Long term field characterisation of polymer modified bitumen using a new torsional dynamic resonance rheometer

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ABSTRACT: When a rod is performing torsional vibrations at one of its resonance frequencies, any interaction with a viscoelastic medium will change both its resonance frequency and it's damping characteristics. By measuring this change, one can obtain the viscoelastic material properties of the medium. The new high frequency torsional dynamic resonance rheometer presented below is based on this principle. The device is very robust in environments involving spurious low frequencies, which makes it ideal for in situ measurements. In the present case, a polymer modified asphaltic plug joint of a Swiss highway was monitored continuously from August 1998 until December 2000. The data on resonance frequencies and damping have been interpreted by means of a mechanical model involving both the vibrating sensor and the portion of the bituminous binder participating in the vibrations. The values for damping and elastic constant of the bituminous binder have been recovered from this model. These values give clear indications on the long -term influence of climate and ageing on the material.

The experimental field results obtained over a time span of several years show that the data from the high frequency rheometer lead to valuable information for material optimisation and improved performance behaviour of asphaltic plug joints.

1 INTRODUCTION

The asphaltic plug joint being investigated is located on a highway A3 bridge near Basel, Switzerland, and was constructed in 1998. The field monitoring started two years after the construction of the plug joint and data were collected from August 1998 until September 2000. During this time the plug joint was exposed to temperatures ranging from –6 to 50 °C.

This study is part of a research co-operation between the Institute of Mechanical Systems of ETH in Zurich and the Department of Road Engineering/Sealing Components of EMPA in Dübendorf focussing on the in situ performance of polymer modified asphaltic plug joint material under traffic. A new high frequency torsional dynamic resonance rheometer developed at ETH is used to characterise the material investigated by EMPA non-destructively and in a cost-effective manner. This method has the potential to access asphaltic plug joint behaviour based on continuous surface monitoring and thus reduce the need for destructive testing.

2 THE TORSIONAL DYNAMIC RESONANCE RHEOMETER

2.1 *System specifications and description*

The dynamic rheometer (material: 18-8 CrNi steel) consists of an outer tube rigidly joined at its end E to a cylindrical inner rod through an end plate (Figs. 1 and 5). The tube is free of loading along its lateral surface and attached at one end F to a thick plate PL of large diameter in comparison to the diameter of the tube. See Table 1 for the rheometer specifications and Fig. 3 for its dimensions.

Since the torsional rigidity of the plate is much larger than the tube, it acts as a decoupling mass enforcing a node of the torsional vibration mode in its immediate vicinity. The other end E of the tube where it joins the internal rod is solidly closed with an end plate. With an electromagnetic transducer, fixed at the free end F of the internal rod, the system

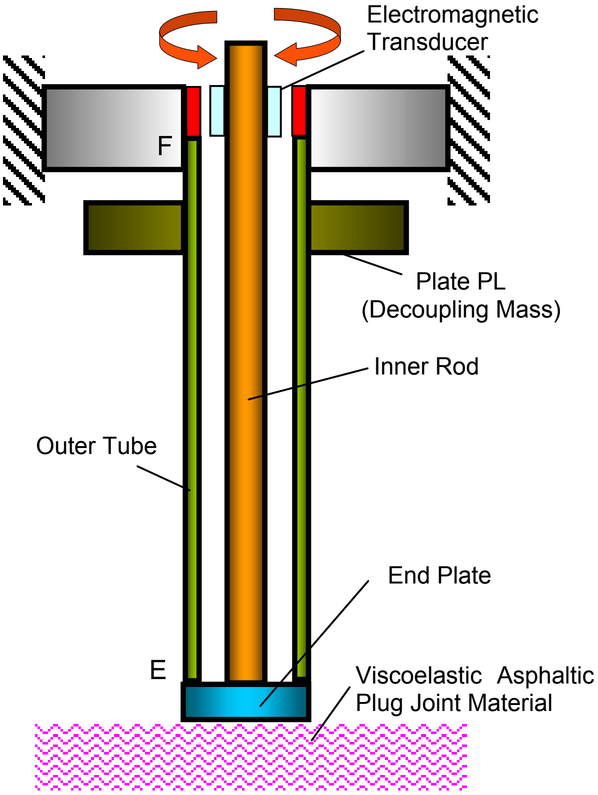

Figure 1. Schematic of the torsional dynamic resonance rheometer

is forced to perform high frequency vibrations of very low amplitude at one of its torsional eigenmodes. The frequency (5.4 kHz in the present case) is stabilised within 0.01 Hz with the help of a phase-locked loop fixing the phase between the applied torque and the measured angle of rotation. Further details including those of the electronic control circuitry can be found in Goodbread (1998).

Table 1. Rheometer specifications

Frequency range	1kHz to 60 kHz
Stability of resonance frequency	10^{-2} Hz at 10 kHz
Sensor amplitude	Less than 1 micrometer
Temperature range	-50 to 300 °C

2.2 *Measurement principle*

The resonance frequency corresponds to a phase angle of 90°. The damping (ε) is proportional to the frequency difference df_α of the frequencies $f_{-\alpha}$ and $f_{+\alpha}$ at two values 90°±α of the phase angle in the vicinity of resonance (Fig. 2):

$$df_\alpha = f_{-\alpha} - f_{+\alpha} \tag{1}$$

When the end plate is placed on the surface of the viscoelastic asphaltic plug joint material, only a boundary layer of the bituminous binder in the immediate vicinity of the contact surface participates in the motion, provided that the frequency is sufficiently high. Nonetheless, the measured resonance frequency and the damping will change in comparison to similar measurements taken in air. Shear storage and loss moduli of the bituminous binder at driving frequency follow from the changes in df_α due to interaction with the viscoelastic medium.

In Sayir (1999) similar experiments were performed with the rheometer embedded in the asphaltic plug joint material. In the current experiment the rheometer sits on top of the asphaltic plug joint and is allowed to sink due to it's own weight to a depth of approximately 4-mm.

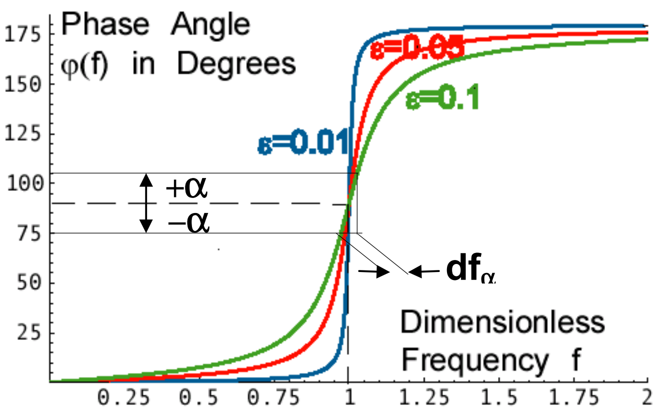

Figure 2. Phase spectrum

3 CALCULATION OF MATERIAL PARAMETERS

3.1 *Mechanical model*

With the help of a suitable theoretical model of the vibrating system {outer tube + end plate + inner rod + bituminous binder}, one can calculate from the measured frequencies for given phase angles the real part (G´) and imaginary part (G´´) of the complex shear modulus G* of the bituminous binder. The inner rod and the outer tube of the rheometer have been modelled as linear elastic structures whereas, the decoupling plate PL and the end plate at E joining the rod and the tube have been approximated as rigid bodies (Fig. 3).

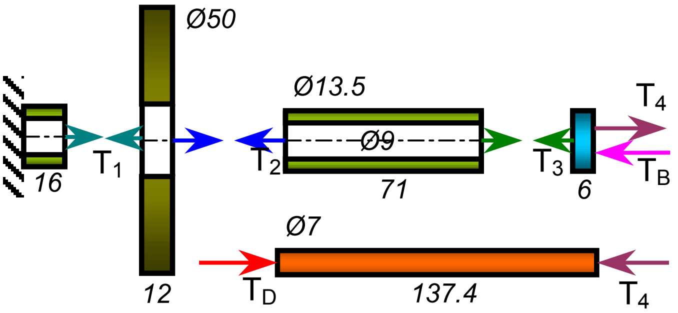

Figure 3. Mechanical model and dimensions of the rheometer parts in mm

3.2 *Material parameters*

First, the resonance frequency f_A of the rheometer in air has been calculated using the model and found to agree with the f_A readings from the rheometer. These two values should agree. The contact area with the bituminous binder has been modelled as a linear viscoelastic spring with a complex spring constant C* according to

$$T_B = C^*\theta_B = (C' + i\, C'')\, \theta_B \qquad (2)$$

where T_B is the torque and θ_B the angular displacement transmitted at the contact surface. The resonance frequency f_B and the frequency difference $df_{\alpha B}$ calculated for given values of temperature and complex spring constant C* should correspond to the measured frequencies. Hence, by inversion, for each pair of measured $\{f_B, df_{\alpha B}\}$ at a given temperature, one gets the two parts $\{C', C''\}$ of the complex spring constant. Dimensionless values of the elastic ($cd=C'/C_0$) and viscous ($ld= C''/C_0$) parts of the complex spring constant were calculated with the help of a reference spring constant C_0.

$$C_0=G\, \pi\, [(R_a)^4-(R_i)^4]/2 \qquad (3)$$

C_0 being the torsional spring constant of a steel tube of length 1 m with the same polar moment as the tube of the sensor and it's value being 197.5 Nm. The elastic constant, cd, is mainly related to the increase in resonance frequency δf_{res} from air to bitumen

$$\delta f_{res} = f_{resB} / f_{resA} - 1 \qquad (4)$$

while the viscous constant, ld, is mainly connected with the non dimensionalised frequency difference Δf_α for phase angles $\varphi=90\pm\alpha$.

$$\Delta f_\alpha = df_\alpha / f_{resA} \qquad (5)$$

Solving the problem of an oscillatory torsional load distributed in a circle on the surface of a half space as described by Dorn (1979) gives the connection between C* and the complex shear modulus G* of the material. The later results will be reported elsewhere.

4 EXPERIMENTAL SETUP AND MAIN FEATURES OF THE MEASUREMENTS

4.1 *Characteristics of the plug joint*

Figure 1 shows a cut through a polymer-modified asphaltic plug joint, which is typically 500mm wide and 70 to 160 mm thick. The gap has a width of 10 to 60mm and is covered by a steel plate, which prevents the asphaltic plug joint material to be squeezed into the gap under traffic load. To avoid stress concentrations and cracks, friction between the steel plate and the joint material should be reduced to a minimum. Asphaltic plug joints are required to work within a temperature range from -25°C to +45°C and to take gap closings and openings of -12.5mm to 25mm. With respect to bridge bearing replacements they should also be able to suffer vertical gap movements up to a maximum of 5mm.

The asphaltic plug joint material is polymer-modified bitumen (PmB); produced from B40/50 and about double the amount of the polymer Styrene-Butadiene-Styrene (SBS) as normally used for pavement binders (Fig. 4).

The binder is poured in layers of 3 to 4 cm at a temperature of 180 °C with an equal layer of hot stones (max 22 mm aggregate size) added immediately. Then this layer is allowed to cool to about 80°C and another layer is added until a height of 16 cm is reached.

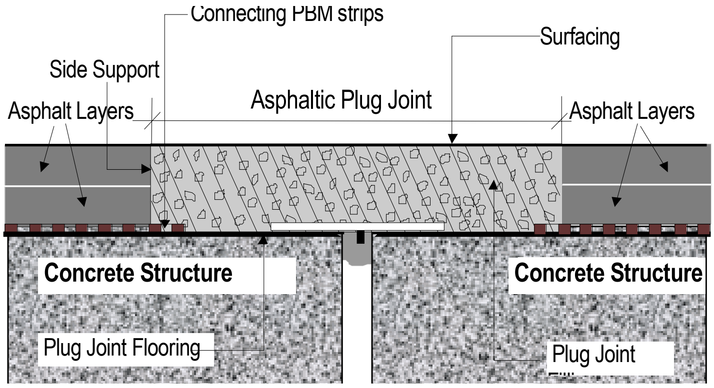

Figure 4 .Cross section of a typical bridge asphaltic plug joint

4.2 *Measurement features*

Before placing the rheometer on the plug joint, the values in air (indicated by subscript A) of resonance frequency f_A (phase angle 90°) and frequency differences $df_{\alpha A}$ for phase angles $90\pm\alpha$ (in the present case $\alpha=15.4°$) are measured. In addition, these air values were re-checked in December 1999 and 2000 to verify that the rheometer is functioning properly.

A support/protection shell was designed for the rheometer to allow movements in the vertical direction and to provide stability in the lateral direction (Fig. 5). Light and temperature sensors are located on the surface of the bitumen. Air can circulate freely around the material so that the sensors register the actual environmental conditions.

Subsequently, the values on bitumen (indicated by subscript B) of resonance frequency f_B and frequency differences $df_{\alpha B}$ are measured continuously. In the present case six measurements were conducted every half-hour.

Material inhomogeneities do not affect the results as long as the rheometer is not in immediate contact with large aggregates.

Prior laboratory experiments showed that once the rheometer is placed on the surface of the bitumen and is free to move vertically, it begins to sink slowly in the viscoelastic bitumen due to its weight. Subsequently the vertical downward displacement reaches an asymptotic value of about 4-mm. The rheometer is free to move up or down depending on the temperature.

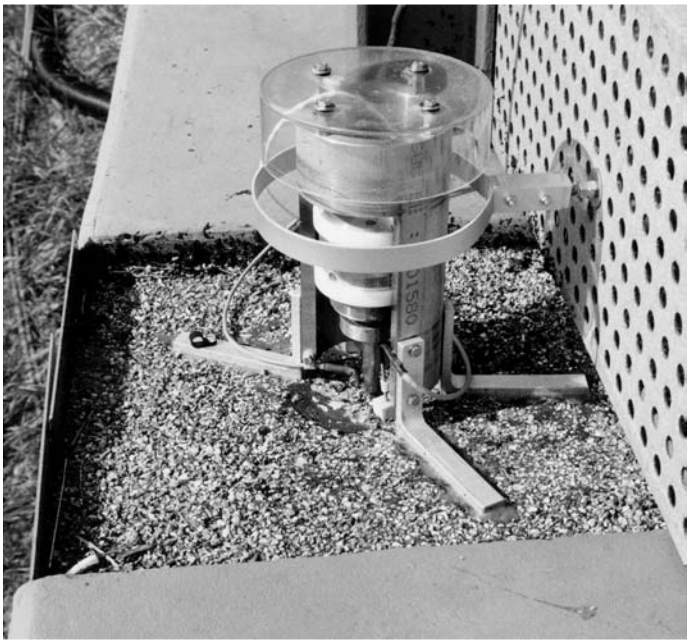

Figure 5. In situ set up on the bridge asphaltic plug joint consisting of rheometer with protection shell, lateral support, temperature and light sensors

Readings from the rheometer after one year, up to August 1999, indicated fluctuations due to temperature only, reported by Poulikakos (1999).

Figure 6 shows the fluctuations of resonance frequency (phase angle of 90°) f_B and $df_{\alpha B}$ (a function of damping) at 90±15.4° in March 2000 with respect to temperature during approximately a 24 hour period. As expected, the resonance frequency increases with decreasing temperature and can be interpreted as an increase in the stiffness of bitumen. This fluctuation was originally temporary and both the resonance frequency and df were returning to their original values at given temperatures. However with ageing the original values in resonance frequency and df could not be recovered. This is further discussed in section 5. In addition, $df_{\alpha B}$, which characterises damping, was fairly constant over this range of temperature.

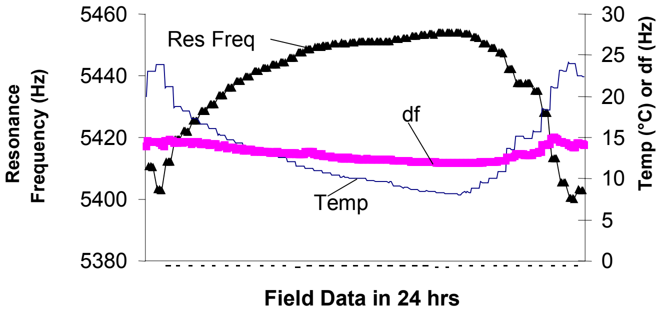

Figure 6. Typical field data

4.3 *Problems associated with in situ measurements*

Naturally as is often the case with long-term in situ measurements various technical problems occurred, such as power outages resulting in lost data. The rheometer was exposed to the elements, which resulted in its final break down in Dec 2000. Accumulation of dust and particles around the contact area may have affected the results, however, in a minor way since good contact was established at the time of installation. Formation of ice under the contact area resulting from condensation did temporarily affect the results in the winter of 1999 when temperatures fell below freezing.

5 DISCUSSION OF RESULTS

Ageing of bituminous mixtures occurs over time due to exposure to air and climatic loading, specifically heat. In the case of polymer modified bitumen the ageing of bitumen and polymers occurs simultaneously. "Age hardening" referring to the loss of volatiles of the binder and oxidation results in increased binder stiffness and subsequently in an increase of mixture stiffness as well as a reduction in the asphaltic plug joint deformation properties. On the other hand, overheating may destroy the polymer chains. This can result in shorter chains and consequently, depending on the polymer, in a hardening or softening effect. According to the results in this study an overall hardening effect has resulted over time.

Figures 7 to 11 compare data from the same time of year in 1998, 1999 and 2000. Both df and resonance frequency and as a result cd and ld have increased every year, indicating stiffening of the material. ld displays more scatter and shows a clearly reduced temperature dependency in 2000 as compared to the first year.

The scatter can be due to lack of proper contact between the rheometer and the asphaltic plug joint surface also caused by a "drying" effect in the bituminous binder.

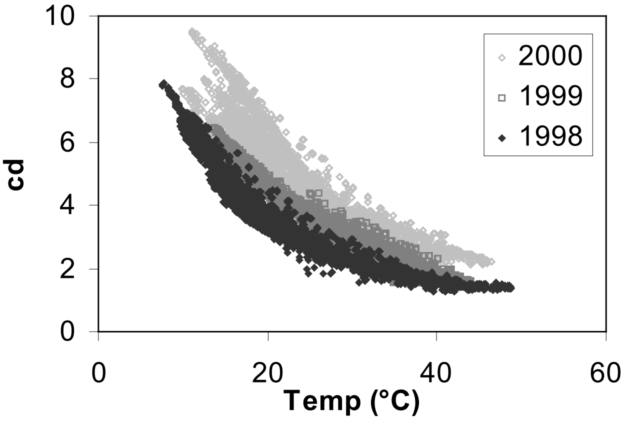

Figure 7. Comparison of elastic constants, cd (scatter diagram) in July, August and September

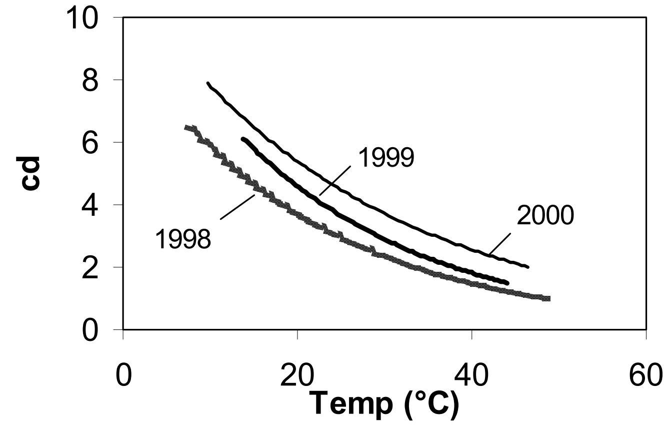

Figure 8. Comparison of regression of elastic constants cd in July, August and September.

The mean values of elastic and viscous constants have shown an increase of 53% and 48% at 20°C from 1998 to 2000 respectively. Although this is an indication of drying out of the material, this change has not affected the performance of the plug joint at the bridge. In addition, a visual inspection in Dec 2000 did not show any indications of distress/failure in the joint. What remains to be determined is the amount of tolerable change in resonance frequency and damping as well as a relationship between in situ and laboratory simulations.

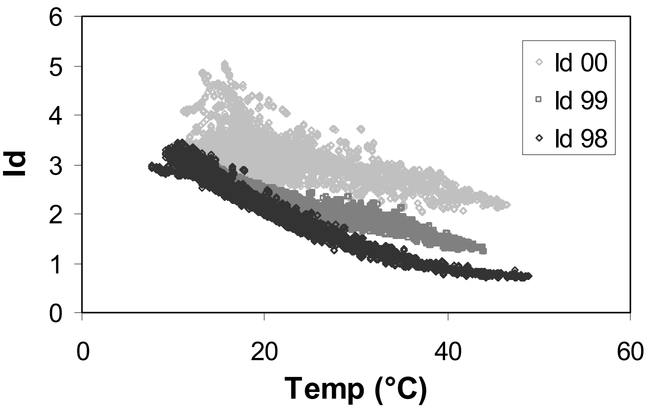

Figure 9. Comparison of viscous constant, ld, (scatter diagram) in July, August and September.

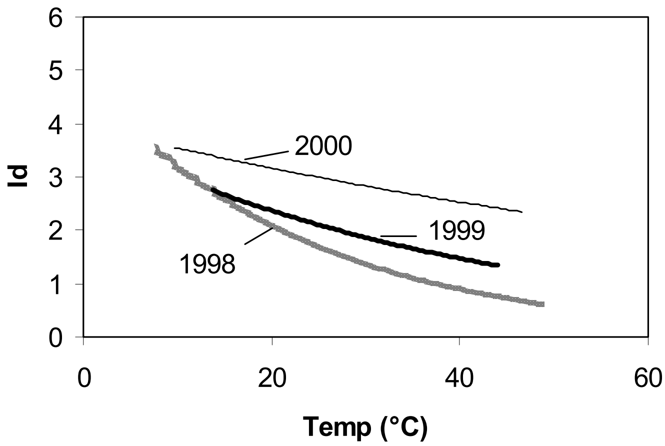

Figure 10. Comparison of regression of ld in July, August and September

6 REGRESSION ANALYSIS

The results of the regression analyses are shown in Figures 8, 10 and 11 and Tables 2, 3and 4 with r^2 being the coefficient of determination. These exponential curves are valid for the temperature ranges shown on the figures and can be used to draw conclusions about the dependency of cd and ld on temperature over time and on each other. As it is apparent from Figure 8 and Table 2, a higher correlation existed between cd and temperature in 1998. This correlation has clearly decreased by 2000.

Table 2. Results of regression analysis cd vs. Temperature, T (°C)

Year	Regression	r^2
1998	$cd=9.2e^{-0.045T}$	0.93
1999	$cd=11.62e^{-0.047T}$	0.96
2000	$cd=11.33e^{-0.037T}$	0.85

In the temperature range observed here, cd/ld ratios are comparatively unchanged at higher tem peratures (low cd and ld) and ageing is less apparent. On the other hand at lower temperatures (high cd and ld) the effects of ageing can be seen clearly from the divergence of the curves (Fig. 11).

Table 3. Results of regression analysis ld vs. Temperature, T (°C)

Year	**Regression**	**r^2**
1998	$ld=4.88e^{-0.042T}$	0.98
1999	$ld=3.8e^{-0.024T}$	0.91
2000	$ld=3.9e^{-0.01T}$	0.42

Similarly from Figures 10 and Table 3 as well as from Figure 11 and Table 4 it can be concluded that the dependence of ld on temperature has decreased with time.

The behaviour of cd and ld can best be represented by an exponential regression as shown.

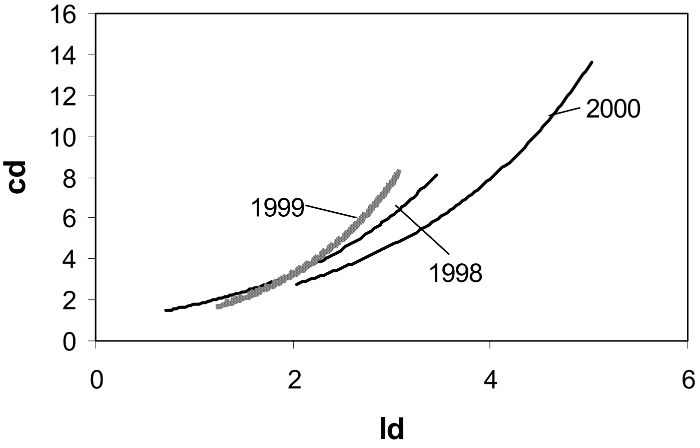

Figure 11. Regression analysis of elastic constant, cd vs. viscous constant, ld

Table 4. Results of regression analysis cd vs. ld

Year	**Regression**	**r^2**
1998	$cd=0.94e^{0.62ld}$	0.94
1999	$cd=0.58e^{0.86ld}$	0.89
2000	$cd=0.95e^{0.53ld}$	0.52

7 SUMMARY AND CONCLUSIONS

In field measurements of resonance frequency and frequency differences for given phase angles between the applied torque and the displacement are obtained with the help of a newly designed torsional dynamic resonance rheometer placed on an asphaltic plug joint of a Swiss highway. From the measured values, the spring constant and the damping of the bituminous material were determined. Using these properties ageing of the polymer bitumen plug joint was characterised.

In particular the following can be concluded:

- The torsional dynamic resonance rheometer can be used for continuous in situ characterisation of bituminous binders non-destructively and in a cost-effective manner. Furthermore, this method has proven successful in laboratory experiments and has been used to characterise other materials such as studies on the influence of additives on the mechanical properties of rubber, viscoelasticity of living tissue etc.
- High frequencies allow for measurement under traffic conditions without interference of traffic induced frequencies.
- The experiments conducted since August 1998 indicate that the viscoelastic properties of the subject plug joint have altered significantly at least up to a depth of 4 mm after more than two years of climatic exposure and traffic.
- What remains to be determined is the amount of tolerable change in resonance frequency and damping. Current ageing experiments at EMPA using a pressure-ageing vessel (PAV) and oven should shed some light into this aspect. While the material has shown signs of ageing, this effect could be a result of ageing of the surface and the rest of the material could be affected in a lesser degree as the plug joint is still in operation and does not show signs of distress or failure.

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