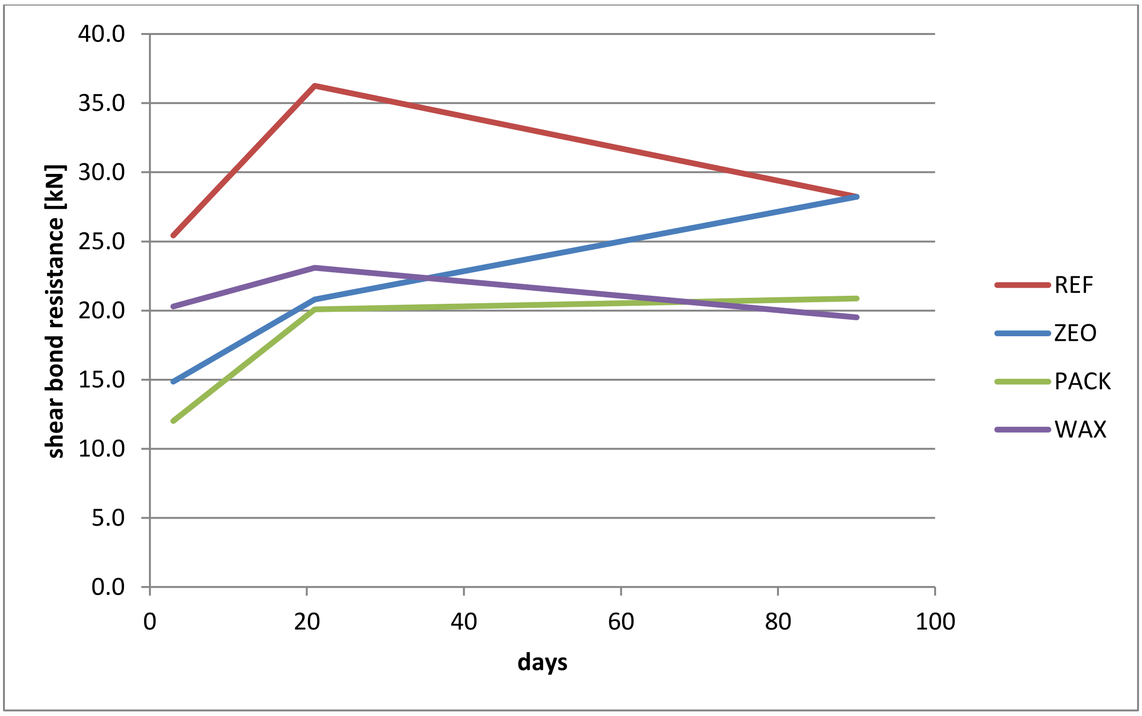

Figure 6: Development of the layer-bonding under laboratory conditions

In general it can be stated, that already after 3 days the shear bond resistance for all mixtures fulfil the Swiss requirement of > 12 kN. The shear bond resistance for the HMA is higher than for the WMA. Analogous to the experience in practise, the values increase slightly during the storage in the laboratory.

4.4 Warm-temperature behaviour

Uniaxial compression and triaxial tests were performed on laboratory compacted samples after 10 days of storage at 22 °C. The results of the uniaxial compression tests are represented in Figure 7. The foamed technologies WATER and WATER+RAP show the worse results while the reference mixture REF has the lowest rutting susceptibility. The results of the penetration test on the recovered binder are indicated in red letters. As expected, the mixture REF has the lowest value, followed by the mixture with recycled asphalt WATER+RAP. It can be seen that PACK and ZEO have a lower deformation rate than WATER+RAP, although the binder of the WATER+RAP is harder. In Switzerland, there is a long experience with the uniaxial test. Values (rate of deformation) above 30 are estimated to be problematic. The values for both foamed mixtures, WATER and WATER+RAP, are expected to give rutting deformation under heavy traffic.

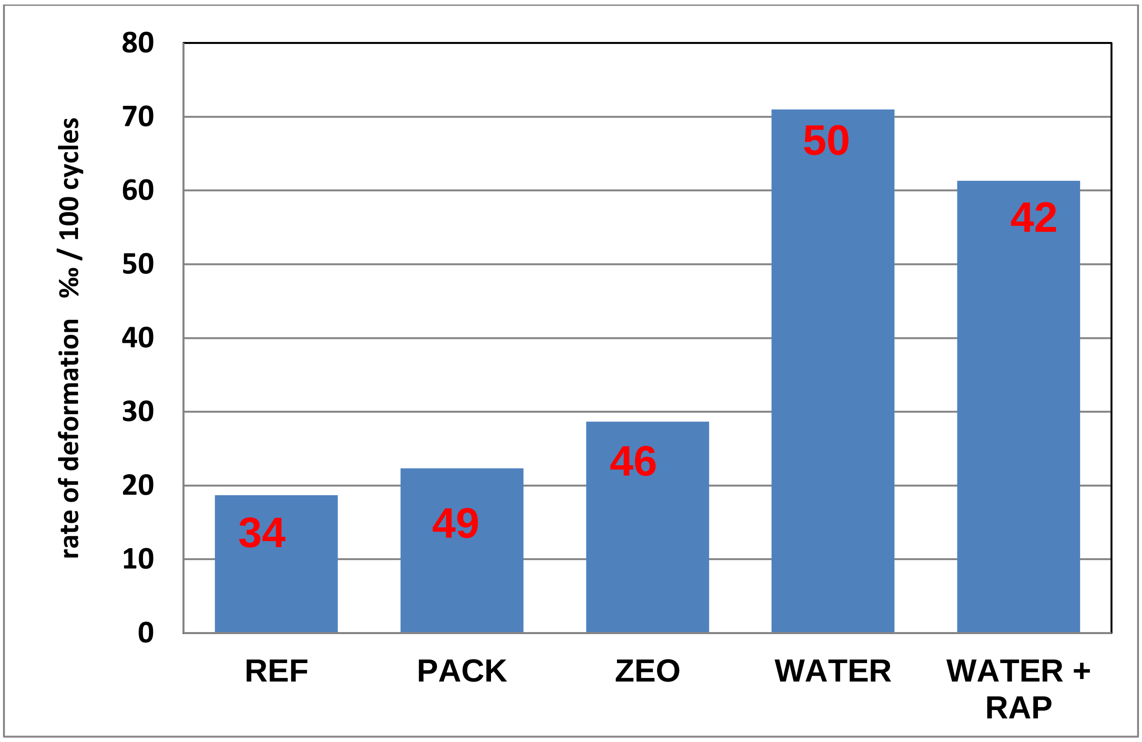

Figure 7: Uniaxial compression test (EN 12697-25); Penetration of the binder in red

The triaxial test results in Figure 8 show the same ranking of the mixture as the uniaxial tests. Considering the penetration values – marked in red – it is obvious that the values are almost the same for all WMA mixtures. Therefore, the triaxial test results are more meaningful: All WMA mixtures show a bigger deformation rate than the reference REF. PACK and WATER+RAP have similar values while ZEO and WATER have the biggest deformation rates.

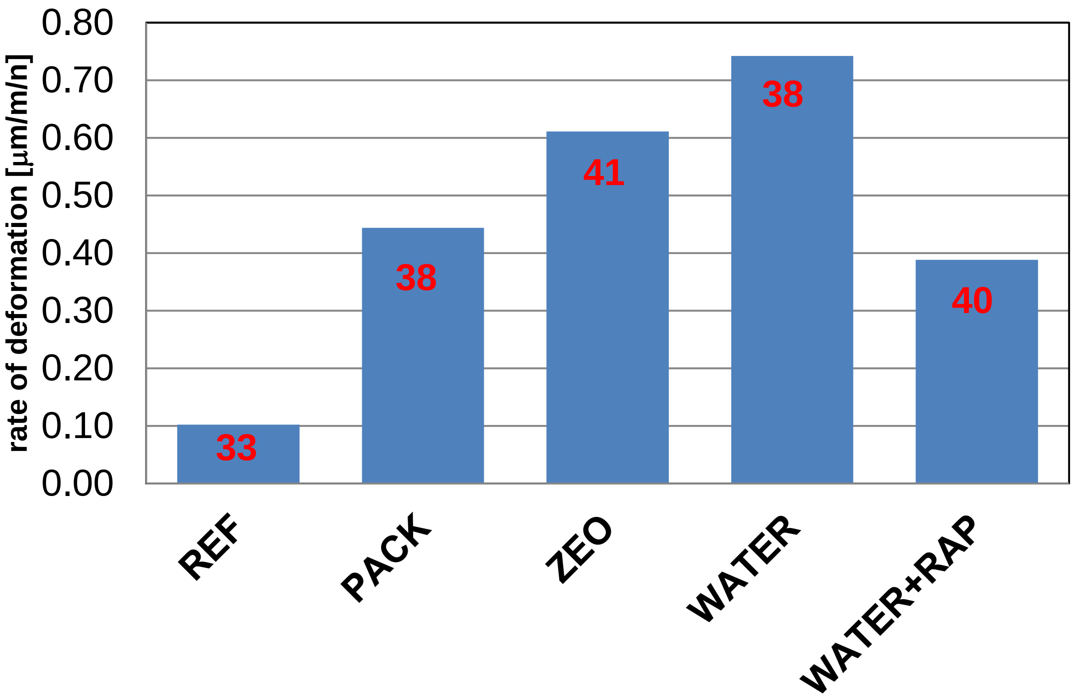

Figure 8: Triaxial compression test (EN 12697-25); Penetration of the binder in red

4.5 Low-temperature behaviour

The low temperature behaviour of the different mixtures were tested in the laboratory used the mean of uniaxial tension test (uniaxial tension stress test UTST) performed at + 5 ° C, according to EN 12697-46. For each mixture, 4 prismatic samples 50x50x160 mm were taken from laboratory prepared slabs of 180x100x500 mm. The results including the maximum tensile stress and corresponding failure strain at the test temperature are given in Figure 9. The temperature of + 5°C is, of course, not a "cold temperature", but it is a temperature that occurs very often and for long periods in the central part of Switzerland.
It can be seen that the PACK mixture has a slightly higher failure stress in comparison with the other mixtures tested. Considering the errors bars, the difference cannot be considered as being significant. The failure strain of the ZEO and WATER mixtures are also slightly higher than the other mixtures' values. This difference could be related to a softer binder than the other tested mixtures.

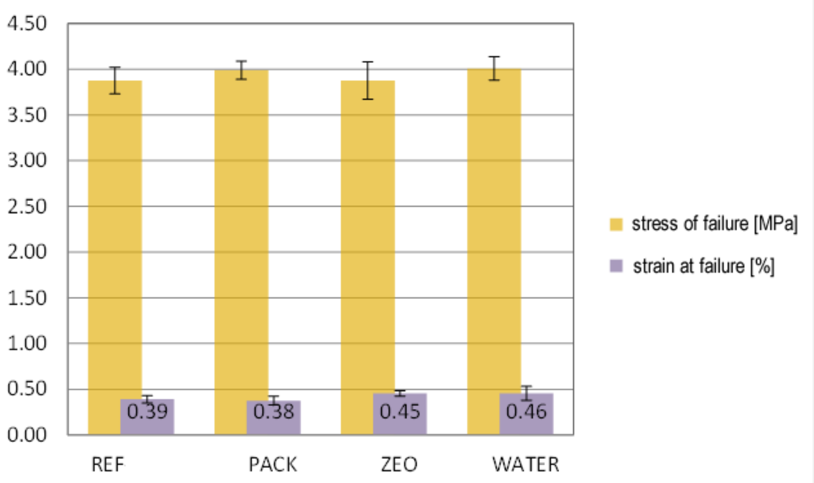

Figure 9: Uniaxial Tension UTST at + 5 °C (EN 12697-46)

5. SUMMARY

- The WMA mixtures were laid without any problems on the test site
- Compactability:
  the WMA mixtures needed clearly less energy to be compacted to the same degree than the reference HMA mixture. The mixture with a chemical additive (PACK) and the foamed mixture (WATER) showed the best results
- Bonding of the layers:
  the in situ tests were not consistent enough. A laboratory programme to assess the bonding of WAM mixtures was realised. Under laboratory conditions, the tested WAM behaved satisfactory, no significant difference were seen between the WAM mixtures, however the highest values were measured for the reference HMA.
- Water sensitivity:
  Considering the ITSR ratio and the stresses at failure of the samples, one can suspect that the WMAs tested are more sensitive than the reference HMA, particularly for the foamed mixture WATER.
- Warm temperature behaviour
  The warm temperature behaviour is highly influenced by the binder ageing which occurs during the mixing and laying processes. Due to the lower temperature of the WMA, the binder hardens less than under hot mix conditions. Therefore, the WMA cannot be directly compared with the reference hot mix.
  Of the WMAs, the chemical additive showed the best behaviour in the triaxial tests, followed by the zeolite. The foamed mixtures seem to have a higher rutting susceptibility.
- Cold temperature behaviour
  There were no deep temperature tests run; “cold temperature” was defined as + 5°C. The direct tension test UTST showed no relevant differences between the tested mixtures.

In figure 10 an attempt was made to present the summary in a graphic. In general it can be stated that the advantage of the WMA concerning the reduction of required compation-energy is clearly demonstrated. However, it seems that the WMA do not reach the same mechanical properties than a hot mix asphalt.

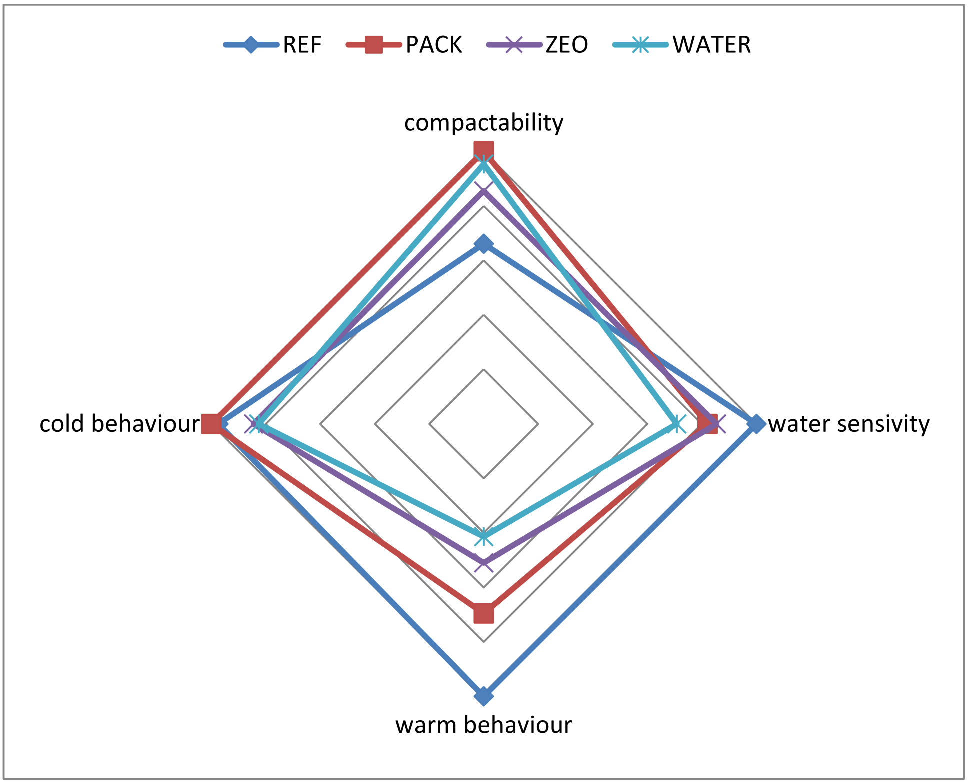

Figure 10: Summary of the comparison of the mixtures

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