Instrumentation and in-situ evaluation of warm mix asphalt test sections

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Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.163

ABSTRACT

Warm Mix Asphalt (WMA) is widely considered as a potential alternative to conventional Hot Mix Asphalt (HMA) that enables reducing the environmental impacts of the road construction phase. Thus, an ambitious project dedicated to WMA has been launched in 2011 by the Federal Roads Office (FEDRO). The PLANET (PotentieL et ANalyse des Enrobés Tièdes) project contains a specific work package dedicated to the construction, monitoring and evaluation of four different WMA test sections in addition to a reference HMA. The tested techniques involved chemical additives, the uses of zeolite as well as bitumen foaming. RAP addition has also been considered. Several in-situ testing have been conducted in order to compare the WMA techniques. To do this, the test sections have been instrumented using strain gauges and temperature sensors and two measurements campaigns performed with a control truck load. The pavement bearing capacity has also been analyzed through falling weight deflectometer (FWD) measurements. Besides, an extensive laboratory testing campaign has been conducted on the asphalt mixtures and cores taken after different periods of time in order to assess a potential evolution of some mechanical properties or characteristics. The obtained results permitted to highlight the differences between WMA techniques as well as providing good practice guideline for future applications.

Keywords: Fatigue Cracking, Stiffness, Testing, Warm Asphalt Mixture

1. INTRODUCTION

Thanks to the decreases in energy consumption and related emissions, Warm Mix Asphalt (WMA) is widely considered as a potential alternative to conventional Hot Mix Asphalt (HMA). Several processes and mixtures can be found in order to decrease the production and laying temperature. An extensive description of the processes and challenges is discussed in particular by [1, 2, 3, 4, 5].
In order to promote the uses of such asphalt mixtures in the Swiss context, some specific parameters need to be further investigated. It is especially important to provide practical experiences that will help to identify and promote best practices with such mixtures and also highlighting the potential application boundaries. Based on the abovementioned observation, an ambitious project dedicated to WMA has been launched in 2011 by the Federal Roads Office (FEDRO). This project, called PLANET (Potentiel et Analyse des Enrobés Tièdes) is divided into seven work packages (WP) that have been drafted after completion of a one year initial project [6]. Following aspects are particularly investigated within PLANET: production in plant, mechanical performances and mix design, durability, energy and emissions, and road worker health problems. Besides this, a multi-attribute decision making model will also be provided, this in order to assist the decision maker for the choice of a specific technology. The various work packages have a common central point dedicated to the construction and follow-up of test sections. This paper presents the major findings related to the *in-situ* and laboratory analysis of the test sections.

2. TEST SECTIONS

The test site, located in Bern region (central part of Switzerland), has been divided into five different tests sections of approx. 800 m^2 that have been constructed in November 2012. Each test section has an approximate length of 130 m and a total amount of 130 t warm mix asphalt laid. The traffic loading is 2'500 vehicle/day and the percentage of heavy vehicles could be estimated at around 5%. The choice of the WMA techniques has been made considering the related experience, literature data (in particular [7, 8, 9, 10, 11, 12]), availability for the Swiss market and potential performances of the product [6]. The final choice permits to compare foaming techniques (2 bitumens), the uses of zeolite as well as a well-known chemical additive (tensio-active agent). The selected WMA techniques are summarized in table 1 which contains also the production temperature in the mixing plant and the dosage of the given additives. These two parameters have been defined in accordance with the WMA supplier recommendations.

Table 1: Selected WMA asphalt techniques for the test sections

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

The asphalt pavement structure is indicated in table 2. Note that the top layer has been laid one year after the binder layer (i.e. autumn 2013), meaning that WMA has been directly "loaded" during the first year of service. The WMA is a binder layer with maximal aggregate size 16 mm and a pen 50/70 base binder.

Table 2: Pavement structure (asphalt layers)

Layer	Asphalt type	Asphalt sort (Swiss standards)	Thickness [mm]
Top	*HMA*	*AC 11 S*	*40*
Binder	WMA	AC B 16 S	65
Base	HMA	AC T 22 S	95
Foundation	HMA	AC F 22	100

Various test sections have been instrumented using strain gauges (Kyowa and ASG model) and temperature sensors (Pt100). All the sensors have been laid at the bottom of the WMA layer. However, the results obtained from ASG strain gauges will not be discussed here, since they have been only used in the project for a preliminary and feasibility study purposes. For each test site, 5 Kyowa strain gauges (Kx) have been laid and 2 temperature sensors (Tx). The positioning of the different sensors for a given test section is shown in figure 1. One can highlight that 70% of the Kyowa strain gauges were working after construction of the test sections and 68% after 9 months under traffic loading. This has been founds satisfactory considering the pavement structure, sensors positioning and loading conditions.

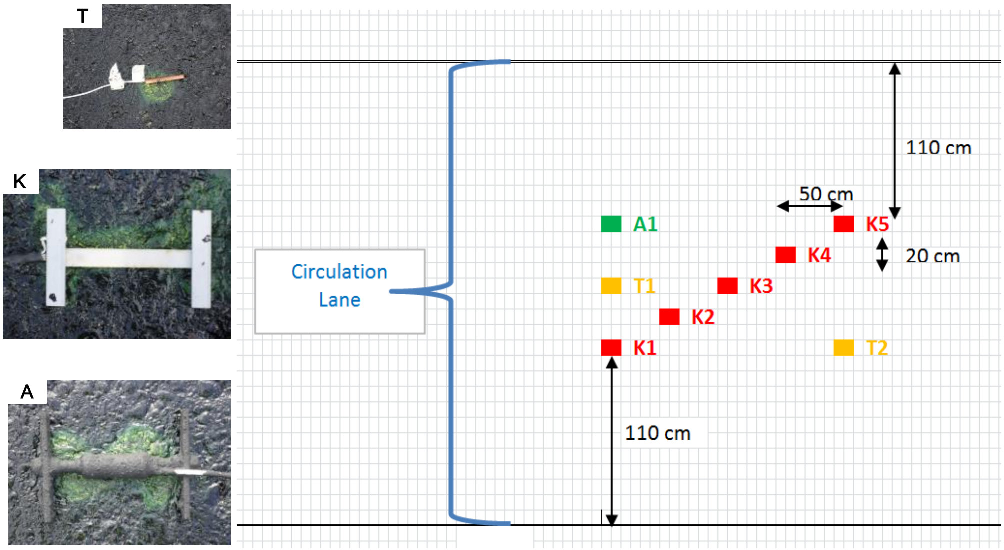

Figure 1: Schematic view of sensors location for a given test section (A=ASG strain gauge, K=Kyowa strain gauge, T=Temperature sensor)

Various tests and measurements have been performed during the laying phase such as thermography measurements, evolution of the compactions degree and air emissions measurements (plant and road workers). These will not be further detailed and the analysis will be focused on laboratory tests and in-situ strain gauges measurements.

3. LABORATORY RESULTS

Laboratory tests have been performed on the samples of asphalt mixture taken from the construction in order to investigate potential differences between the various techniques and also bring some contribution for the evaluation of the in-situ measurements.

Note that before testing the various WMA, a preliminary study has been performed in order to determine the optimal laboratory procedure for asphalt mixture conditioning (i.e. temperature choice and reheating method); the reheating temperature being highly dependent on the warm mix technique. The applied methodology is based in particular on the experience from [13, 14, 15] where WMA samples are compacted at different temperatures and then some specific characteristics (Marshall voids, gyratory compactor compactibility, binder pen and R&B) compared to a reference HMA (target values). Based on this analysis, reheating temperature of 120 °C have been set for FR-PACK and FR-ZEO mixtures and 105 °C for WATER+RAP and FR-WATER (155°C for REF-HOT). Note that these temperatures are also in accordance with the compaction temperature applied on the test site.

The grading curves of the different mixtures are represented in figure 2 which contains also the target grading curve (grey). The different mixtures are rather comparable even if a variation in the filler point can be highlighted (between 6.8% for REF-HOT and 11.6% for FR-WATER). The binder content varies between 4.50%/mix (REF-HOT) and 5.05% (FR-PACK), with a target value of 4.60%. The different measured values are in accordance with the Swiss standards (limit values).

The water content of the asphalt mixtures involving “water” (FR-ZEO, FR-WATER, WATER+RAP) is comprised between 0.09% (FR-ZEO) and 0.14% (WATER+RAP). As discussed in [1, 15], such a moisture content cannot have a significant impact on the mixture performance.

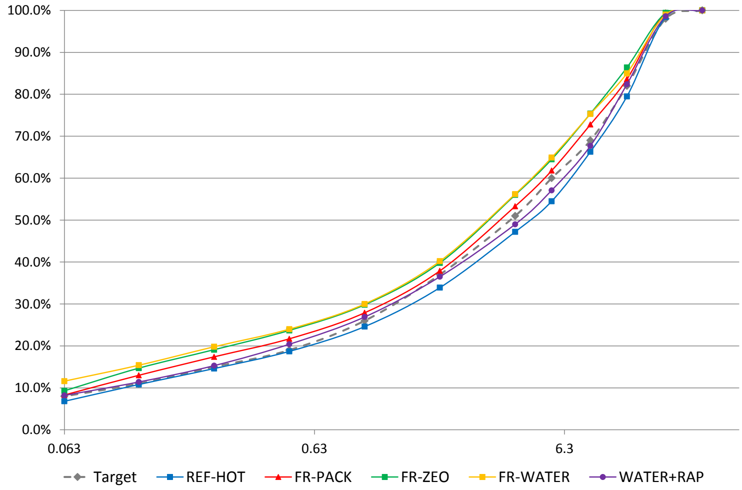

Figure 2: Grading curve of the various mixtures tested

The analysis of the recovered binders (table 3) indicates that the ageing of FR-PACK and foaming techniques with RAP is comparable to the reference HMA. However, FR-ZEO and FR-WATER have a slightly less aged binder, the bitumen penetration is slightly higher and R&B temperature lower than the reference. Viscosity measurements also indicate a lower viscosity for FR-ZEO and FR-WATER, especially in the domain 90 °C to 125 °C (46% lower than REF-HOT binder at 90 °C).

Table 3: Characteristics of recovered binders

	REF-HOT	FR-PACK	FR-ZEO	FR-WATER	FR-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
IP [-]	-0.5	-0.8	-0.8	-1.0	-0.4
Dyn. viscosity [10^{-1} Pa.s]					
90 °C	237.0	186.0	134.0	128.0	186.0
110 °C	36.0	27.2	23.2	22.4	29.6
130 °C	9.6	7.6	7.0	6.2	8.0

In addition to the identification tests discussed above, following characteristics and performances have been evaluated:

- Moisture susceptibility: Determination of water sensitivity through indirect tensile strength ITSR (EN 12697-12), on Marshall 25/25 samples.
- Rutting susceptibility: Wheel tracking tests (EN 12697-22).
- Low temperature behavior: Uniaxial tension test (EN 12697-46).
- Low, medium and high temperature behavior: Indirect tensile strength on Marshall samples (EN 12697-23).
- Stiffness: Complex modulus on trapezoidal samples (EN 12697-26).
- Fatigue testing on trapezoidal samples 2PB (EN 126997-24).

Water sensitivity results (ITSR test) are summarized in figure 3 where transparent bars correspond to dry samples (ITS_d) and the dark bars to samples with water conditioning according to the standard (ITS_w) namely at 22°C; ITSR ratio being indicated in black. Except for the FR-WATER mixture, the rest of the WMA samples meet the requirements according to Swiss standards (ITSR ratio > 70%). According to the experience, ITSR ratio below 80% could be consider as an indicator of a potential water sensitive mixture. A clear difference can also be observed in the measured stresses. In fact, stresses in WMA samples without conditioning are between 11% (FR-PACK) and 51% (WATER+RAP) lower than for the REF-HOT mixture. This measured stress difference varies between 34% (FR-PACK) and 77% (FR-WATER) for the wet samples. Considering the ITSR ratio and the stresses at samples failure, one can suspect that the WMA tested are more sensitive than the reference HMA, this especially for FR-WATER mixture.

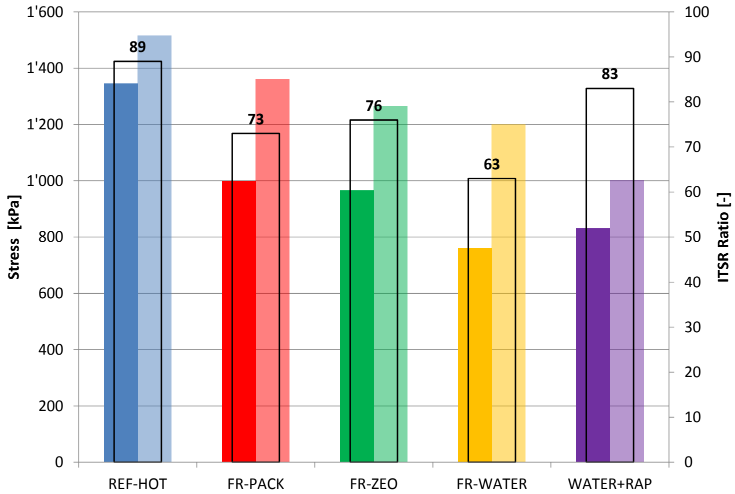

Figure 3: Water sensitivity testing (ITSR)

Wheel tracking test results have been performed on laboratory produced slabs and the results are presented in figure 4. As for previous water sensitivity testing, the reference HMA proves to have better behavior regarding rutting resistance, with a measured rut depth of 3.9% after 10'000 cycles that satisfies Swiss standard SN 640 431-1b-NA (10% after 10'000 cycles). The WMA mixture with RAP presents also a satisfactory rutting resistance (5.1%). On the other hand FR-PACK (8.1% rut depth), FR-WATER (10.0% rut depth) have a substantially higher rutting susceptibility but still in accordance with the standards. The mixture FR-ZEO has a rut depth approximately 3 times higher than the reference mixture. Note that this mixture also presents the "softer" recovered binder (table 3) which could explain the lower performance of the mixture. Note that the RAP aggregates characteristics and RAP binder can have a significant impact on the rutting resistance [16] and consequently the results of mixture WATER+RAP should be considered with precaution.

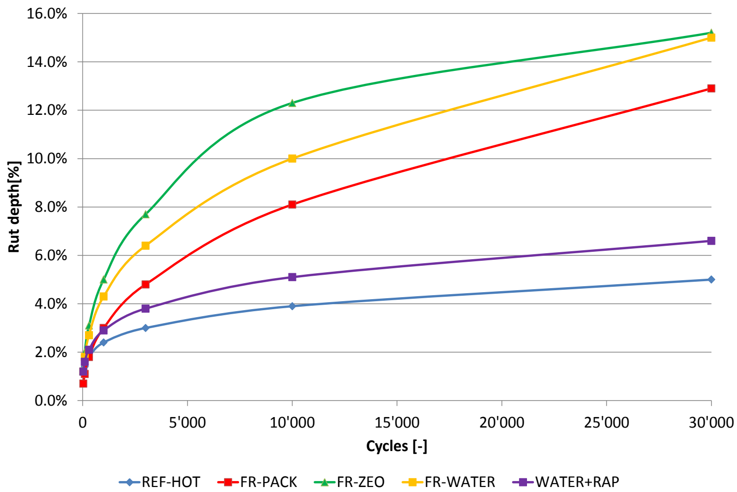

Figure 4: Wheel tracking test results (slab thickness 100 mm, test temperature 60 °C)

The low temperature behavior of the mixtures have been tested in laboratory by the mean of uniaxial tension test (uniaxial tension stress test UTST) performed at 5 °C, according to EN 12697-46. The tested samples have been taken from laboratory prepared slabs. The results are presented in figure 5 in terms of the maximum tensile stress (Spannung) and corresponding failure strain (Dehnung) at the test temperature. One can see that FR-PACK mixture has a slightly higher failure stress in comparison with the other tested mixtures. Considering the errors bars, the difference cannot be considered as significant. The failure strain of the mixture FR-ZEO and FR-WATER is also slightly higher than the other mixtures values. This could be related to a softer binder than the other tested mixtures.

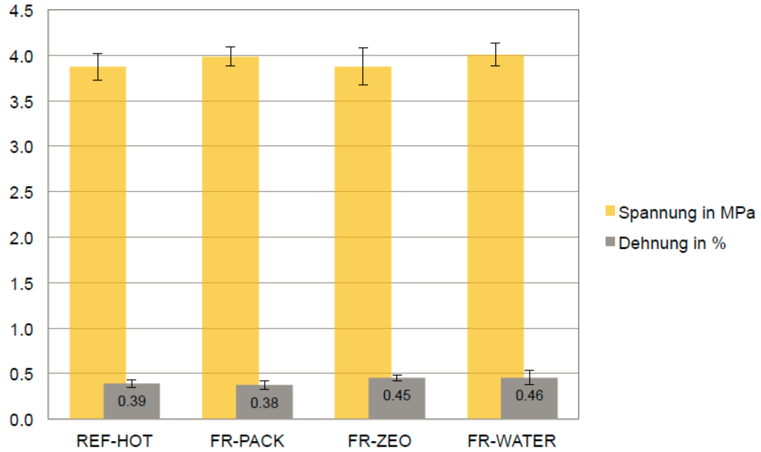

Figure 5: Uniaxial Tension Test results (5 °C)

Indirect tensile strength tests have been performed at a temperature of -10 °C, 15 °C and 40 °C on Marshall samples (50 blows on each side). Note that the various tested samples had comparable voids content. In the low temperature domain (figure 6), the asphalt mixture becomes very brittle (elastic behavior) and the aggregates play a more important role for the mechanical resistance than the binder properties (i.e. less differences between the mixtures binders). Both WMA mixtures with binder foaming appears to be slightly less resistant in low temperature domain in comparison with the other tested mixtures. Note that low temperature sensitivity is a common issue when working with a large proportion of recycling aggregates.

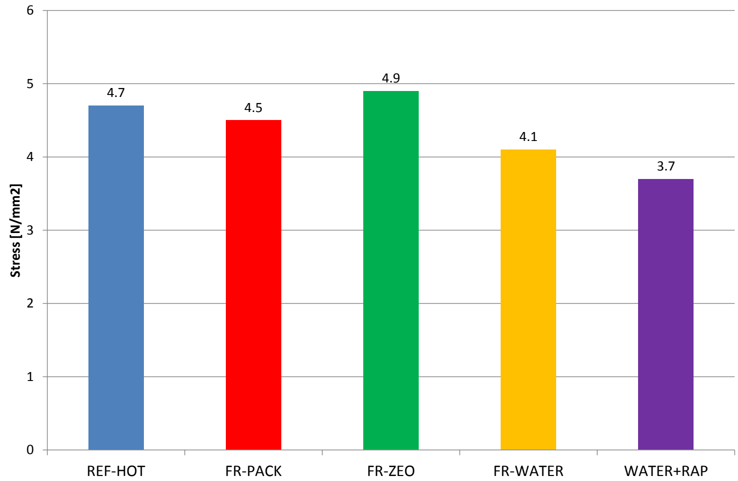

Figure 6: Indirect tensile strength (-10°C)

In the medium temperature domain (figure 7) the effect of the binder intrinsic characteristics on the mixture behavior is more significant than in low temperature domain and consequently the differences between the various WMA could be more visible. The reference hot mix asphalt presents a higher tensile strength while the tensile strength for FR-PACK and FR-ZEO are 8% lower. As for the low temperature domain, the mixtures with bitumen foaming present less resistance; the measured stress for WATER+RAP is approximately 30% lower than for REF-HOT. One can finally mention that in the high temperature domain (40 °C) the reference mix also present better performances than the tested warm mixes (figure 8). The obtained results are in line with [1, 15] that extensively investigated chemical additives, waxes and another foaming technique.

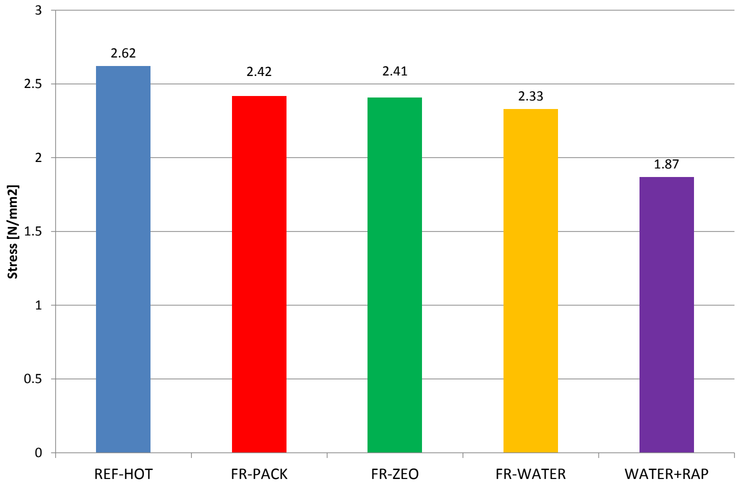

Figure 7: Indirect tensile strength (15°C)

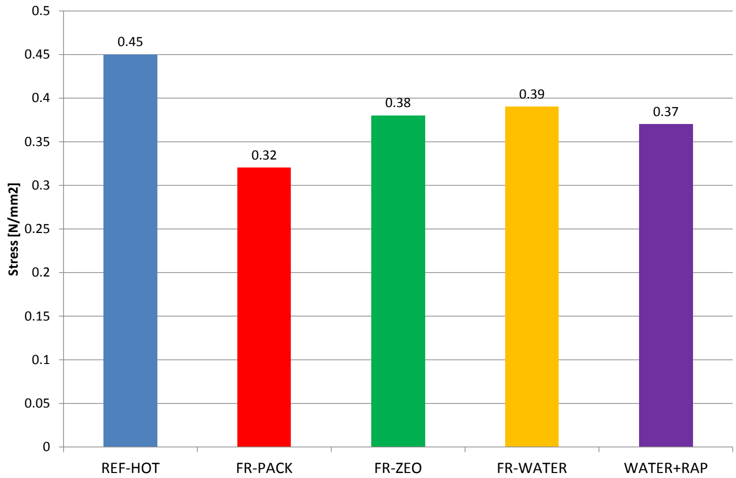

Figure 8: Indirect tensile strength (40°C)

Complex modulus and fatigue tests have been conducted on trapezoidal samples cut in the slabs extracted after one year of service. The complex modulus results are indicated in figure 9 which represents the different mastercurves (T_{ref}=15 °C, Arrhénius law). In the reference conditions (15°C, 10 Hz), FR-PACK has a comparable stiffness with the reference mixture. The modulus of FR-ZEO and WATER+RAP appears to be approximately 6% less while FR-WATER presents 13% difference with the reference HMA. Considering the fact that a value of 5'400 MPa (15°C, 10 Hz) is usually considered in a pavement design procedure (French "béton bitumineux"), the tested mixtures appears to be rather stiff.

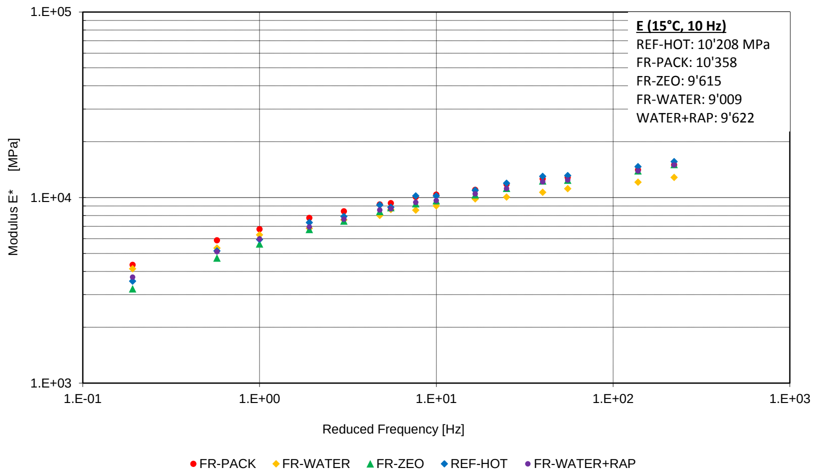

Figure 9: Complex modulus results (mastercurves, T_{ref}=15 °C)

As mentioned above, fatigue testing (15 °C) has been conducted on trapezoidal samples. The results (table 4) indicate that the warm mixes FR-PACK, FR-ZEO and FR-WATER have comparable fatigue resistance although they have quite different mastercurves. The fatigue resistance of the various WMA appears to be even better than the reference hot mix asphalt. Binder characteristics and aging have a significant influence on the fatigue resistance of the mixtures. It is also important to highlight that the WMA containing RAP proves to be more performant regarding fatigue that could be expected based on [16]. Note that the effect of RAP aggregates and binder mixing (RAP and virgin) have a substantial impact that is sometimes complex to assess.

Table 4: Fatigue testing results

	ε_6 [10^{-6}]	b [-]
REF-HOT	93	-0.201
FR-PACK	99	-0.211
FR-ZEO	99	-0.212
FR-WATER	98	-0.168
FR-WATER+RAP	118	-0.172

4. IN-SITU MEASUREMENTS

In-situ measurements related to strain gauges measurements and falling weight deflectometer (FWD) measurements are presented in this chapter

4.1 Strain gauges measurements

The results obtained from the strain gauges installed in the pavement are discussed in this chapter. Two measurement campaigns with strain gauges have been performed:

- 5 months after construction (01.03.2013), T_{WMA}=1 °C
- 9 months after construction (04.07.2013), T_{WMA}=24 °C

For each campaign, measurements have been performed on the various test sections (except FR-WATER+RAP) with a dedicated measurement truck (load 20 t.) passing at three different speeds (20 km/h, 40 km/h and 60 km/h) above the sensors. In figure 10 a measured signal has been shown for the reference mixture. In this study, the highest tensile strain (i.e. the peak with highest negative magnitude) which belongs to the heaviest truck axle have been considered in the analyses.

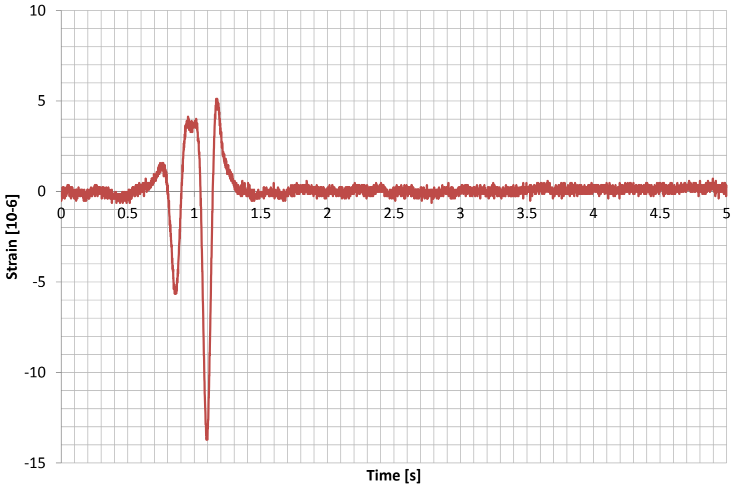

Figure 10: Signal example (04.07.2014, REF-HOT, 60 km/h, K4, traction negative)

In a first phase, the repeatability of the measurements has been assessed and the measurements have been found very stable. For each single test section, the effect of speed (*i.e.* loading frequency) and temperature have firstly been evaluated. The results for FR-ZEO test section can be found in figure 11. The temperature effect can be clearly identified with a factor 2 between strains measured at 24 °C and strains at 1 °C. One can also observe that the increasing of frequency corresponds to an increase of the layer stiffness and consequently a decrease in the recorded strains.

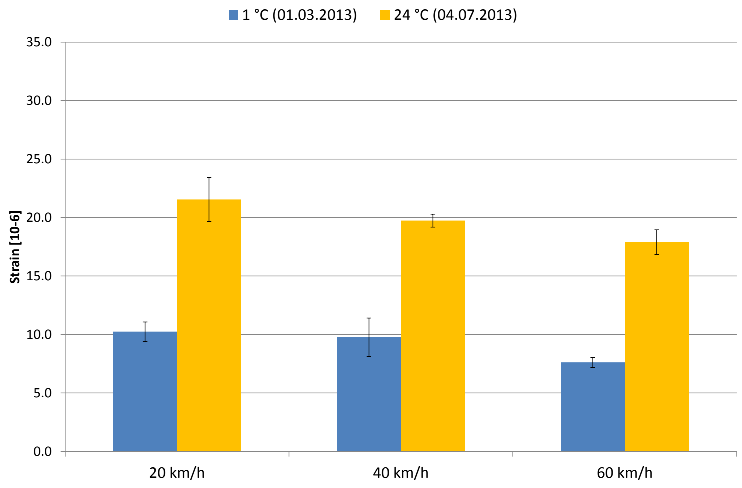

Figure 11: Effect of speed and temperature (FR-ZEO, 01.03.2013=1 °C, 04.07.2013=24 °C, traction positive)

A comparison between the different test sites is depicted in figure 12 which contains the single sensor values (K) and the average for every tested material. The analysis of the various parameters (speed, temperature) did not permit to highlight a significant difference between the mixtures. This could be explained by the fact that the only difference between the test sites is the 65 mm WMA binder layer which effect is rather limited on the global pavement structure stiffness. Besides, the measurements have been performed only a few months after construction and it could be expected that the different layer did not present any degradations at that time. Thus, some further measurements would be required.

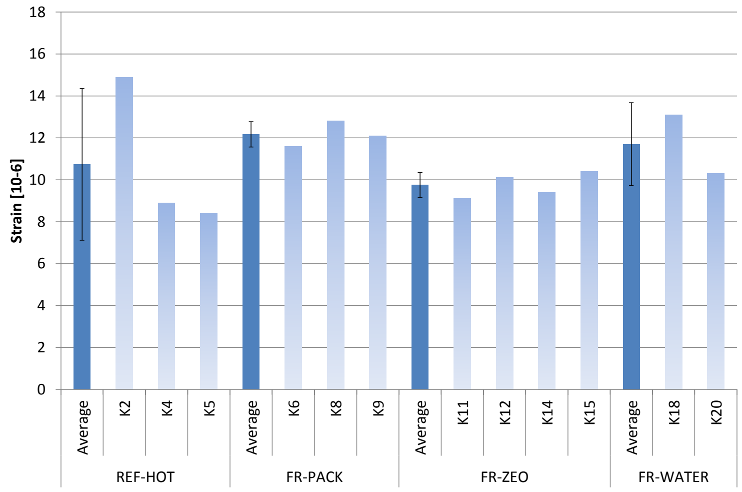

Figure 12: Comparison between different test sites (TWMA=1 °C, v=40 km/h, traction positive)

Based on the measurements performed with strain gauges, a backcalculation procedure will be further applied, this in order to calculate the stiffness of the pavement and permit some comparisons and evaluations of the pavement deterioration between the two measurements campaigns.

4.2 Falling Weight Deflectometer measurements

A measurement campaign using FWD has been performed 9 months after pavement construction (04.07.2013) with the aim of comparing the different asphalt mixtures and identifying a potential initiation of pavement degradation. For each test section, 14 (WMA sections) or 18 (FR-REF) measurements have been performed.
A backcalculation procedure has been applied in order to calculate the stiffness modulus of the asphalt and base layers. The major hypotheses that have been made for the calculation are:

- Backcalculation according to the method of equivalent thickness (MET), based on Odemark-Boussinesq equations.
- 2-layers model in which E1 [MPa] corresponds to the stiffness of the asphalt layers and E2 [MPa] to the stiffness of the unbound foundation (gravel+soil).
- Poisson ratio ν=0.35.
- Temperature in the asphalt layer during measurements of 25 °C. The calculated modulus for the asphalt layers have been corrected to the reference temperature (15 °C) using BELLS3 formula.

The results of the asphalt stiffness calculated for each single measurement station are represented in figure 13. One can observe that low stiffness values have been measured for some specific REF-HOT stations. These points correspond to measurements very close to the beginning of the test section (near the joint) and these low values can then be allocated to a difference in pavement construction (probably compaction rate). They will not be further considered in the analysis (*i.e.* non-representative).

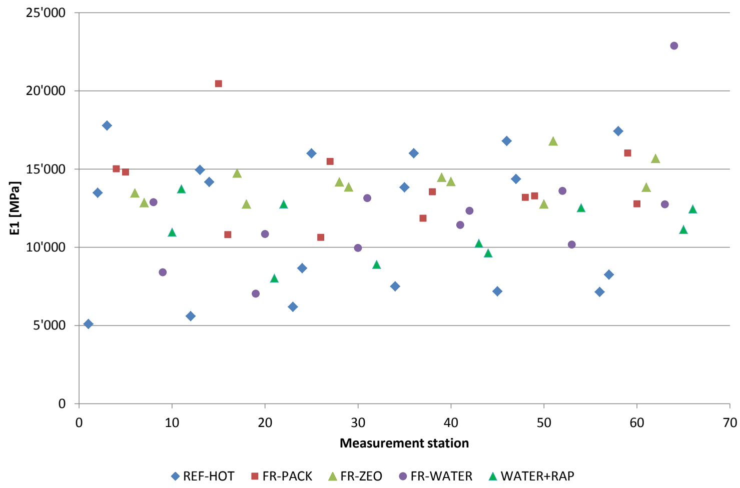

Figure 13: Stiffness of the asphalt layer E1 for each measurement station

The results of the stiffness calculation for each test section are summarized in table 5 in which the values into bracket for REF-HOT mixture correspond to the consideration of every measurement points, including the abovementioned "non-representative" points.

Table 5: Calculated stiffness values (backcalculation results)

	E1 (15 °C) [MPa]			E2 [MPa]		
	Average	Std. dev.	COV	Average	Std. dev.	COV
REF-HOT	14'309	3'070	21%	180	27	15%
	(11'690)	(4'573)	(39%)	(186)	(26)	(14%)
FR-PACK	13'992	2'675	19%	190	56	29%
FR-ZEO	14'131	1'203	9%	144	12	9%
FR-WATER	12'118	3'937	32%	175	41	24%
WATER+RAP	11'043	1'846	17%	136	21	15%

Following comments can be made:

- The stiffness moduli of the asphalt layer (E1) for the different test sections are rather comparable. However, it seems that REF-HOT, FR-PACK and FR-ZEO test sections have slightly higher asphalt stiffness while WATER+RAP test section have a lower calculated elastic modulus. Considering the standard deviations, these trends have to be carefully considered.
- The calculated asphalt stiffness values E1 are slightly higher than the values usually considered in a pavement design procedure (approximately 9'300 MPa at 15 °C). This could be expected considering the total asphalt thickness (260 mm) and the fact that the road is quite recent (9 months under traffic loading).
- The total asphalt thickness is 260 mm in which 65 mm are WMA. Thus, the effect of WMA layer on the total stiffness is rather limited.
- The average variation coefficients are in line with what can be expected with such measurements analysis (in general COV up to 30%).
- The analysis of the FWD data in terms of stiffness modulus did not highlight any pavement degradation initiation. This could be expected after only 9 months loading.
- The calculated modulus E2 (gravel+soil) are rather consistent and the standard deviation lower than for the asphalt mixtures (except FR-PACK).

An average deflection basin for the different test sections is represented in figure 13 in which one can observe that the deflections are more important for the WATER+RAP section that corresponds to the lower stiffness values calculated.

Considering that the figure below contains average basins, it is difficult to observe some differences between the other tested mixtures.

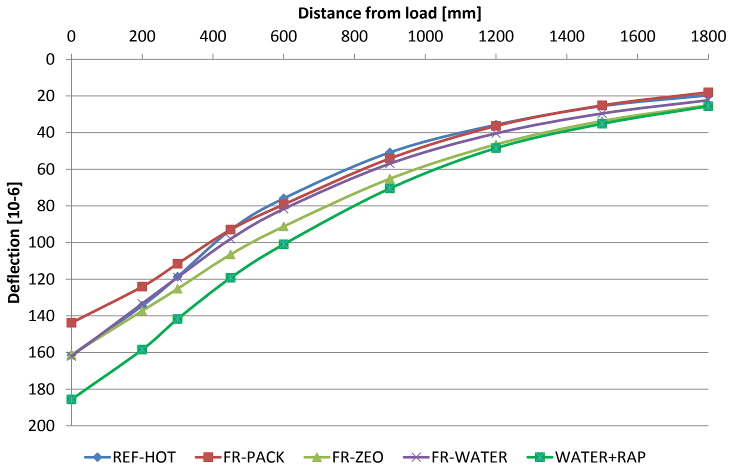

Figure 13: Average deflection basin for the tested mixtures

5. PRELIMINARY CONCLUSIONS

In the framework of the Swiss PLANET project dealing with warm mix asphalt, four different warm mix asphalt and reference hot mix asphalt have been evaluated through the construction of test sections.
The extensive laboratory tests performed highlighted some differences between the reference HMA and the WMA mixtures. For instance, the tested WMA showed significantly higher water sensitivity than the reference HMA and proved to be less performant regarding rutting resistance. Some differences between WMA techniques have also been highlighted. Moreover, fatigue tests indicated better performances for WMA than for the reference HMA and some WMA had comparable indirect tensile strength performances than the reference mixture.
The test carried on in-situ (strain gauges and FWD measurements) did not highlight some major differences between the various WMA section although the WATER+RAP obtained slightly lower stiffness values. Some additional measurements campaigns would be needed in order to observe a potential degradation process in the test sections.
One can finally mention the potential benefits related to the uses of RAP in WMA, this for instance for rutting resistance and fatigue behavior. This aspect would however need further investigations. Considering the mix design, it has to be mentioned that a similar recipe has been used for the various asphalt mixtures tested. Therefore, an optimization procedure in the mix design, for instance considering the specific WMA technique and can be considered in future studies. One can for instance recommend to slightly modifying the bitumen type (penetration grade) in function of the WMA technique, this in order to improve the rutting resistance but without affecting too much the low temperature resistance of the mixture.

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