Annex 2: Tests on cores – Phase 3

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 3: Performance assessment of cored materials from laboratory asphalt mixtures. Interlaboratory comparisons.

Summary:

Two asphalt mixtures of high modulus asphalt, previously tested at BRRC, was tested at VTI to ensure that similar results are obtained for the same material in the two laboratories. Furthermore, pros and cons for measuring the stiffness with the indirect tension test for cylindrical samples in different modes were studied, to select a suitable method for follow-up studies of the asphalt in the ALT at LAVOC.

The tests done on the asphalt samples at VTI include:

- Bulk density according to EN 12697-6, procedure B
- Maximum density according to EN 12697-5, procedure B
- Water sensitivity according to EN 12697-12
- Stiffness according to EN 12697-26, method IT-CY at different temperatures in
  - single pulse mode with 122 ms rise time
  - single pulse mode with 50 ms rise time
  - sinusoidal loading, strain measured across the envelope of the specimen (IT-CY/E)
  - sinusoidal loading, strain measured at the center of the specimen (IT-CY/C)

The difference between the last two methods is that, in the latter, no assumption about the Poisson ratio has to be done, and secondly the strain is measured over an almost uniform stress distribution.

The comparative testing indicates:

- Bulk densities were the same for the two laboratories for one sample (499, 40% reclaimed asphalt) but differed more than the reproducibility limit for the other sample (491, 0% reclaimed asphalt) The difference is probably due to different compaction of the samples tested by VTI and BRRC
- The maximum densities determined for the two asphalt materials in the two laboratories were the same.
- The average air void content for samples of asphalt mixture 491 and 499 was 3.6% and 5.1% respectively.
- There was a small tendency for the indirect tensile strength to decrease with increasing air void content
- The attained water sensitivity for the two asphalt materials, expressed as the indirect tensile strength ratio (ITSR), were the same for the two laboratories.
- The stiffness modulus measured with the IT-CY, single pulse mode, is not directly comparable with the stiffness modulus measured with the 2PB-TR, sinusoidal loading mode. At low temperatures, the IT-CY test protocol yields higher stiffness moduli than the 2PB-TR test protocol and vice versa at high temperatures, possibly due to the assumption in IT-CY method of temperature independent Poisson ratio.
- The complex modulus measured with the IT-CY/E, sinusoidal loading, and complex modulus measured with the 2PB-TR, sinusoidal loading, did not give identical results.

- The IT-CY/E method for measuring the complex modulus is a preferred method (compared to IT-CY/C) for follow-up studies of asphalt in the ALT, due to its simplicity.

Introduction:

The objective of this study was to compare or attune the tests between two laboratories. The comparisons are necessary to ensure that similar results are obtained for the same material in the laboratories of BRRC and VTI. This is a prerequisite for making an assessment of the evolution of the mechanical properties of the material in the accelerated loading tests, since the original data were collected at BRRC and the drilled cores will be tested at VTI.

Ten samples of drilled specimens of materials 491 and 499 were sent to VTI. Both materials were made of Swiss aggregate and had 0% and 40% reclaimed asphalt, respectively. The compositions were the same as later used for two sections in the ALT hall. The samples were numbered from A1 to A5 and B1 to B5. The top and bottom of these specimens were cut with a saw. The heights of the samples after the treatment were 44-48 mm. Six of the samples were used for retained indirect tensile tests according to EN 12697-12. Three samples were used for stiffness modulus test at different temperatures according to EN 12697-26 with the IT-CY test geometry. The latter three samples were also used to measure the complex modulus according to the method developed in [1]. The bulk densities were determined according to EN 12697-6 for all tested samples. The maximum densities of the asphalt mix were determined for three of the samples. The void content for each sample was determined from the average maximum density of the material and the particular bulk density of the sample.

1.1 Retained Indirect Tensile tests – water sensitivity an densities

The water sensitivity of the mixes was determined by measuring the Indirect Tensile Strength (ITS) before and after conditioning in water (72h at 40°C) according to EN 12697-12. The assessment of the moisture damage is made by the ratio of the conditioned to unconditioned strength (ITSR). The procedure of the ITS test is given in EN 12697-23. The cylindrical test specimens were obtained following slab compaction of the mixes. All tests were performed at 25°C.

A typical result from the Indirect Tensile Test is presented in Figure 1.

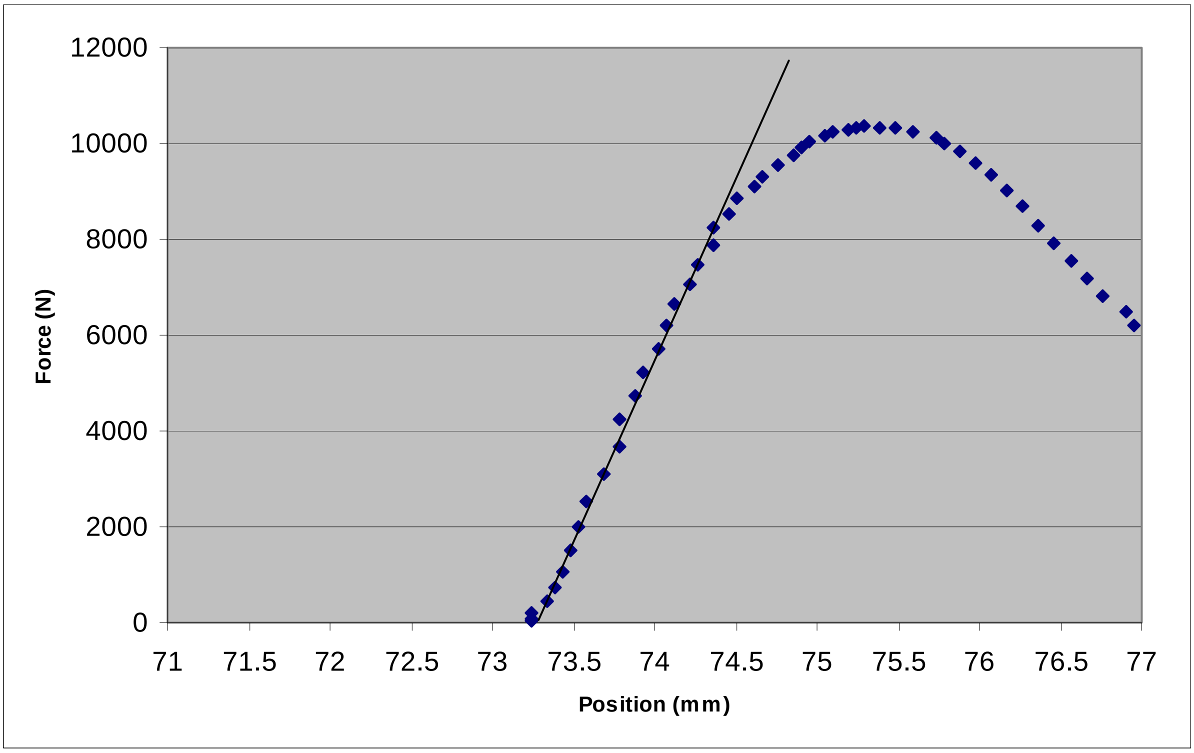

Figure 1: Tensile test for sample 499–B5. Maximum force was 10380 N and the deformation was 2.0 mm.

In Table 1 and 2, the results are shown from indirect tensile tests performed on dry and conditioned samples of asphalt mixtures 491 and 499 respectively. Furthermore these tables present also the dimensions, the densities and the void content of respective samples.

Sample	Condition	Diameter (mm)	Height (mm)	Bulk density (kg/m3)	Maximum density (kg/m3)	Air voids (%)	Peak load (N)	Deformation (mm)	ITS (MPa)
491A-4	Dry	99.9	47.5	2352.0	2450.6	3.8	15775	1.7	2.116
491A-5	Dry	99.9	47.6	2335.3	2448.4	4.4	14783	1.8	1.979
491B-1	Dry	99.9	47.4	2379.7	2432.6	2.6	16271	2.0	2.188
Mean	Dry	99.9	47.5	2355.7	2443.9	3.6	15610	1.8	2.09
491A-1	Wet	99.9	47.5	2334.1		4.5	13610	2.2	1.826
491A-2	Wet	99.9	47.5	2362.6		3.3	17566	1.8	2.357
491B-5	Wet	100.0	47.5	2371.6		3.0	17832	1.8	2.390
Mean	Wet	99.9	47.5	2356.1	2443.9	3.6	16336	2.0	2.19

Table 1: Dimensions, densities, void content and tensile strength of asphalt mixture 491.

Sample	Condition	Diameter (mm)	Height (mm)	Bulk density (kg/m3)	Maximum density (kg/m3)	Air voids (%)	Peak load (N)	Deformation (mm)	ITS (MPa)
499A-5	Dry	100.0	44.4	2301.6	2447.8	6.1	8553	2.4	1.226

499B-1	Dry	99.9	44.4	2326.0	2451.6	5.1	9569	2.2	1.373
499B-5	Dry	99.9	44.4	2345.8	2453.4	4.3	10380	2.0	1.490
Mean	Dry	99.9	44.4	2324.5	2450.9	5.2	9501	2.2	1.36
499A-4	Wet	100.0	44.5	2291.3		6.5	8734	2.1	1.250
499B-2	Wet	100.0	44.4	2347.6		4.2	11602	1.9	1.663
499B-3	Wet	99.9	44.1	2336.8		4.7	10985	2.0	1.587
Mean	Wet	100.0	44.3	2325.2	2443.9	5.1	10440	2.0	1.50

Table 2: Dimensions, densities, void content and tensile strength of asphalt mixture 499.

More than 90% of aggregates were covered with bitumen after failure for both materials. The retained indirect tensile strength ratios (ITSR) were 105% and 110% for asphalt mixtures 491 and 499 respectively. These values are, considering the reproducibility of the method (R=23%), not different from what was previously determined at BRRC, namely 92% and 94% for mixtures 491 and 499 respectively [2]

The average bulk densities for asphalt mixture 491 and 499 were 2356 kg/m^3 and 2325 kg/m^3, In [2] the average densities for samples of the same asphalt mixtures were determined to be 2429 and 2338 kg/m^3. The reproducibility limit for bulk density is approximately 22 kg/m^3. The difference between the measured bulk densities for 491 is unclear, but is probably due to difference in compaction of the samples tested by VTI and samples tested at BRRC.

The average maximum densities measured at VTI for asphalt mixture 491 and 499 were 2444 kg/m^3 and 2451 kg/m^3. In [2] the calculated densities for 491 and 499 were determined to be 2462 and 2458 kg/m^3. The reproducibility limit for bulk density according to EN 12697-5 is approximately 22 kg/m^3. Thus the differences noted between the laboratories are within the reproducibility limit.

From the data it is obvious that there is a tendency that the ITS decreases with increasing air void content. In figure 2 ITS is plotted against the air void content to illustrate this tendency.

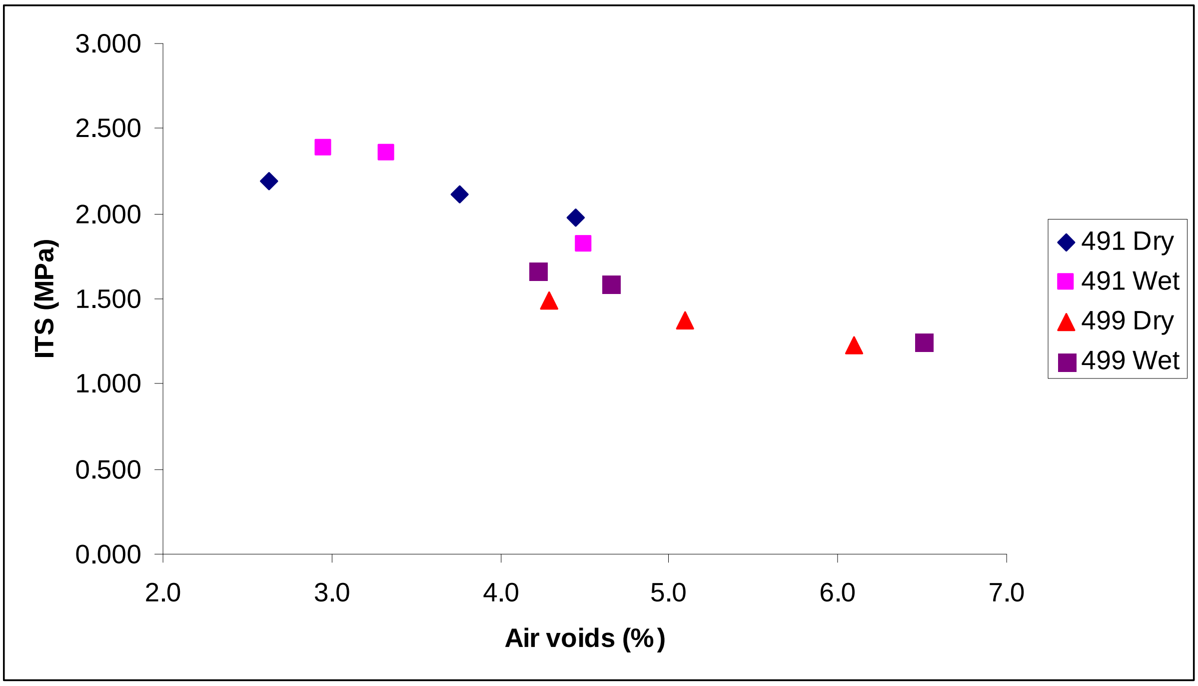

Figure 2: Indirect tensile strength versus air void content for asphalt mixtures 491 and 499.

1.2 Stiffness modulus IT-CY

The stiffness modulus was determined according to EN12697-26 with the IT-CY geometry, which is one of the alternative geometries specified in the standard. Previously the two point bending geometry was used in BRRC to determine the stiffness modulus [2]. Here, the test was performed at -10, 0, 15 and 30 °C. The haversine pulse rise time was 122 ms, which is according to the standard. Additional to this, the tests were also conducted with a shorter rise of 50 ms. The results are presented in tables 3 and 4 as well as in figures 3 and 4.

Sample	Diameter (mm)	Height (mm)	Bulk density (kg/m3)	Air voids (%)	E @ -10°C (MPa)	E @ 0°C (MPa)	E @ 15°C (MPa)	E @ 30°C (MPa)
491A-3	99.9	47.3	2372.6	2.9	29003	21377	10814	3484
491B-3	99.9	47.5	2376.9	2.7	29315	21654	10742	3843
491B-4	99.9	47.4	2372.0	2.9	28880	21868	10738	3669
Mean	99.9	47.4	2373.8	2.9	29066	21633	10765	3666
499A-1	100.0	44.5	2248.1	8.3	20494	14434	6229	1806
499A-2	100.0	44.5	2262.5	7.7	20528	14523	6147	1753
499B-4	99.9	44.3	2351.3	4.1	23558	16988	7583	2261
Mean	100.0	44.4	2287.3	6.7	21527	15315	6653	1940

Table 3: Stiffness modulus at four temperatures for asphalt mixtures 491 and 499. IT-CY mode with 122 ms rise time and 2.75 s rest time.

Sample	Diameter (mm)	Height (mm)	Bulk density (kg/m3)	Air voids (%)	E @ -10°C (MPa)	E @ 0°C (MPa)	E @ 15°C (MPa)	E @ 30°C (MPa)
491A-3	99.9	47.3	2372.6	2.9	30833	23587	12976	4841
491B-3	99.9	47.5	2376.9	2.7	30576	23681	12958	5206
491B-4	99.9	47.4	2372.0	2.9	30901	24119	12891	5098
Mean	99.9	47.4	2373.8	2.9	30770	23796	12941	5048
499A-1	100.0	44.5	2248.1	8.3	21985	16398	7794	2582
499A-2	100.0	44.5	2262.5	7.7	22267	16257	7677	2534
499B-4	99.9	44.3	2351.3	4.1	25597	19199	9372	3230
Mean	100.0	44.4	2287.3	6.7	23283	17285	8281	2782

Table 4: Stiffness modulus at four temperatures for asphalt mixtures 491 and 499. IT-CY mode with 50 ms rise time and 2.9 s rest time.

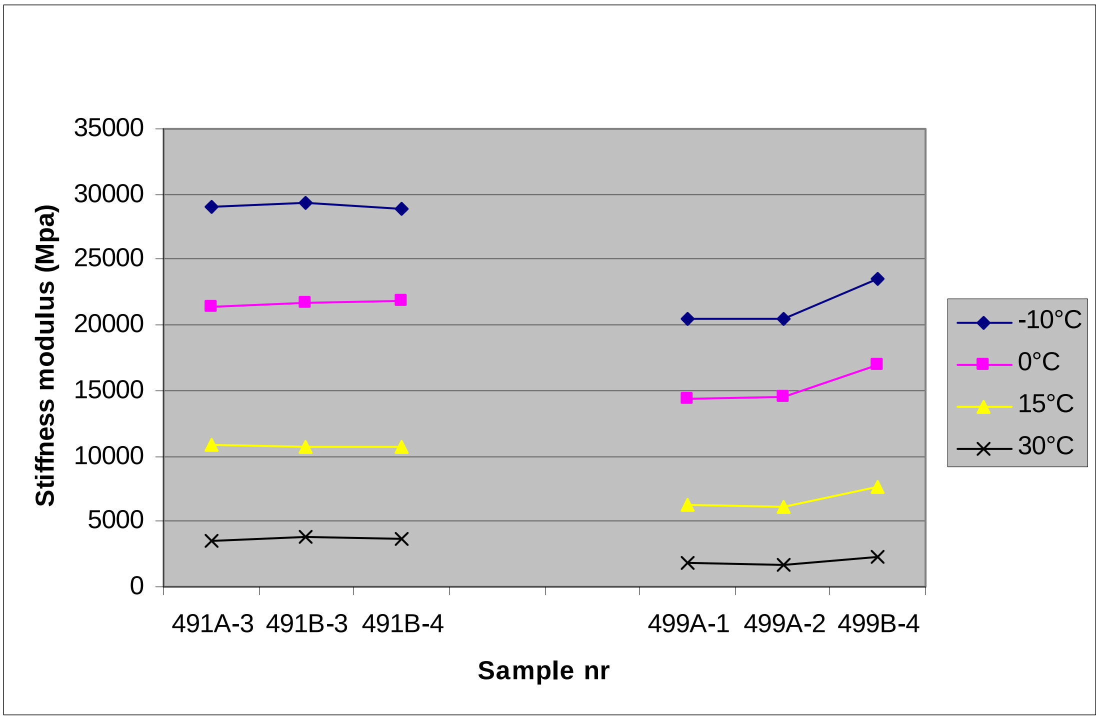

Figure 3: Stiffness modulus at four temperatures for asphalt mixtures 491 and 499. IT-CY mode with 122 ms rise time and 2.75 s rest time.

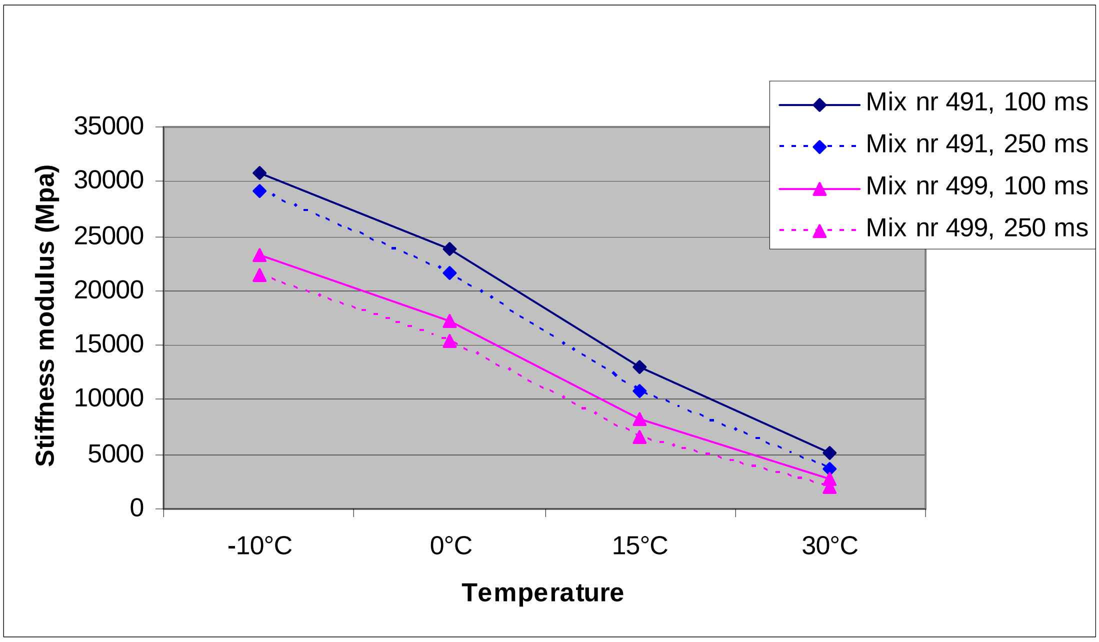

Figure 4: Average stiffness modulus, IT-CY mode, at four temperatures for asphalt mixtures 491 and 499. The stiffness moduli were measured with both 122 ms rise time plus 2.75 ms rest time and with 50 ms rise time plus 2.90 ms rest time.

The lower air void content of sample 499B-4 compared to the other two samples of 499, is causing the higher stiffness of this sample compared to the other two samples. The overall higher air void content of sample 499 compared to sample 491 could probably explain the lower stiffness modulus for this material to some extent, although their differences in compositions are responsible for the main part of the difference in stiffness modulus.

Assuming that a 122 ms rise time approximately correspond to 1/0.244 Hz ~ 4 Hz and 50 ms rise time approximately correspond to 1/0.1 Hz ~ 10 Hz the measured stiffness modules could be compared to what was previously recorded using 2PB-TR measurement method at 3 Hz and 10 Hz [2]. The average stiffness moduli measured with the two methods are compared side by side in table 5.

Asphalt mixture	T/°C	Method	Frequency or rise time	Average stiffness modulus/ MPa
491	-10	IT-CY (VTI)	122 ms	29 066
491	-10	2PB-TP (BRRC)	3 Hz	22 450
491	-10	IT-CY (VTI)	50 ms	30 770
491	-10	2PB-TP (BRRC)	10 Hz	23 550
491	0	IT-CY (VTI)	122 ms	21 633
491	0	2PB-TP (BRRC)	3 Hz	19 030
491	0	IT-CY (VTI)	50 ms	23 796
491	0	2PB-TP (BRRC)	10 Hz	20 580
491	30	IT-CY (VTI)	122 ms	3 666
491	30	2PB-TP (BRRC)	3 Hz	4 130
491	30	IT-CY (VTI)	50 ms	5 048
491	30	2PB-TP (BRRC)	10 Hz	5 490
499	-10	IT-CY (VTI)	122 ms	21 527
499	-10	2PB-TP (BRRC)	3 Hz	18 970
499	-10	IT-CY (VTI)	50 ms	23 283
499	-10	2PB-TP (BRRC)	10 Hz	20 010
499	0	IT-CY (VTI)	122 ms	15 315
499	0	2PB-TP (BRRC)	3 Hz	15 350
499	0	IT-CY (VTI)	50 ms	17 285
499	0	2PB-TP (BRRC)	10 Hz	16 590
499	30	IT-CY (VTI)	122 ms	1 940
499	30	2PB-TP (BRRC)	3 Hz	2 790
499	30	IT-CY (VTI)	50 ms	2 782
499	30	2PB-TP (BRRC)	10 Hz	3 880

Table 5 Stiffness modulus measured with IT-CY test protocol (single pulse mode) compared to stiffness modulus measured with 2PB-TP test protocol (sinusoidal loading)

According EN 12697-26 the reproducibility limit using the 2PB-TR for AC10 at 15°C and 10 Hz is 6%. In table 5, we can see that the two test protocols yield nearly the same stiffness modulus at 0°C, but the IT-CY protocol gives considerably higher stiffness moduli than the 2PB-TR protocol at lower temperatures and vice versa at higher temperatures. This is to a large extent due to the assumption in the IT-CY protocol, that the Poisson ratio is equal to 0.35, regardless of the temperature.

1.3 Stiffness modulus IT-CY master curves

A more complete picture of how the stiffness modulus varies with the temperature and frequency could be summarized in master curves where the modulus and phase angle is plotted as a function of the reduced frequency. The standard EN12697-26 for stiffness modulus does not specify a procedure for this with the indirect tensile test geometry. In this task we have used two methods for measuring the complex modulus with the IT-CY geometry.

1. The first method employs the same setup of measuring devices as is defined in EN12697-26. In this report we call this **IT-CY/E**, as the strain gauges is measuring the strain across the envelope of the specimen. At each temperature, -10, 0, 15 and 30°C in our case, a sinusoidal load is applied to the specimen. The load and deformation versus time is recorded. It has to be mentioned that only the last 8 cycles for each frequency tested, are used for further analysis. In this study we have used the frequencies 20,10,5, 2, 1, 0.5, 0.2 and 0.1 Hz. The last 8 cycles of load and deformation data is then vertically centered and a Fourier analysis is done on the data to give the complex modulus and phase angle between the stress and the strain. The modulus and phase angle is booked for a reduced frequency defined by the following equation:

   $$f_r = \mathrm{Log}(aT \times F) = 10920(1/T - 1/Ts) + \mathrm{Log}(F); \qquad (1)$$

   in which Ts is 283 K, T is the absolute temperature (K) and F is the frequency of the sinusoidal load.
   This test procedure is easy to perform and is suitable for routine analysis. In the analysis of the data it was noticed that the noise in the data was sometimes too high at the highest frequencies. This is probably due to the appearance of a resonance. But further analysis is needed to investigate this phenomenon.

2. A more rigorous method where the biaxial symmetry of the IT-CY setup has been taken into account has been developed by Kim et al [1]. In their method the strain gauges are mounted on the surface at the center of the cylindrical specimen to measure the strain over an almost uniform stress distribution. We call this set-up **IT-CY/C** in this report. A setup of the strain gauges is shown in figure 5.

Figure 5: Mounting of strain gauges for measuring the complex modulus according to Kim et al [1].

Using this more rigorous approach, not only the modulus and phase angle could be determined but also the Poisson ratio, which is fixed to 0.35 in the first method described. However, there seems to be some limitations on this method and the theory as it was reported in [1]. It was noticed that the Poisson ratio at very low frequencies and high temperatures could reach values above the linear elastic limit of 0.5. In our study, we also have found values above 0.5. The initial data treatment, the temperatures and frequencies have been the same as for the more simple method described above. Only a very limited number of samples have been analysed with the latter method.

In figures 6 A and B, 7 A and B the complex modulus and phase angles of asphalt mixtures 491 and 499 are presented. These data have been collected with the first method described above, the IT-CY/E test protocol.

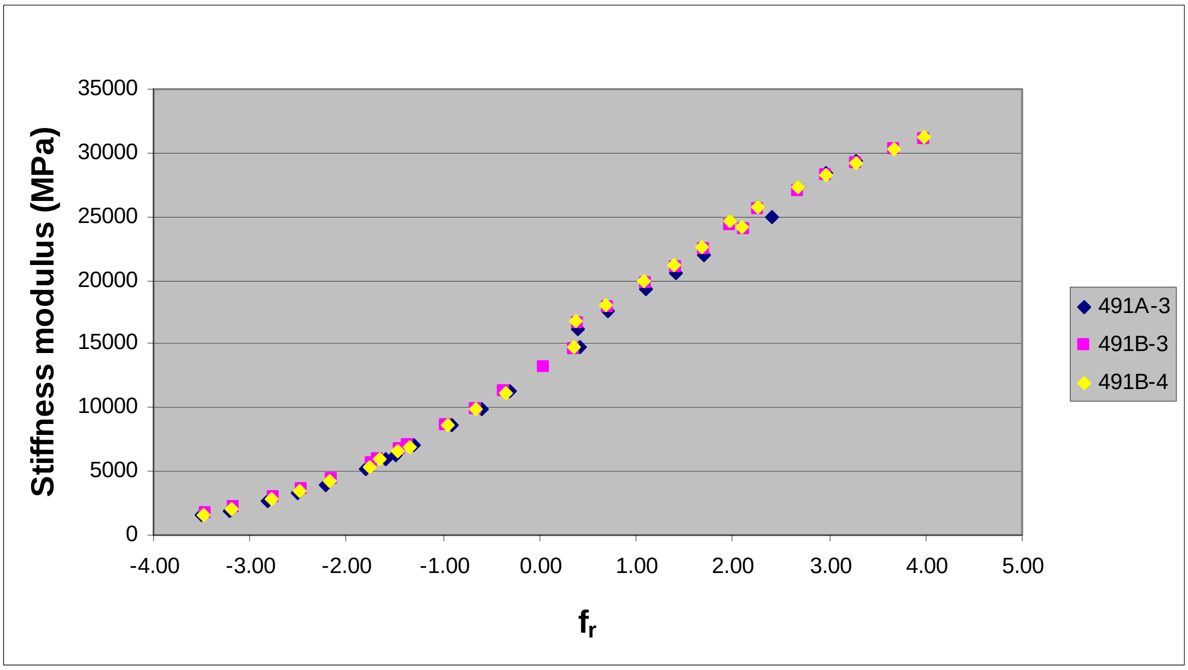

Figure 6A: Complex modulus (IT-CY/E) versus reduced frequency for asphalt mixture 491. The air void content of the samples is 2.9, 2.7, 2.9% for A-3, B-3 and B-4 respectively.

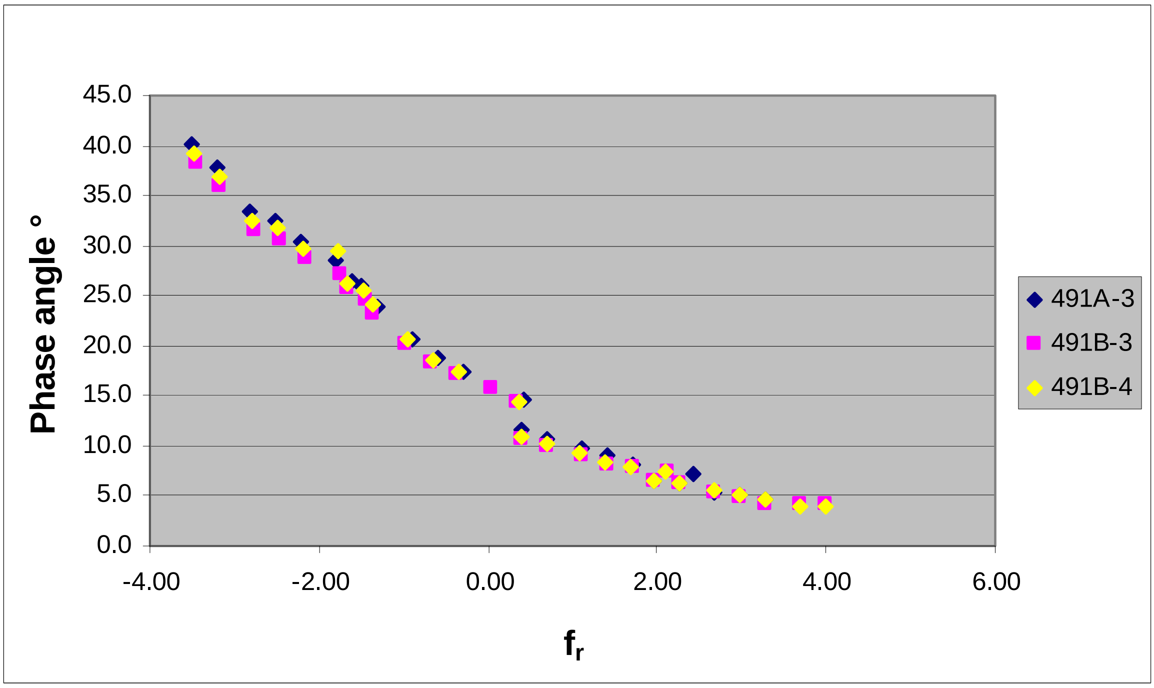

Figure 6B: Phase angle (IT-CY/E) versus reduced frequency for asphalt mixture 491.

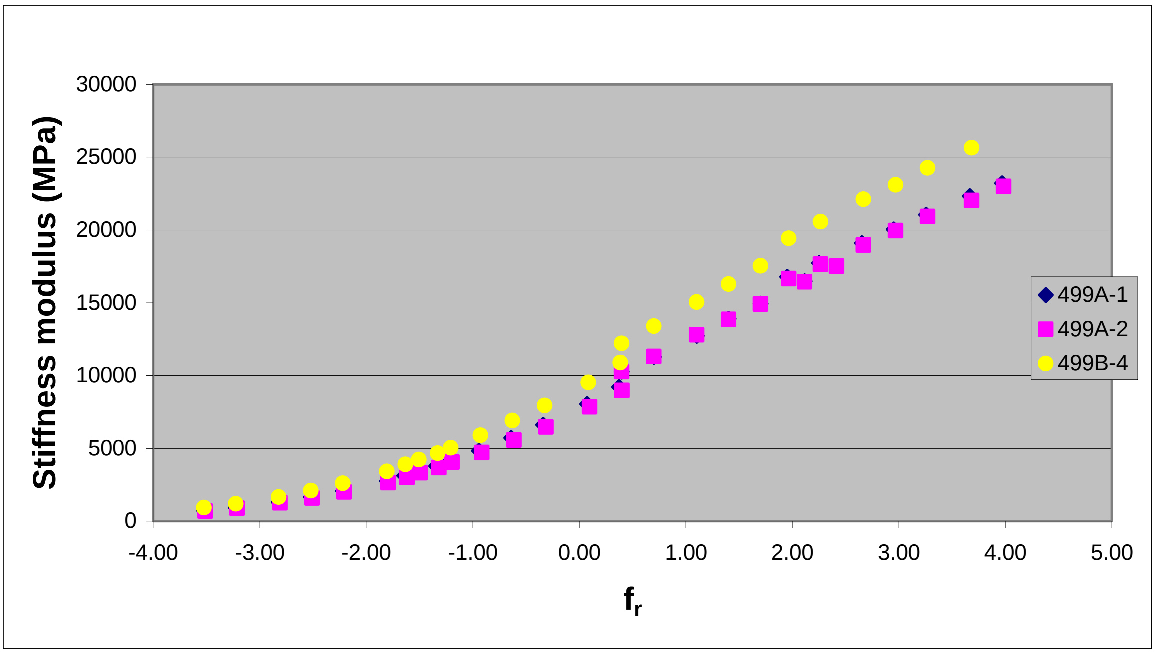

Figure 7A: Complex modulus (IT-CY/E) versus reduced frequency for asphalt mixture 499. The air void content of the samples is 8.3, 7.7 and 4.1% for A-1, A-2 and B-4 respectively.

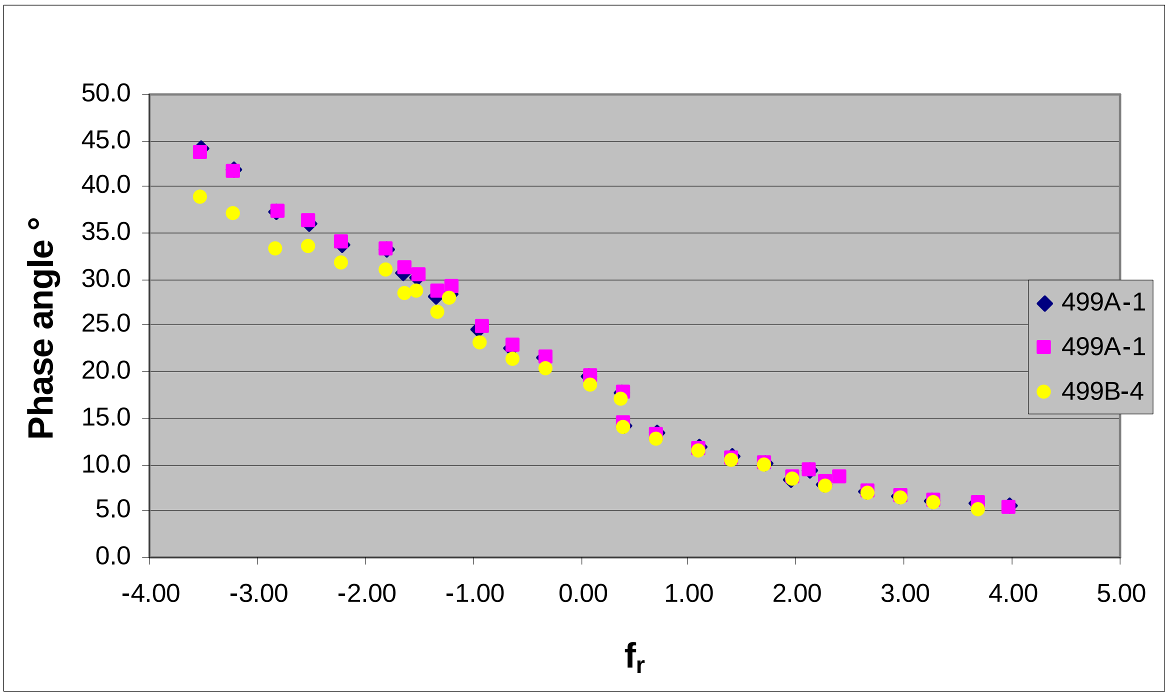

Figure 7B: Phase angle (IT-CY/E) versus reduced frequency for asphalt mixture 499.

The complex modulus is generally lower for asphalt mixture 499 than for mixture 491, but also the air void content is higher for 499 than for 491.

The measurements of the complex modulus, phase angles and Poisson ratios according to the method described in [1], IT-CY/C, are presented in figures 8 A-C and 9 A-C each time for samples of mixture 491 and 499 respectively.

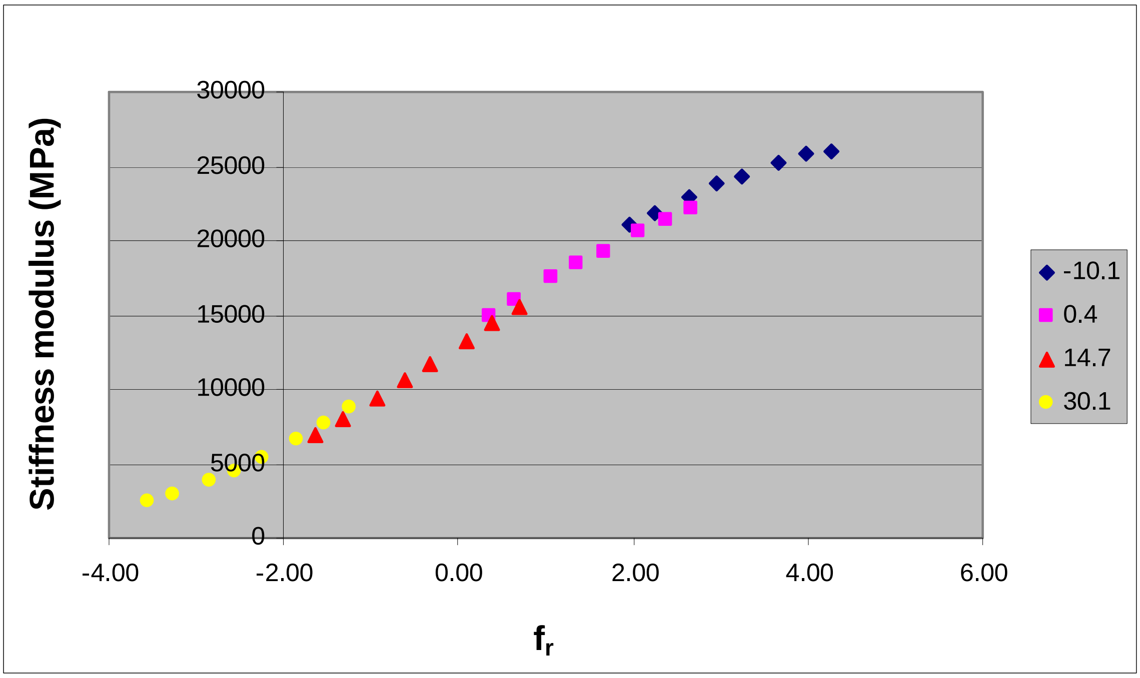

Figure 8A: Complex modulus (IT-CY/C) versus reduced frequency for sample 491B-4.

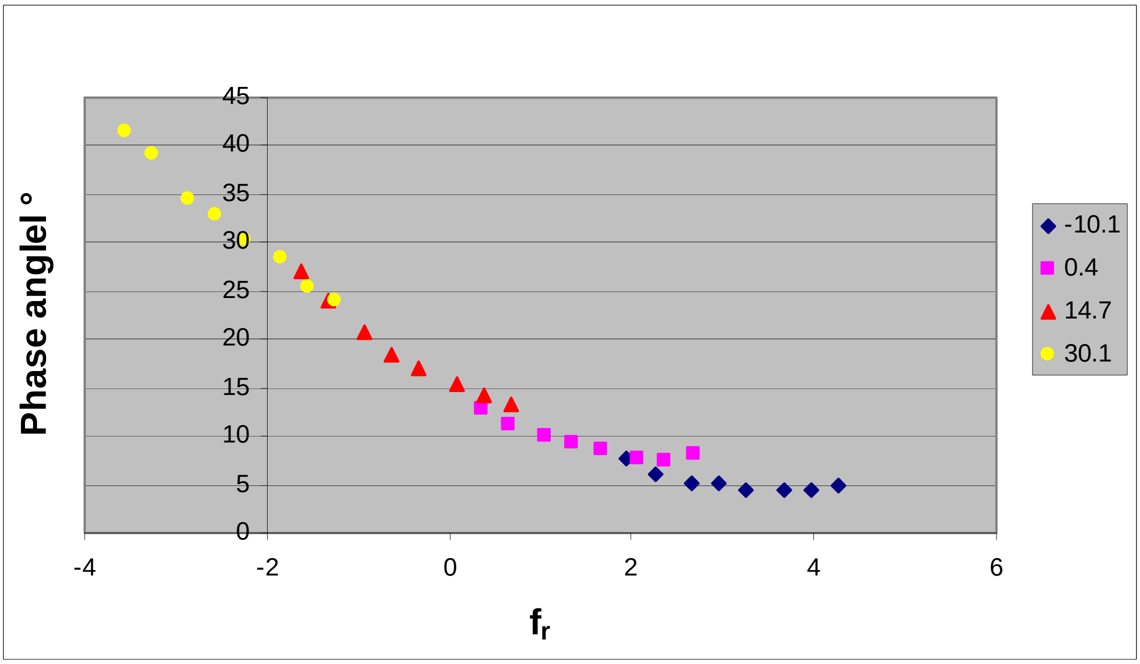

Figure 8B: Phase angle (IT-CY/C) versus reduced frequency for sample 491B-4.

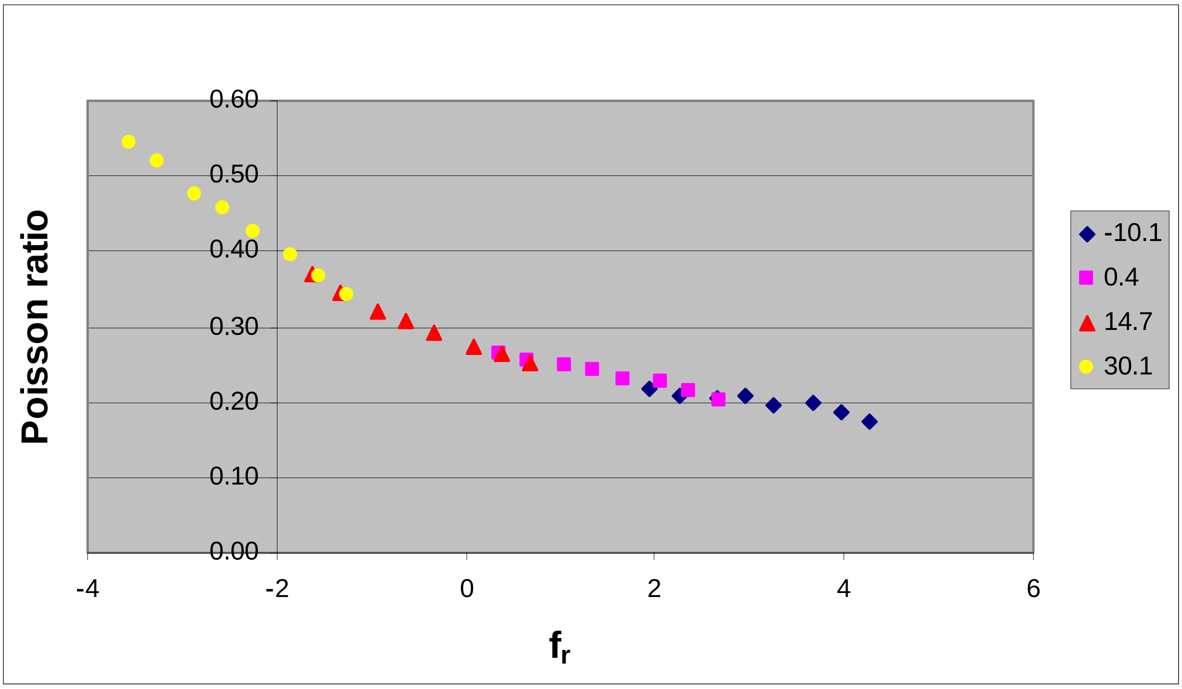

Figure 8C: Poisson ratio (IT-CY/C) versus reduced frequency for sample 491B-4.

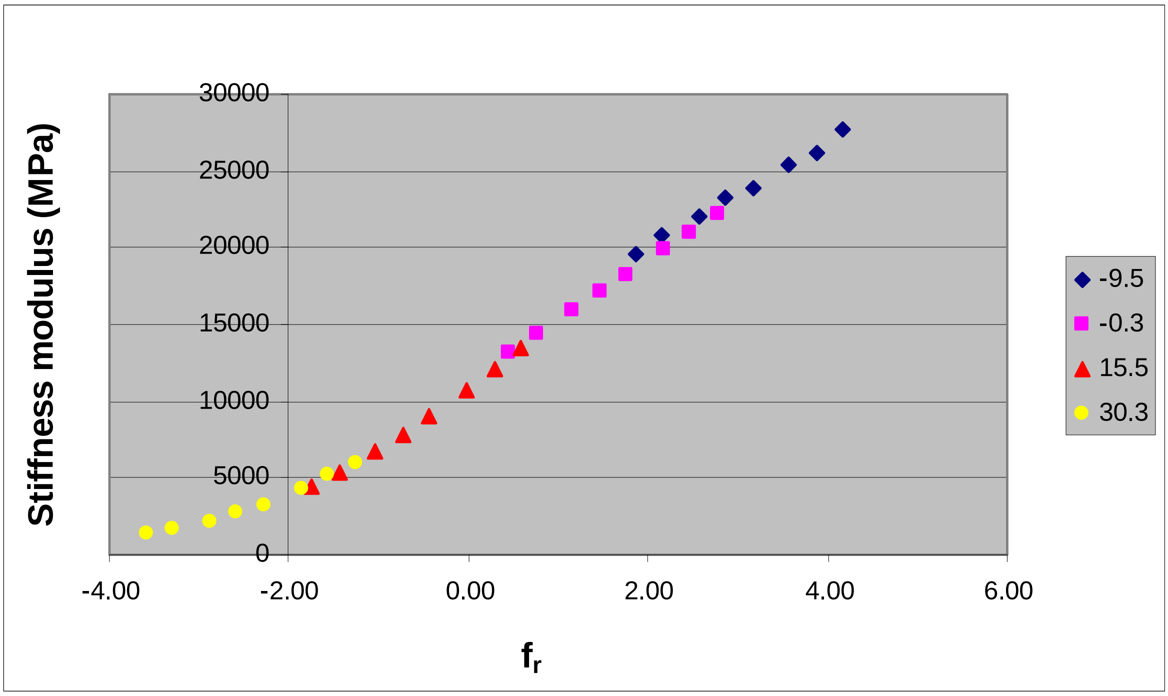

Figure 9A: Complex modulus (IT-CY/C) versus reduced frequency for sample 499B-4.

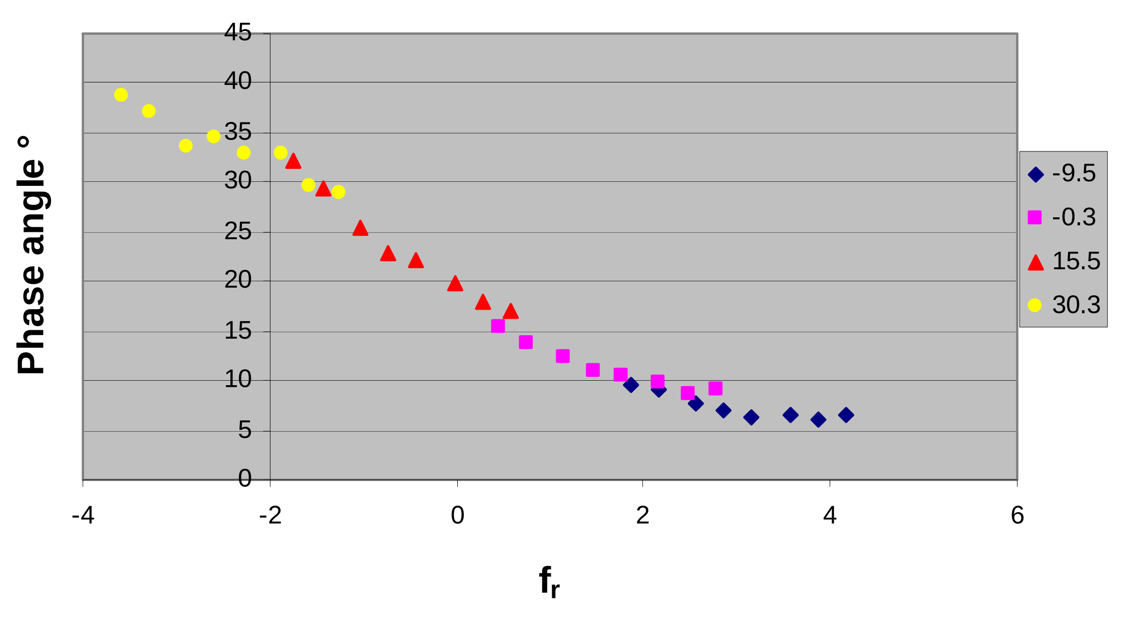

Figure 9B: Phase angle (IT-CY/C) versus reduced frequency for sample 499B-4.

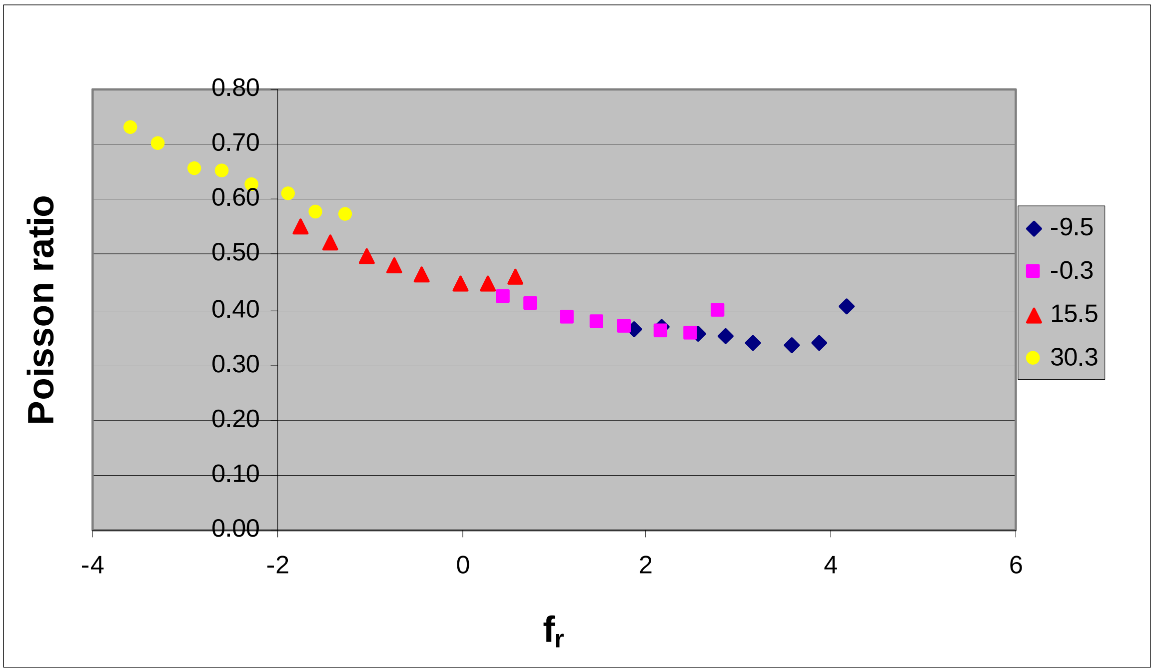

Figure 9C: Poisson ratio (IT-CY/C) versus reduced frequency for sample 499B-4.

In figure 9C it can be observed that the Poisson ratio for the highest frequencies is much larger than for slightly lower frequencies. This could be due to the appearance of a resonance in the measuring setup. This phenomenon could also be observed for the phase angle in figure 8B and 9B. The modulus, however, seems to be unaffected by this resonance. As already noted in [1] the calculated Poisson ratio reaches values above 0.5 at high temperatures and low frequency, see figures 8C and 9C, which could not be correct. Possibly, the method is not applicable at high temperatures and low frequencies.

Once again, the stiffness modulus is lower for specimens with higher air void content than for specimens from the same asphalt mixture with lower air void content as already noted for the IT-CY/E tests and the indirect tensile strength tests.

Comparing stiffness moduli obtained with the IT-CY/E and IT-CY/C protocols, see figures 6A and 8A, the IT-CY/E method yield higher stiffness modulus at high reduced frequencies than the IT-CY/C method while the opposite is true for low reduced frequencies. If stiffness modulus obtained with the IT-CY/E, figure 6A, is corrected with the actual Poisson ratio, see figure 8C, then the two protocols give similar stiffness moduli.

Even though the IT-CY/C protocol will result in more correct values on the stiffness modulus the IT-CY/C test protocol is more time consuming in the sample preparation compared to the IT-CY/E protocol. Considering this and the unrealistic Poisson ratios at high temperatures and low frequencies, the IT-CY/E protocol is preferred when a large number of samples is to be tested and relative differences is more important than absolute levels.

Interlaboratory comparisons:
The complex modulus measurements obtained with IT-CY/E method were compared with the method of two-point bending of trapezoidal specimens described in EN 129697-26 and used at BRRC [2]. To make this comparison the data from the two experimental setups had to be reduced to the same reduced frequency scale. In [2] and reference therein, the frequency had been reduce with 15°C as the reference temperature, as compared to 10°C in this report. Also, another procedure had been used to obtain the translation factors than the Arrhenius type of equation (1) used in this report. Thus the frequency, temperature and stiffness data in [2] had to be transformed with equation (1) to facilitate a comparison between the two different experimental setups.
Examples of two master curves obtained for two specimens of mixture 499 studied with the two experimental set-ups are presented in figures 10 A and 10 B.

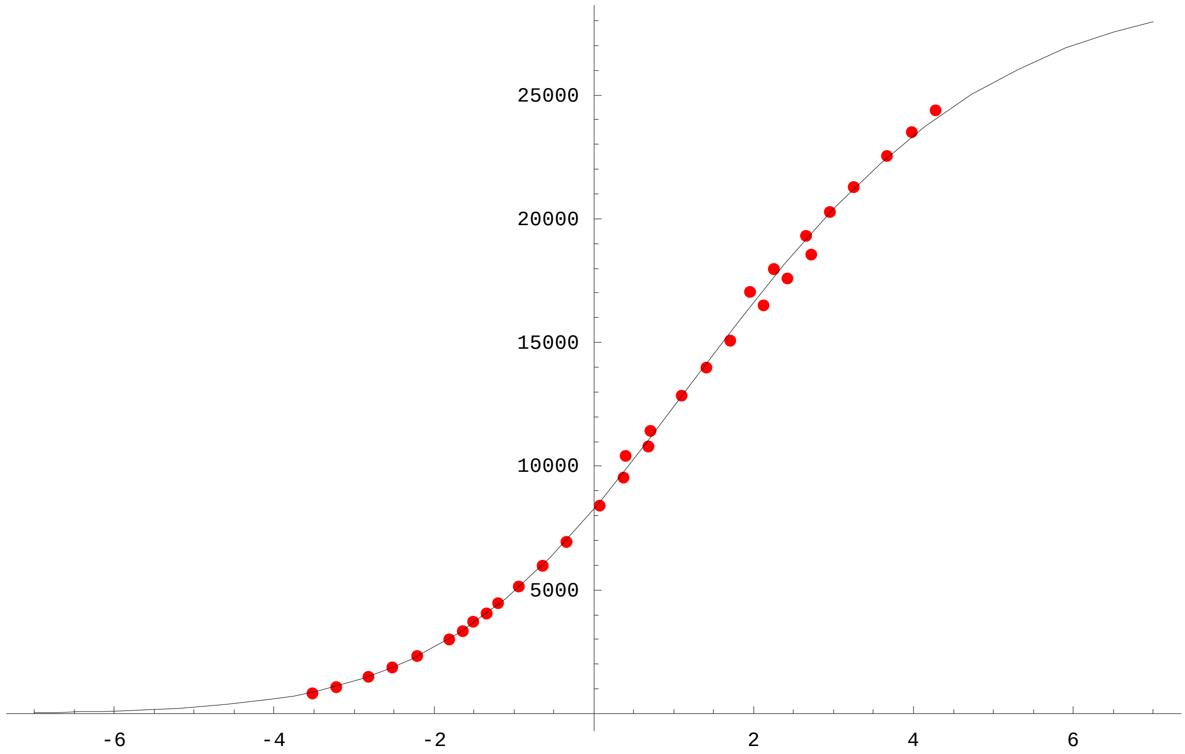

Figure 10A: Stiffness modulus versus reduced frequency for sample 499A1. Measurements were done with the IT-CY/E method. Reduced frequency calculated with equation (1).

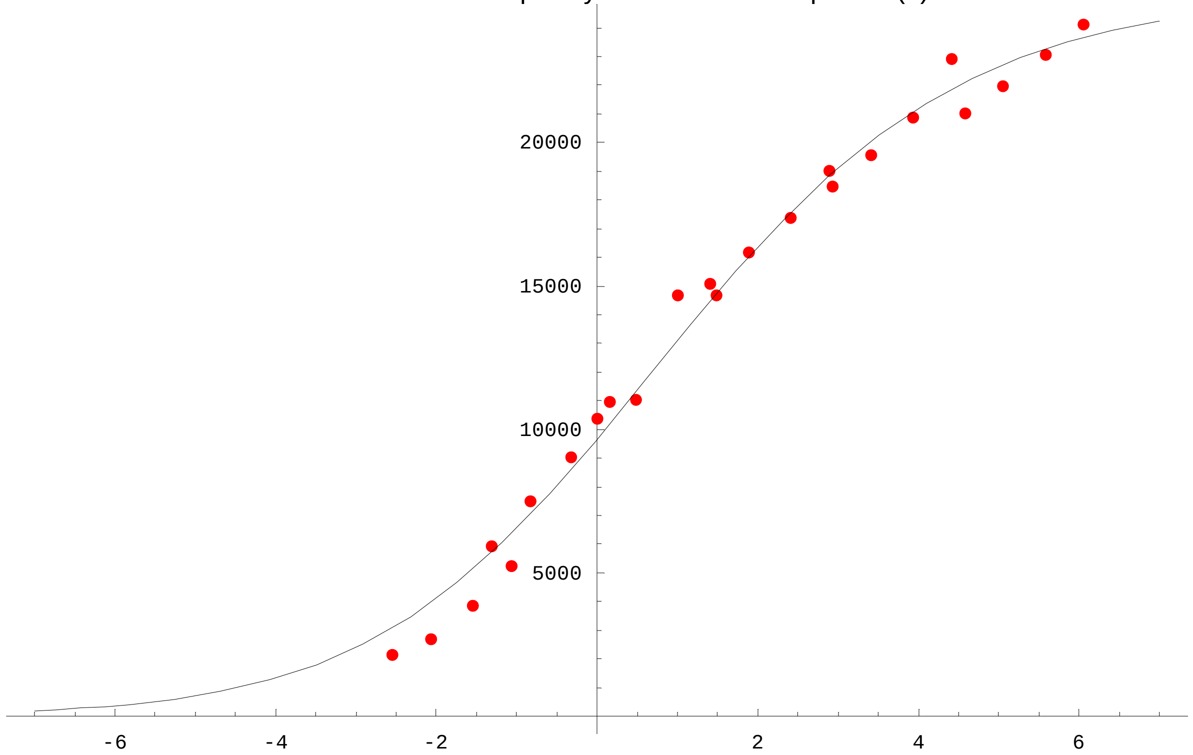

Figure 10B: Stiffness modulus versus reduced frequency for sample 499-4 E. Measurements were done with 2PB-TR method. Reduced frequencies were calculated with equation (1).

Figures 10A and 10B are quite similar, e.g. the stiffness moduli is approximately 8-10 000 MPa at the reduced frequency 0 and around 20 000 MPa at the reduced frequency of 4 in both cases.

In figures 10A and 10B a fitted curved have been plotted together with the original data.

The fitting equation is given below

$$E = \frac{E_{\max}}{\left(1 - \mathrm{Exp}(-0.5 f_r)\right)^h} \qquad (2)$$

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 equation (2) is discussed in detail in [3].

The fitted curve indicates different limiting stiffness's for data in figures 10A and 10B. In these cases the limiting stiffness's are 29 500 MPa and 25 300 MPa respectively.

Tests on specimens of mixture 491 at VTI and at BRRC and an analysis to obtain $E_{\max}$ and h describing the best fit of the data with an equation (2),are presented in table 6.

Asphalt mixture - sample names	**Laboratory**	**Method**	***h***	**$E_{\max}$ / MPa**
491 – 16 & 2	BRRC	TP Trapezoidal EN 12697-26	1,23	28 200
491 – A3, B3 & B4	VTI	IT-CY	1,56	38 600
499 – A1, A2 & B4	VTI	IT-CY	1,87	30 900
499 – 4 & 5	BRRC	TP Trapezoidal EN 12697-26	1,42	24 600
499 – 6(bis) & 9(bis)	BRRC	TP Trapezoidal EN 12697-26	1,40	27 100

Table 6: Best fit parameters (h and $E_{\max}$) for complex stiffness modulus measurements with two methods at two laboratories.

The 95% repeatability limit, r, for $E_{\max}$ and h, has been estimated in [3] to be 10% and 0.16 respectively. For both asphalt mixture 491 and 499, $E_{\max}$ and h obtained when data produced at VTI and BRRC are fitted to equation 2, differed more than the repeatability limits as can be seen in table 6. Thus, the two experimental set-ups, IT-CY and the 2PB-TR for obtaining the complex stiffness moduli do probably not give similar results. A more rigorous statistical method should to be used to check this assumption as comparing repeatability limits for the two parameters in the model function could be misleading. A reason for the discrepancy between the methods is probably partly due to the assumption of constant Poisson ratio in the IT-CY/E method.

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 4: Performance assessment of cored materials from the pavements in the ALT study.” by B. Kalman & H. Hakim