Annex 3: Tests on cores – Phase 4

Deliverable 2.2 - Development, Assessment, and Application of Innovations for Interurban Infrastructures

Innovation 2.1 A technical report - Development of high performance underlayers with low cost materials and high percentage of re-use

Partners: BRRC and LAVOC

Phase 4: Performance assessment of cored materials from the pavements in the ALT study

Summary:

The objective of this study was to assess the evolution of densities, stiffness moduli and the water sensitivity of the asphalt concrete pavements in an ALT at LAVOC. The study concludes in following sub-tasks:

- Assess if there were any differences between the asphalt laid in the test hall at LAVOC and the asphalt samples produced in the laboratory.
- Assess any differences in terms of densities, stiffness and water sensitivity between the three different asphalt pavements laid in the test hall at LAVOC.
- Describe the evolution of the aforementioned properties during the course of the ALT.

To be able to characterize and compared the stiffness moduli measured on the cored samples efficiently, it was considered necessary to study in some detail, models that could be used to summarize the master curve of the moduli. The repeatability standard deviations of the governing parameters in these models were estimated.

The study concluded:

- The maximum densities of the test sections did not change during the ALT study. The section with 40 % RA had 20 kg/m^3 less maximum density compared to the laboratory mix with the same content of RA. The difference is probably due to the larger variability of RA compared to clean aggregate. The maximum densities for the other test sections matched the densities of the laboratory mixes.
- The bulk densities were used to calculate the air void content. In the sections with 0% and 40% RA, the air void content were approximately 2.5%, although the measurements indicated that the air void content was approximately 1% higher initially. This recorded decrease could be the result of compaction by the loading tests done, but this conclusion is contradicted by the tests done on drilled cores outside the wheel path after the ALT and low temperature tests had been finalized. These cores had the same air void content as the ones in the wheel path after the ALT. For the section with 25% RA, the air void content was approximately 5%, which is higher than what was recorded in the laboratory studies. Also for this section there is an indication that the air void content was initially higher.
- The water sensitivity as measured by the indirect tensile strength ratio, did not change during the course of the ALT. It remained close to 90% for all test sections during the accelerated tests, which is similar to the values recorded for the laboratory mixes.
- The stiffness modulus measured at four temperatures did not appear to change during the accelerated loading tests done on the test sections.
- Master curves of stiffness moduli were recorded and described by the equation: $E = \frac{E_{\max}}{\left(1 - \mathrm{Exp}(-0.5 f_r)\right)^h}$, which has only two parameters, the limiting stiffness modulus, *Emax*, and the factor *h*. The repeatability limits for these factors for a mean of three

samples were determined to be 10% and 0.16, respectively. There were no recorded change above the repeatability limits for *Emax*,or *h* during the course of the ALT study for the three test sections. The master curves for the tests sections with 0% and 40% RA were also almost identical to the master curves recorded for the laboratory mixes with the same compositions.

1.1 Collection of bore cores

Collection of bore cores was done at three occasions during ALT and low temperature test, and from different positions relative the wheel paths:

- Before the start of the ALT. Cores were collected outside the upcoming wheel paths.
- After the ALT. Cores were collected in the wheel paths.
- After the ALT and the low temperature test. Cores were collected in the wheel paths.
- After the ALT and the low temperature test. Cores were collected outside the wheel paths.

In the ALT hall there were four sections (0;1;2;3), three of them (0;1;2) had two bound layers with 3 cm of a surface layer with “AC MR8” and an underlayer of 8 cm made of EME of different compositions. The fourth section (3) consisted of a single layer of 8 cm made of EME with the same composition as in section 2. The four sections are presented in table 1 below.

	Section 0	Section 1	Section 2	Section 3
Bound layer 1 (top)	3 cm AC MR8	3 cm AC MR8	3 cm AC MR8	
Bound layer 2 (bottom)	8 cm EME, 0% RA (= mix 0)	8 cm EME, 25% RA (= mix 2)	8 cm EME, 40% RA (= mix 1)	8 cm EME, 40% RA (= mix 1)

Table 1: Description of the four test sections in the ALT study.

The designated names and positions of the cores taken from the ALT hall are presented graphically in Appendices A and B. In table 2 short forms of the designations are presented. From this table the descriptions of when, and where from, the cores were drilled out from the test sections, relative to the different phases of the test programme, is also presented.

Section and description / **Position and time**	**Section 0** 8 cm EME, 0% RA	**Section 1** 8 cm EME, 25% RA	**Section 2** 8 cm EME, 40% RA	**Section 3** 8 cm EME, 40% RA, no wearing course
Ex wheel path, prior to ALT	**C10-C18**	**C19-C27**	**C6-C9**	C1-C5
In wheel path, after ALT	**C34-C39**		**C28-C33**	
In wheel path, after ALT and low temperature treatment	**C52-C57**	**C64-C69**	**C40-C45**	
Ex wheel path, after low temperature	C58-C63	C70-C75	C46-C51	

treatment				

Table 2: Designations of the samples drilled out from the test sections.

1.1 Density and air void content.

Maximum density

The maximum densities were measured from a selection of the samples. The method used was EN 12697-5. In table 3 the maximum densities for the selected samples are presented. Before any measurements were done, the EME layers were cut clean from the wearing courses, if present.

Section and description / Position and time	Section 0 8 cm EME, 0% RA		Section 1 8 cm EME, 25% RA		Section 2 8 cm EME, 40% RA		Section 3 8 cm EME, 40% RA, no wearing course	
Ex wheel path, prior to ALT	C14 - 2434 C15 - 2432 C17 - 2432	2433	C19 - 2438 C20 - 2439 C22 - 2444	2441	C6 - 2434 C7 - 2427	2430	C5 - 2432	2432
In wheel path, after ALT	C36 - 2453 C37 - 2439 C38 - 2437	2443			C29 - 2430 C30 - 2437 C33 - 2439	2435		
In wheel path, after ALT and low temperature treatment	C52 - 2448 C53 - 2443 C56 - 2442	2444	C64 - 2441 C65 - 2437 C68 - 2445	2441	C40 - 2427 C41 - 2426 C45 - 2429	2427		
Ex wheel path, after low temperature treatment	C58 - 2436 C61 - 2437 C63 - 2441	2438	C70 - 2431 C73 - 2435 C75 - 2441	2436	C47 - 2431 C49 - 2434 C51 - 2430	2432		
Mean maximum density	2439		2439		2431			

Table 3 Maximum density according measured according to EN 12697-5 for a selected number of samples. Individual and average values are presented. All figures are in kg/m^3.

The repeatability limit *r* of the method used for measuring the maximum density is 11 kg/m^3. In general, all individual results are much closer to each other than *r*. The only sample that could be suspected to be an outlier is C36 which differ 14 and 16 kg/m^3 in comparisons with the samples C37 and C38, respectively. Statistically we should expect one of every 20 samples to differ more than *r* from in comparison with similar samples. The differences between the results for C36-38 are rather small and thus we consider the result for C37 as valid as all other measurements. As expected, there is no discernable trend in the density data with respect position and time for the different sections. For further calculations based partly on the maximum densities of the mixes we will use the average value for each mixture.

In the laboratory produced mixes (see [3]) of the Swiss material, the maximum densities for the mix with 0% RA (sample 491) and the mix with 40% RA (sample 499) were determined to be 2444 kg/m^3 and 2451 kg/m^3 respectively [3]. The difference between the value obtained for the material at the ALT facility and the laboratory prepared mix, for the 0% RA mix is 5 kg/m^3, which is less than r. However for the 40% RA mix, the difference in the results of the maximum density measurement on laboratory prepared material and the material used at the ALT facility is 20 kg/m^3. We have no explanation for this large difference, except that the repeatability limit for maximum density measurements might be larger for asphalt mixes produced with reclaimed asphalt due to the larger variability of the raw material, than for mixes produced with fresh aggregates and bitumen. In the further calculations of the air void content in the samples, we will use the maximum density measured from the samples collected at the ALT facility.

Bulk density and air void content

The bulk densities of the samples were measured according to EN 12697-6, method A. The repeatability limit, r, and reproducibility limit, R, for this method depends to some extent of the percentage of material larger than 11.2 mm. For the current mixes the limits are: r: 23 kg/m^3 (0% RA), 22 kg/m^3 (25% RA), 20 kg/m^3 (40% RA), and for R: 33 kg/m^3 (0% RA), 31 kg/m^3 (25% RA), 29 kg/m^3 (40% RA). Translating those figures into air void contents results in r ~ 1.0% and R ~ 1.3%.

The bulk densities and the air void contents for the different samples are presented in table 4 to 6. In these tables it is also indicated which test were performed on each sample. ITS is the acronym for Indirect Tensile Strength (EN 12697-23) and wet or dry stand for if the sample was treated with water prior to the test or not. Stiffness measurements were done according to EN 12697-26, method IT-CY at different temperatures in single pulse mode with 122 ms rise time and single pulse mode with 50 ms rise time, but also with sinusoidal loading, where strain was measured across the envelope of the specimen (IT-CY/E). In a few cases, indicated in the tables, stiffness was also measured with sinusoidal loading and strain measured only at the center of the specimen (IT-CY/C).

For section 0 with 0% RA in the mix, the air void content is 3.4% prior to any loading or low temperature tests, while after loading and loading plus low temperature treatment, the recorded air void content is only 2.4% both in and outside the wheel path. It is very tempting to suggest that the ALT decreased the air void content by compaction. However, it is more far fetched to suggest that the EME layer has self compacted as a result of the low temperature treatment as indicated by the lower air void content outside the wheel path after all test had been performed. This is nevertheless the only explanation we have, except the trivial explanation that there had been some mistake in the measurements, or difference in the procedure which we have not noticed. The relatively high air void content prior to any ALT is not due to the leverage of an outlier as all values are rather high compared to what were recorded later on as the test proceeded.

Section 1 with 25% RA in the mix had considerable higher air void content compared to sections 0, 2 and 3. Initially the recorded air void content was 6.9% and after ALT and the low temperature tests the value had decreased to 5.0%. Also this time the air void content was lower (5.3%) outside the wheel path after the low temperature tests compared to the initial value. The higher air void content of this section is in line with the initial compaction test done, where a higher air void content was recorded for this mix when subjected to equal compaction in a gyratory compaction device as the other mixes [2].

For section 2 and 3, with 40% RA in the mix, the air void content was initially 3.6% and after ALT and afterwards around 2%.

Position and time	Sample	Bulk density (kg/m^3)	Mean bulk density (kg/m^3)	Air void content (%)	Mean air void content (%)	Tests performed
Ex wheel path, prior to ALT	C10	2361.3	2356.0	3.2	3.4	ITS wet
	C11	2365.5		3.0		ITS wet
	C12	2342.1		4.0		ITS wet
	C13	2322.7		4.8		Stiffness
	C14	2365.1		3.0		ITS dry
	C15	2367.0		3.0		ITS dry
	C16	2380.6		2.4		Stiffness**
	C17	2345.4		3.9		ITS dry
	C18	2354.4		3.5		Stiffness
In wheel path, after ALT	C34	2371.8	2380.2	2.8	2.4	ITS wet
	C35	2387.5		2.1		ITS wet
	C36	2396.0		1.8		Stiffness & ITS dry
	C37	2366.5		3.0		Stiffness** & ITS dry
	C38	2379.0		2.5		Stiffness & ITS dry
	C39	2380.3		2.4		ITS wet
In wheel path, after ALT and low temperature treatment	C52	2383.1	2381.6	2.3	2.4	Stiffness & ITS dry
	C53	2375.3		2.6		Stiffness & ITS dry
	C54	2371.1		2.8		ITS wet
	C55	2390.4		2.0		ITS wet
	C56	2386.2		2.2		Stiffness & ITS dry
	C57	2383.6		2.3		ITS wet
Ex wheel path, after low temperature treatment	C58	2376.5	2380.9	2.6	2.4	Stiffness & ITS dry
	C59	2383.9		2.3		ITS wet
	C60	2375.6		2.6		ITS wet
	C61	2366.8		3.0		Stiffness & ITS dry
	C62	2390.1		2.0		ITS wet
	C63	2392.4		1.9		Stiffness & ITS dry

Table 4: Samples taken from section 0, with 0% RA in the mix. Bulk density, air void content and tests performed on the different samples are given. **) Stiffness modulus was also performed at the centre of core (IT-CY/C)

Position and time	Sample	Bulk density (kg/m^3)	Mean bulk density (kg/m^3)	Air void content (%)	Mean air void content (%)	Tests performed
Ex wheel path, prior to ALT	C19	**2275.9**	**2270.4**	**6.7**	**6.9**	**ITS dry**
	C20	**2251.7**		**7.7**		**ITS dry**
	C21	**2232.2**		**8.5**		**ITS wet**
	C22	**2269.8**		**6.9**		**ITS dry**
	C23	**2252.7**		**7.6**		**Stiffness**
	C24	**2327.5**		**4.6**		**Stiffness****
	C25	**2284.8**		**6.3**		**ITS wet**
	C26	**2276.4**		**6.7**		**ITS wet**
	C27	**2262.9**		**7.2**		**Stiffness**
In wheel path, after ALT and low temperature treatment	C64	**2331.1**	**2316.3**	**4.4**	**5.0**	**Stiffness & ITS dry**
	C65	**2309.2**		**5.3**		**Stiffness & ITS dry**
	C66	**2317.5**		**5.0**		**ITS wet**
	C67	**2314.9**		**5.1**		**ITS wet**
	C68	**2307.1**		**5.4**		**Stiffness & ITS dry**
	C69	**2317.9**		**5.0**		**ITS wet**
Ex wheel path, after low temperature treatment	C70	**2239.1**	**2310.5**	**8.2***	**5.3**	**Stiffness & ITS dry**
	C71	**2287.7**		**6.2**		**ITS wet**
	C72	**2300.3**		**5.7**		**Stiffness & ITS dry**
	C73	**2327.5**		**4.6**		**ITS wet**
	C74	**2316.3**		**5.0**		**Stiffness & ITS dry**
	C75	**2320.8**		**4.8**		**ITS wet**

Table 5: Samples taken from section 1, with 25% RA in the mix. Bulk density, air void content and tests performed on the different samples are given. *) The value considered as an outlier and is not included in the calculation of the mean values. **) Stiffness modulus was also performed at the centre of core (IT-CY/C)

Position and time	Sample	Bulk density (kg/m^3)	Mean bulk density (kg/m^3)	Air void content (%)	Mean air void content (%)	Tests performed
Ex wheel path, prior to ALT	C1*	**2359.3**	**2344.9**	**3.0**	**3.6**	**ITS wet**
	C2*	**2335.2**		**4.0**		**Stiffness**
	C3*	**2370.5**		**2.5**		**Stiffness****
	C4*	**2306.6**		**5.1**		**Stiffness**
	C5*	**2336.1**		**3.9**		**ITS dry**
	C6	**2357.9**		**3.0**		**ITS dry**
	C7	**2354.8**		**3.1**		**ITS dry**
	C8	**2348.1**		**3.4**		**ITS wet**
	C9	**2335.9**		**3.9**		**ITS wet**
In wheel path, after ALT	C28	**2378.7**	**2377.8**	**2.2**	**2.2**	**ITS wet**
	C29	**2355.4**		**3.1**		**Stiffness & ITS dry**
	C30	**2378.3**		**2.2**		**Stiffness** & ITS dry**
	C31	**2386.7**		**1.8**		**ITS wet**
	C32	**2372.0**		**2.4**		**ITS wet**
	C33	**2395.8**		**1.5**		**Stiffness & ITS dry**
In wheel path, after ALT and low temperature treatment	C40	**2367.5**	**2386.8**	**2.6**	**1.8**	**Stiffness & ITS dry**
	C41	**2395.1**		**1.5**		**Stiffness & ITS dry**
	C42	**2391.1**		**1.7**		**ITS wet**
	C43	**2376.8**		**2.2**		**ITS wet**
	C44	**2393.0**		**1.6**		**ITS wet**
	C45	**2397.2**		**1.4**		**Stiffness & ITS dry**
Ex wheel path, after low temperature treatment	C46	**2401.4**	**2376.1**	**1.2**	**2.3**	**ITS wet**
	C47	**2385.1**		**1.9**		**Stiffness & ITS dry**
	C48	**2364.2**		**2.8**		**ITS wet**
	C49	**2375.6**		**2.3**		**Stiffness & ITS dry**
	C50	**2361.9**		**2.9**		**ITS wet**
	C51	**2368.2**		**2.6**		**Stiffness & ITS dry**

Table 6: Samples taken from section 2 and 3, with 40% RA in the mix. Bulk density, air void content and tests performed on the different samples are given. *) Samples from section 3, i.e. without wearing course on top of the EME. **) Stiffness modulus was also performed at the centre of core (IT-CY/C)

1.1 Retained Indirect Tensile tests

The water sensitivity of the materials were tested with the retained indirect tensile test, EN 12697-12, at 25°C. The indirect tensile strengths, the air void content and the indirect tensile strength ratio are presented in tables 7-9 for the test sections 0-3.

Position and time	**Sample**	**Air void content (%)**	**Pre-treatment**	**Tensile strength (MPa)**	**ITSR (%)**
Ex wheel path, prior to ALT	C10	**3.2**	Wet	1.807	**89.7**
	C11	**3.0**	Wet	1.765	
	C12	**4.0**	Wet	1.688	
	C14	**3.0**	Dry	1.934	
	C15	**3.0**	Dry	1.946	
	C17	**3.9**	Dry	1.987	
In wheel path, after ALT	C34	**2.8**	Wet	1.695	**91.2**
	C35	**2.1**	Wet	1.876	
	C36	**1.8**	Dry	2.020	
	C37	**3.0**	Dry	1.947	
	C38	**2.5**	Dry	1.936	
	C39	**2.4**	Wet	1.810	
In wheel path, after ALT and low temperature treatment	C52	**2.3**	Dry	1.853	**88.9**
	C53	**2.6**	Dry	1.774	
	C54	**2.8**	Wet	1.612	
	C55	**2.0**	Wet	1.653	
	C56	**2.2**	Dry	1.921	
	C57	**2.3**	Wet	1.670	
Ex wheel path, after low temperature treatment	C58	**2.6**	Dry	1.997	**94.8**
	C59	**2.3**	Wet	1.902	
	C60	**2.6**	Wet	1.873	
	C61	**3.0**	Dry	1.952	
	C62	**2.0**	Wet	1.732	
	C63	**1.9**	**Dry**	**1.856**	

Table 7: Samples taken from section 0, with 0% RA in the mix. Air void content, indirect tensile strength and indirect tensile strength ratio (ITSR) are presented.

The variation of ITSR is much less than the reported repeatability limit of 15% for the method. The values are also consistent with the values obtained in phase 2 and 3 of these test [2,3]. There were no adverse affect of the water sensitivity due to the ALT or the low temperature tests done on the test section.

Position and time	Sample	Air void content (%)	Pre-treatment	Tensile strength (MPa)	ITSR (%)
Ex wheel path, prior to ALT	C19	6.7	Dry	1.458	**87.9**
	C20	7.7	Dry	1.455	
	C21	8.5	Wet	1.144	
	C22	6.9	Dry	1.503	
	C25	6.3	Wet	1.367	
	C26	6.7	Wet	1.371	
In wheel path, after ALT and low temperature treatment	C64	4.4	Dry	1.713	**92.4**
	C65	5.3	Dry	1.618	
	C66	5.0	Wet	1.517	
	C67	5.1	Wet	1.517	
	C68	5.4	Dry	1.644	
	C69	5.0	Wet	1.561	
Ex wheel path, after low temperature treatment	C70	8.2	Dry	1.349	**93.5**
	C71	6.2	Wet	1.425	
	C72	5.7	Dry	1.515	
	C73	4.6	Wet	1.723	
	C74	5.0	Dry	1.545	
	C75	**4.8**	**Wet**	**1.726**	

Table 8: Samples taken from section 1, with 25% RA in the mix. Air void content, indirect tensile strength and indirect tensile strength ratio (ITSR) are presented.

The same conclusions could be drawn for this test section as the previous one regarding ITSR and water sensitivity.

Position and time	Sample	Air void content (%)	Pre-treatment	Tensile strength (MPa)	ITSR (%)
Ex wheel path, prior to ALT	C1*	3.0	Wet	1.475	**97.4**
	C5*	3.9	Dry	1.485	
	C6	3.0	Dry	1.468	
	C7	3.1	Dry	1.440	
	C8	3.4	Wet	1.348	
	C9	3.9	Wet	1.456	
In wheel path, after ALT	C28	2.2	Wet	1.318	**87.7**
	C29	3.1	Dry	1.443	
	C30	2.2	Dry	1.578	
	C31	1.8	Wet	1.310	
	C32	2.4	Wet	1.310	
	C33	1.5	Dry	1.467	
In wheel path, after ALT and low temperature treatment	C40	2.6	Dry	1.470	**91.7**
	C41	1.5	Dry	1.469	
	C42	1.7	Wet	1.395	
	C43	2.2	Wet	1.370	
	C44	1.6	Wet	1.391	
	C45	1.4	Dry	1.596	
Ex wheel path, after low temperature treatment	C46	1.2	Wet	1.373	**90.7**
	C47	1.9	Dry	1.611	
	C48	2.8	Wet	1.468	
	C49	2.3	Dry	1.481	
	C50	2.9	Wet	1.359	
	C51	**2.6**	**Dry**	**1.541**	

Table 9: Samples taken from section 2 and 3, with 40% RA in the mix. Air void content, indirect tensile strength and indirect tensile strength ratio (ITSR) are presented. *) Sample from section 3, without wearing course.

Once again there are no evidence in the water sensitivity measurements indicating that the performance of the test sections decreased during the ALT and the low temperature tests.

2.2 Stiffness modulus IT-CY

The stiffness modulus was determined according to EN12697-26 with the IT-CY geometry as described in [3]. Two rise times were used, namely 122 ms and 50 ms. The tests were done at four temperatures: -10°C, 0°C, 15°C and 30°C.

The average stiffness modulus of three samples are presented in figures 1-3 for the four temperatures along the progression of the tests.

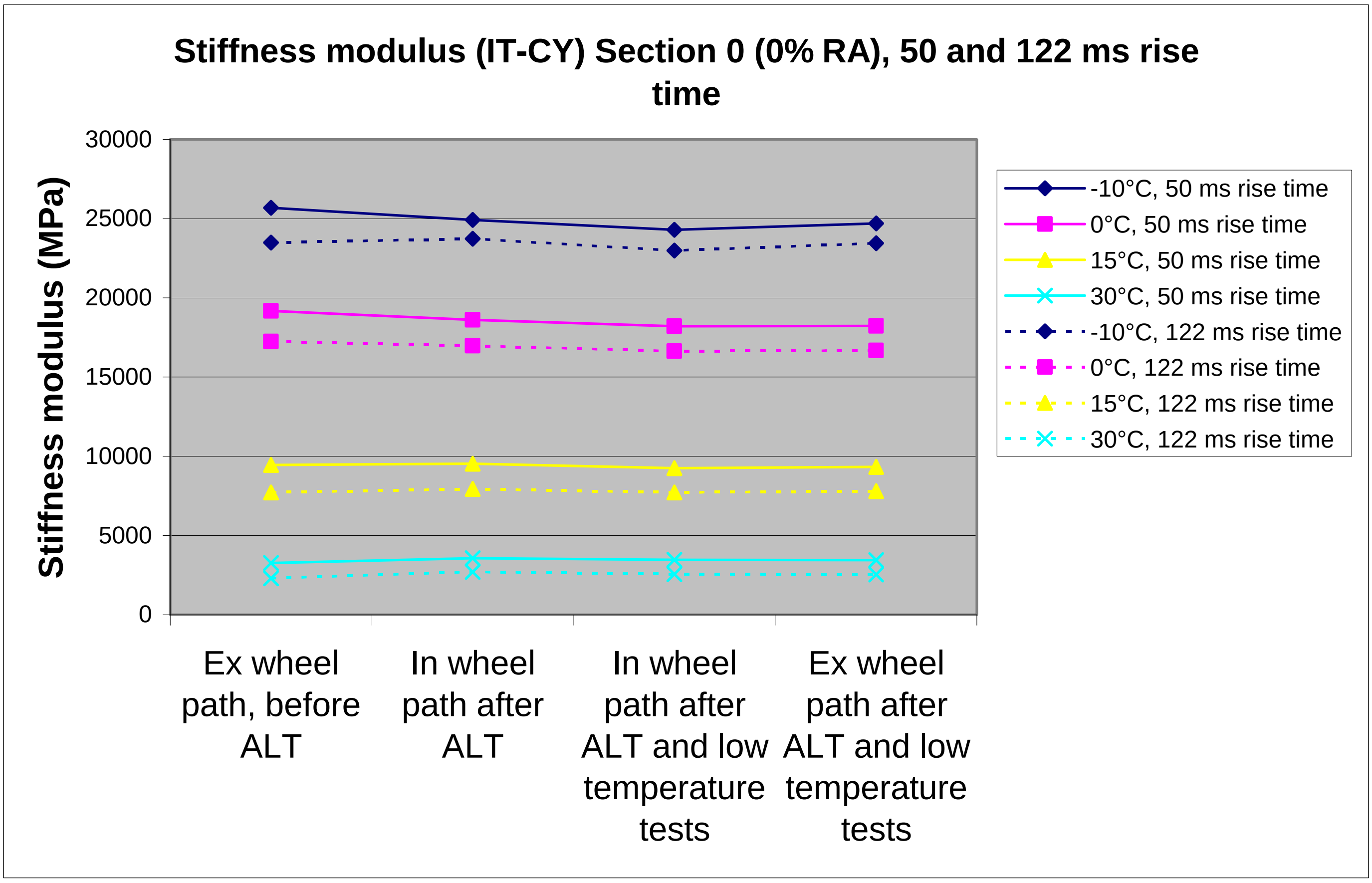


Figure 1 Stiffness modulus for samples from section 0, with 0% RA. The moduli have been recorded at four temperatures and with two different rise times of the load.

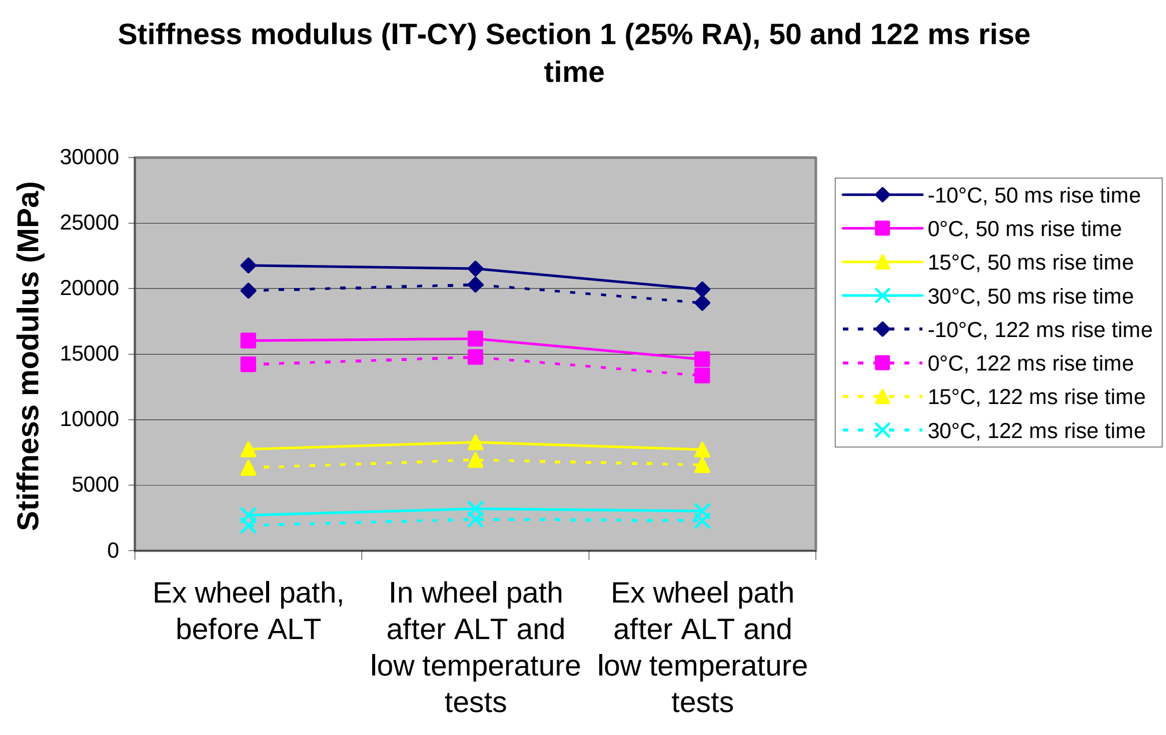


Figure 2 Stiffness modulus for samples from section 1, with 25% RA. The moduli have been recorded at four temperatures and with two different rise times of the load.

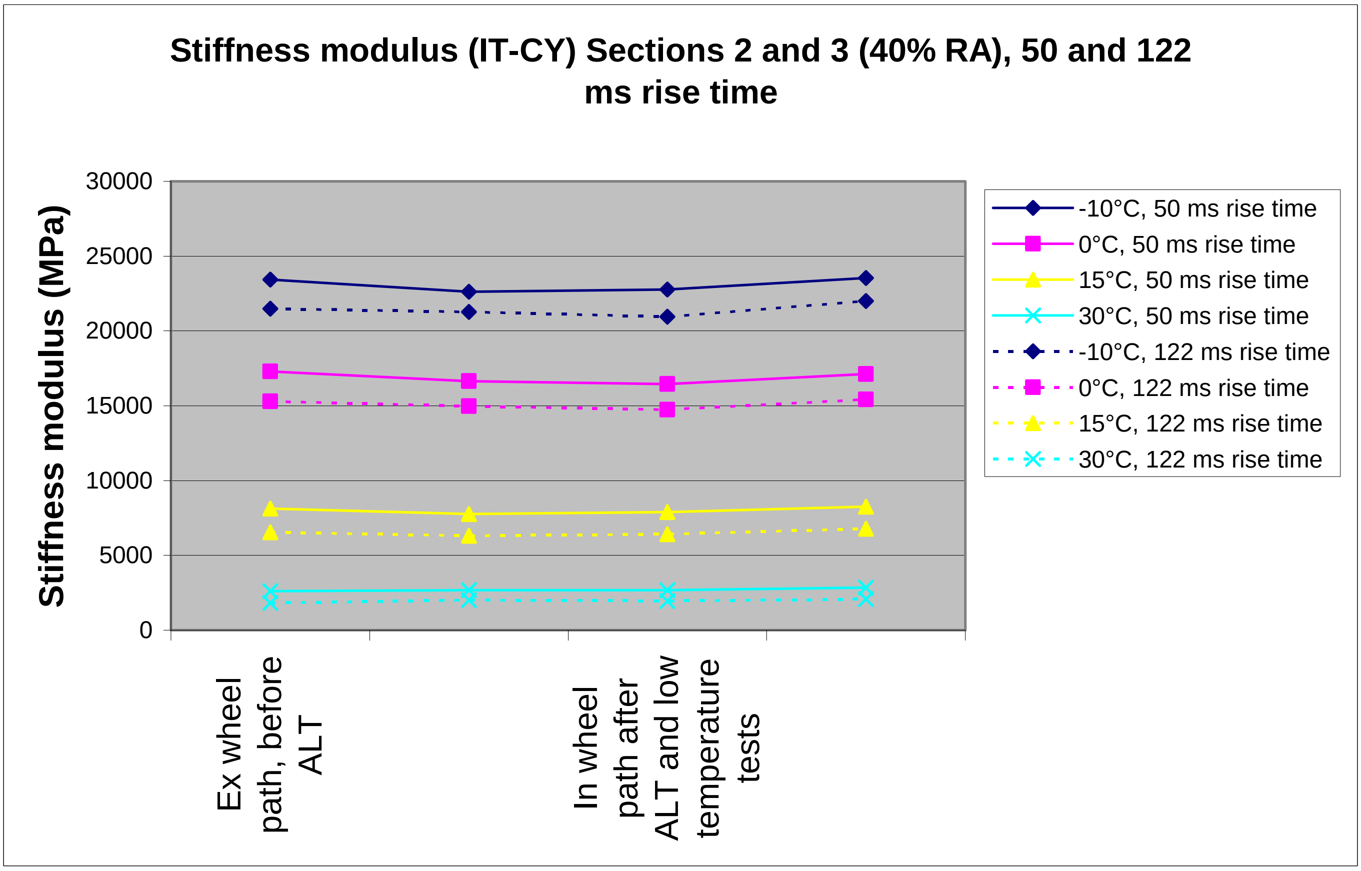


Figure 3 Stiffness moduli for samples from sections 2 and 3, with 0% RA. The moduli have been recorded at four temperatures and with two different rise times of the load.

The figures 1-3 indicates that there is little or no changes in the moduli of the material during the course of the ALT or after the low temperature tests of the test sections. The small noticeable differences in the moduli might be due to variation in the samples, for example the void content.

The stiffest section is section 0, with 0% RA. The stiffness for section 1 with 25% RA is somewhat less stiff than section 2 and 3 with 40 % RA. One reason for section 1 being a little bit less stiff than the other sections could be that the void content of this section is higher than for the other sections, but the composition of this mix is also different from the other. The air void content of section 1 is approximately 5% compared to approximately 2-2.5% for the other sections.

2.3 Stiffness modulus IT-CY master curves

In an attempt to more accurately follow the stiffness properties for the test sections, the method of master curves was used. The master curves, once appropriately summarized in an equation could be used to verify if any recorded differences are within, or exceeds, the statistical variance of the method.

The method of constructing the master curves for the IT-CY/E geometry was detailed in [2]. In this study we have focused on the stiffness modulus and have paid less attention to the phase angle. Two equations were tested to summarize the master curves for the stiffness modulus, e.g. the stiffness modulus versus the reduced frequency was nonlinearly fitted to the equations:
Firstly a quite simple model was used with only two adjustable parameters:

$$E = \frac{E_{\max}}{\left(1 - \mathrm{Exp}(-0.5 f_r)\right)^h} \qquad (1)$$

where f_r is the reduced frequency, $E_{\max}$ is the limiting stiffness and h is a shape factor dictating how fast E is approaching E_{max}.. The adjustable parameters in this model are the $E_{\max}$ and h.
The reduced frequency is calculated from an Arrhenius type of equation:

$$f_r = \frac{10920}{\left(\frac{1}{T} + \frac{1}{283}\right)} + \log(f) \qquad (2)$$

where f is the frequency and T is the absolute temperature. This model is called model r (robust) in this paper.

Equation 1 could be allowed to be more flexible by for example replacing the factor 0.5 with an adjustable parameter, or allowing the stiffness modulus approaching another limit than zero by introducing a (low) limiting stiffness modulus in the equation. However, numerous trials with these more complex equations didn't result in improved fit between the experimental data and the fitting equations as judged by the sums of squares of the residuals etc. Thus, equation r was kept as a good candidate equation to summarize the stiffness modulus over the whole temperature and frequency range with only two parameters.

Secondly a symmetric model was tested as a fitting equation to the master curves for the stiffness modulus:

$$E = \frac{E_{\max}}{\left(1 + \mathrm{Exp}[-\lambda(f_r - f_{shift})]\right)} \qquad (3)$$

This equation has three parameters E_{max}, f_{shift} and λ. This equation is symmetrical (odd) around the coordinates (f_{shift}, E_{max} /2) and λ dictates how fast the equation change from the lower to the upper limiting values. A lower λ indicates a slower transition. This model is called s (symmetric) in this paper.

All the stiffness moduli were measured with a sinusoidal load at different frequencies and temperatures. For each sample the complex modulus was recorded twice. Between the two measurements the sample was rotated 90 degrees. The two measurements are separated with an index v for one of the measurements. The master curves were constructed from the recorded data with the aid of equation 2 and the two equations r and s were nonlinearly fitted to the experimental master curves. These master curves and the fitted equations are presented in a separate appendix C (NR2C Innovation 2-1A performance assessment Phase 4 Appendix C.doc).

The results obtained from the two models r and s were compared, but as the s model didn't improve the corrected sums of squares compared to the r model, the latter one was chosen as it contains fewer parameters (data is not shown).

The bet fit parameters of model r for the samples of section 0-3 is presented in table 9-11 below.

	Sample	**Emax (MPa)**	**h**
0% RA, between tracks	**c13**	**3.14E+04**	**1.70**
(Section 0)	**c13 v**	**3.06E+04**	**1.68**
	c16	**3.42E+04**	**1.79**
	c16 v	**3.49E+04**	**1.92**
	c18	**3.16E+04**	**1.70**
	c18 v	**3.37E+04**	**1.85**
0% RA, in tracks	**c36**	**3.51E+04**	**1.71**
(Section 0)	**c36 v**	**3.30E+04**	**1.66**
	c37	**3.18E+04**	**1.72**
	c37 v	**3.16E+04**	**1.72**
	c38	**3.16E+04**	**1.70**
	c38 v	**3.26E+04**	**1.81**
0% RA, between tracks	**c58**	**3.11E+04**	**1.64**
(Section 0)	**c58 v**	**3.14E+04**	**1.73**
	c61	**3.17E+04**	**1.73**
	c61 v	**3.34E+04**	**1.79**
	c63	**3.42E+04**	**1.85**
	c63 v	**3.32E+04**	**1.83**
0% RA, in tracks	**c52**	**3.19E+04**	**1.70**
(Section 0)	**c52 v**	**3.11E+04**	**1.74**
	c53	**2.98E+04**	**1.70**
	c53 v	**2.97E+04**	**1.78**
	c56	**3.38E+04**	**1.74**
	c56 v	**3.47E+04**	**1.78**

Table 9 Best fit parameters for the master curves from samples from section 0 with 0 % RA, using the r model, equation 1.

	sample	Emax (MPa)	h
RA25% between tracks	**c23**	**2.53E+04**	**1.85**
(Section 1)	**c23 v**	**2.56E+04**	**1.87**
	c24	**2.88E+04**	**1.72**
	c24 v	**3.20E+04**	**1.88**
	c27	**2.74E+04**	**1.73**
	c27 v	**2.75E+04**	**1.82**
RA25% between tracks	**c70**	**2.35E+04**	**1.85**
(Section 1)	**c70 v**	**2.26E+04**	**1.84**
	c73	**2.72E+04**	**1.70**
	c73 v	**2.72E+04**	**1.72**
	c75	**2.79E+04**	**1.67**
	c75 v	**2.77E+04**	**1.66**
RA25% in tracks	**c64**	**2.82E+04**	**1.68**
(Section 1)	**c64 v**	**2.99E+04**	**1.78**
	c65	**2.84E+04**	**1.74**
	c65 v	**2.70E+04**	**1.72**
	c68	**2.66E+04**	**1.61**
	c68 v	**2.83E+04**	**1.74**

Table 10 Best fit parameters for the master curves from samples from section 1 with 25 % RA, using the r model, equation 1.

	Sample	Emax (MPa)	h
RA40% between tracks	**c2**	**3.01E+04**	**1.81**
(Section 3)	**c2 v**	**3.11E+04**	**1.96**
	c3	**3.26E+04**	**1.91**
	c3 v	**3.42E+04**	**2.03**
	c4	**2.69E+04**	**1.75**
	c4 v	**2.90E+04**	**1.89**
RA40% in tracks	**c29**	**2.87E+04**	**1.98**
(Section 2)	**c29 v**	**2.84E+04**	**1.91**
	c30	**3.24E+04**	**1.94**
	c30 v	**3.14E+04**	**1.92**
	c33	**3.11E+04**	**1.84**
	c33 v	**3.28E+04**	**1.95**
RA40% in tracks	**c40**	**2.88E+04**	**1.83**
(Section 2)	**c40 v**	**2.88E+04**	**1.92**
	c41	**3.14E+04**	**1.94**
	c41 v	**3.04E+04**	**1.98**
	c45	**3.09E+04**	**1.90**
	c45v	**3.08E+04**	**1.95**
RA40% between tracks	**c47**	**3.14E+04**	**1.91**
(Section 2)	**c47 v**	**3.15E+04**	**1.88**
	c49	**3.09E+04**	**1.83**
	c49 v	**3.09E+04**	**1.92**
	c51	**3.06E+04**	**1.90**
	c51 v	**3.26E+04**	**2.00**

Table 11 Best fit parameters for the master curves from samples from sections 2 and 3 with 40 % RA, using the r model, equation 1.

Combining the variances for the repeated measurements on the same sample in the tables 9-11, the estimated variance associated with the nonlinear fit, and the variance between different samples of the same test section, results in an estimation of the total standard deviation.

For a single sample the estimate standard deviation of determine E_{max} and h in model r are 1800 MPa and 0.086. For a mean value of two measurements on three different samples are calculated, the estimated standard deviation for E_{max} and h in model r are 1100 MPa and 0.058, respectively. Thus the repeatability limit, r, for determine E_{max} and h using three samples and in total six measurements are 3200 MPa, or 10%, and 0.16, respectively.

A summary of the values obtained for the master curves are presented in table 12.

	Position	**E_{max} (MPa)**	***h***
Section 0, RA 0%	Ex wheel path, prior to ALT	**3.27E+04**	**1.77**
	In wheel path, after ALT	**3.26E+04**	**1.72**
	In wheel path, after ALT and low temperature treatment	**3.18E+04**	**1.74**
	Ex wheel path, after low temperature treatment	**3.25E+04**	**1.76**
	MEAN	**3.24E+04**	**1.75**
Section 1, RA 25%	Ex wheel path, prior to ALT	**2.78E+04**	**1.72**
	In wheel path, after ALT and low temperature treatment	**2.81E+04**	**1.71**
	Ex wheel path, after low temperature treatment	**2.60E+04**	**1.74**
	MEAN	**2.73E+04**	**1.72**
Section 2 and 3, RA 40%	before ALT	**3.06E+04**	**1.89**
	In wheel path, after ALT	**3.08E+04**	**1.92**
	In wheel path, after ALT and low temperature treatment	**3.02E+04**	**1.92**
	Ex wheel path, after low temperature treatment	**3.13E+04**	**1.91**
	MEAN	**3.07E+04**	**1.91**

Table 12 Best fit of E_{max} and h in equation 1 to the master curves describing the stiffness modulus versus the reduced frequency.

From the repeatability limits of E_{max} and h and the results presented in table 12 it is now clear that we couldn't detect any change in the stiffness properties for the different sections during the ALT and low temperature tests. However, the sections differ in their stiffness properties, e.g. the section 1 has a lower limiting stiffness than the other sections and the stiffness rises more slowly for sections 2 and 3 when the reduced frequency increases than for sections 0 and 1, although the difference between the sections is almost within the repeatability limit.

Having the repeatability limits as tools for analysis of dissimilarities in the master curves, we could now turn back and look for differences between the material tested in the laboratory prior to the ALT study in LAVOC and the test sections laid at the ALT facility. For the laboratory mix 491 made of Swiss material having 0% of RA in the mix, the mean of the best fit parameters of E_{max} and h are 38600 MPa and 1.56 respectively. E_{max} for mix 491 being larger than E_{max} for sections 0 also having 0% RA in the mix. But on the same time h=1.56 is also less than 1.75 for the same type of mix. The two differences cancel each other to some extent in the range where the modulus rapidly increases and is probably not of any importance.

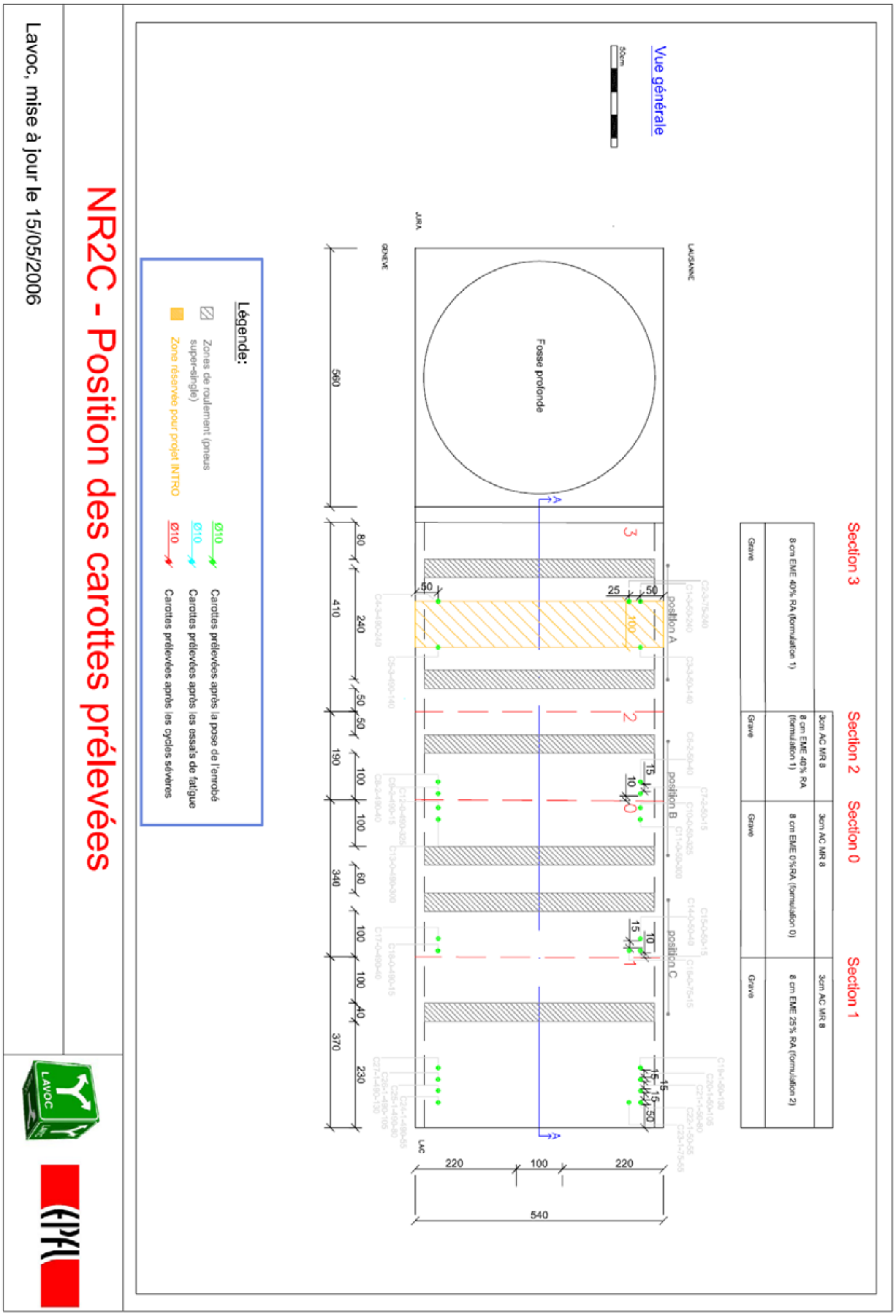
For the laboratory mix 499 which is made of Swiss material, having 40% RA in the mix, the E_{max} and h are 30900 MPa and 1.87, which is very similar to was recorded for sections 2 and 3, namely 30700 MPa and 1.91.

References:

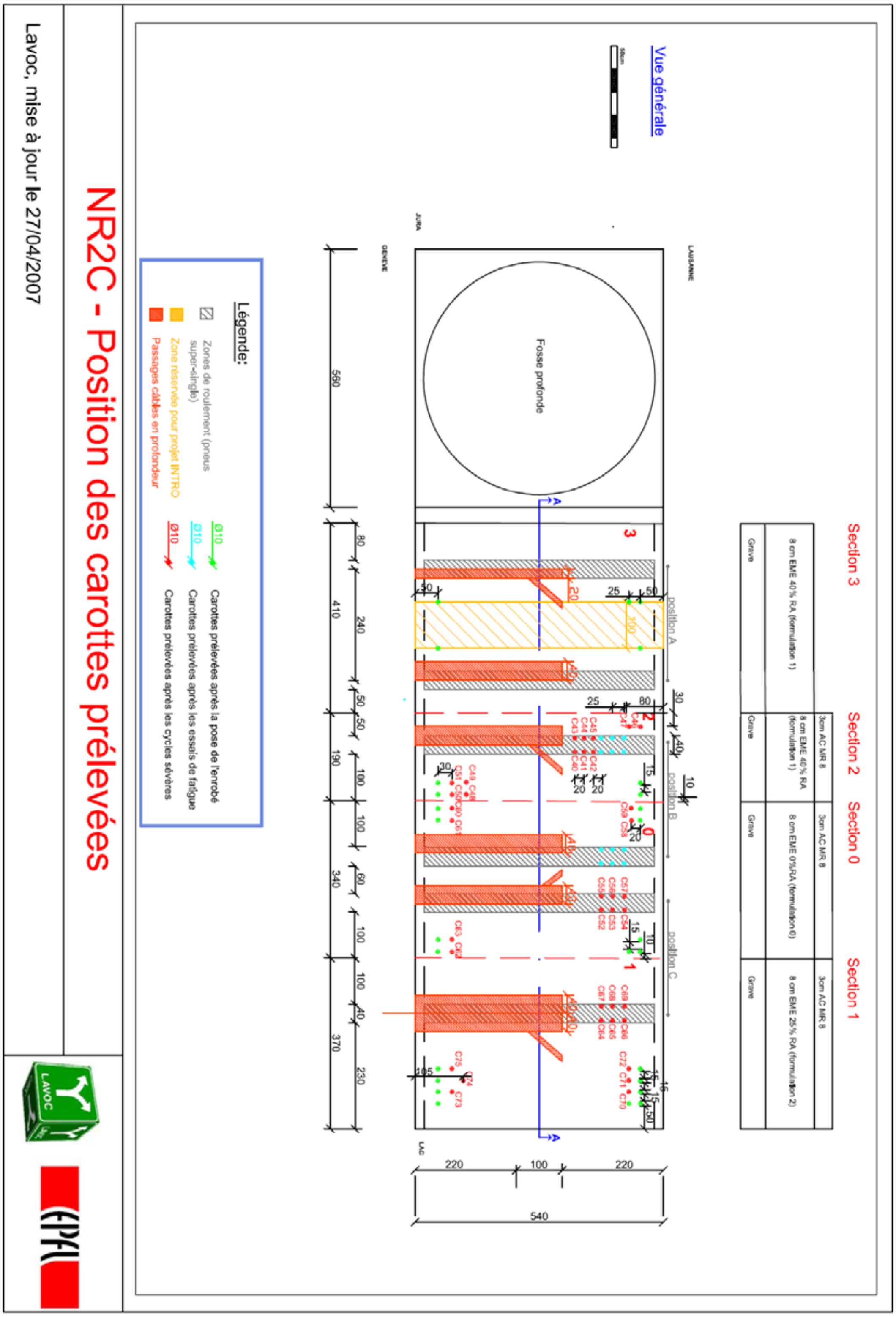
[1] Kim,R. Y.; Seo, Y.; King, M. and Momen, M., "Dynamic modulus testing of asphalt concrete in indirect tension mode" TRB 2004 Annual Meeting CD-ROM.

[2] NR2C-report "Innovation 2.1: Low cost pavement construction and maintenance techniques. Part A: Development of high performance underlayers with low cost materials and high percentages of re-use. Phase 2: Mix design and performance assessment with the Swiss materials", by J. De Visser, A. Vanelstraete & S. Vansteenkiste

[3] NR2C-report "Innovation 2.1: Low cost pavement construction and maintenance techniques. Part A: Development of high performance underlayers with low cost materials and high percentages of re-use. Phase 3: Performance assessment of cored materials from laboratory asphalt mixtures. Interlaboratory comparisons.", by B. Kalman & H. Hakim



Appendix A Position and names of drilled cores prior to the ALT



Appendix B Position and names of drilled cores after the ALT and the low temperature tests.