# Complex Modulus of Cold Recycled Mixtures: measurement and modelling

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**ABSTRACT**

In the present study, the complex modulus *E** of three types of cold recycled mixtures was measured in the laboratory using cyclic compression tests. The mixtures, that were produced in situ using the full-depth reclamation technique, were characterised by the same 100% reclaimed aggregate composition, whereas bitumen emulsion, foamed bitumen and portland cement were employed as binding agents. Complex modulus testing was carried out on cylindrical specimens cored from the pavement seven years after construction. A sinusoidal strain with amplitude of 30 microstrain was applied at testing temperatures ranging from 0 to 50 °C and frequencies ranging from 0.1 to 20 Hz. Results showed that the time-temperature superposition principle was fully verified for the stiffness modulus whereas some discrepancy was highlighted by the loss angle. The Huet-Sayegh rheological model was applied to simulate the experimental data. Model fitting based only on the stiffness modulus provided excellent results. Indeed, the fitted rheological model was also able to simulate the loss angle variation quite well, but with some underestimation (about 3°) of the measured values. It can be concluded that other dissipation mechanism, in addition to the "classical" viscous type, were influent for behaviour of the studied cold recycled mixtures.

**Keywords**: Cold recycling, bitumen emulsion, foamed bitumen, complex modulus, Huet-Sayegh model.

## 1. INTRODUCTION

Cold recycling technologies have been developed over the last 20 years as a cost-effective and sustainable alternative for the rehabilitation of asphalt pavements. Among these technologies, the full-depth reclamation (FDR) allows 100% recycling of the existing pavement materials [1,2]. The aggregate blend of cold recycled mixtures (CRM) produced in-place using FDR is composed mainly of reclaimed asphalt pavement (RAP) and reclaimed aggregate, the latter coming from the unbound or cement bound layers. The other CRM components are virgin aggregate (added to adjust the grading curve), water and different types of binders [3].

When only cement is used, the CRM is actually a cement-treated material (CTM) [4-5]. Whereas, if both cement and bitumen (in form of emulsion or foam) are used a bitumen-stabilized material (BSM) or a cement-bitumen treated material (CBTM) is obtained (for BSM the bitumen/cement ratio is greater than one and cement content is lower than 1% while for CBTM the bitumen/cement ratio is greater than one and cement content is greater than 1%) [6-8].

The mechanical properties of CRM depend on the nature and proportion of the binders. They may range from a stiff and brittle behaviour (typical of CTM), to a stress-dependent granular-like behaviour (typical of BSM), to an asphalt-like behaviour with cumulative damage failure (typical of CBTM) [9]. Besides their mechanical response, it is underlined that, because of the presence of water and cement, CRM are subjected to a curing process, which entails an evolution of their physical and mechanical properties over time [10].

In recent years, many researchers investigated CRM properties in terms of stiffness, resistance and fatigue behaviour [11-15]. In particular, various studies focused on the evaluation of the rheological properties of CRM, which are strictly related to the presence of bitumen in the mix [8, 16-18]. Indeed, the CRM inherit the thermo-dependency and the viscoelastic behaviour of the bitumen, both from the fresh binding agent (bitumen emulsion or foamed bitumen) and from the RAP. In particular, it has been shown [16] that the aged and oxidized bitumen in the RAP determines a limited, but yet measurable, time- and temperature-dependent behaviour in cold recycled CTM.

The present paper focuses the linear viscoelastic (LVE) characterization of different CRM, produced in-place with the FDR technology, through the measurement and modelling of the complex Young's modulus $E^*$. The same experimental approach and analytical models normally used for hot mix asphalt (HMA) are applied to CRM produced using different binders: only cement, bitumen emulsion and cement, foamed bitumen and cement.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Materials

The cores tested in this study were extracted from an experimental pavement section constructed in 2007 during the rehabilitation of the SS38 highway in the north of Italy. In the project, the existing HMA layers were milled and the RAP was used to produce a new 300 mm CRM layer above the subgrade. The experimental pavement was divided into three subsections, where the reclaimed aggregates were stabilised with the FDR technology using different binders: foamed bitumen and cement (CRM-FB), bitumen emulsion and cement (CRM-EM) and only cement (CRM-PC). Finally, three HMA courses (total thickness of 190 mm) were placed on top of the CRM layer.

The foamed bitumen was produced with a recycler machine model WR 2000, combining a 50/70 pen bitumen with 3% of foamant water (by bitumen weight). The bitumen emulsion was an over-stabilised cationic type, specifically designed for cold in-place recycling, with designation C 60 B 10, according to EN 13808. The cement was a pozzolan-lime type IV/A, strength class 32.5 R (EN 197-1). The binder dosages (by dry aggregate weight) adopted in the three subsections are reported in Table 1.

Seven years after construction, 100 mm diameter full-depth cores were taken from the pavement. The CRM and HMA layers were sawed in order to obtain cylindrical specimens for complex modulus testing. The air voids characteristics of the specimens are shown in Table 1.

### 2.2 Complex modulus testing

The complex modulus was measured using a servo-hydraulic testing system AMPT PRO. Axial stress was measured with a load cell, whereas axial strain was measured on the middle part of the specimen using three LVDT, placed 120° apart, with a measuring base of 70 mm. A haversine compression loading was applied in order to obtain an axial strain with a target amplitude of 30 microstrain. Testing temperatures ranged from 0 to 50 °C and frequencies ranged from 0.1 to 20 Hz; 20 loading cycles were applied at each frequency.

The steady-state sinusoidal component of stress and strain were employed to calculate the complex Young's modulus:

$$E^* = \frac{\sigma_0 \exp[\mathrm{j}(\omega\tau + \phi)]}{\epsilon_0 \exp[\mathrm{j}(\omega\tau)]} = \frac{\sigma_0}{\epsilon_0}\exp[\mathrm{j}\phi] = E_0 \exp[\mathrm{j}\phi] = E_1 + \mathrm{j}E_2 \qquad (1)$$

where j is the imaginary unit, $\sigma_0$ and $\epsilon_0$ are the steady state amplitudes of stress and strain, respectively, $E_0$ is the absolute value of $E^*$(also indicated as stiffness modulus), $\phi$ is its loss (or phase) angle, and $E_1$, $E_2$ are its storage and loss components, respectively.

**TABLE 1 Properties of the tested cores**

| Mixture | Bitumen content [%] | Cement content [%] | Specimen ID | Air voids [%] |
|---|---|---|---|---|
| Hot Mix Asphalt | 4.50 (Hot binder) | / | HMA1 | 7.0 |
| | | | HMA2 | 9.0 |
| | | | HMA3 | 7.5 |
| | | | HMA4 | 7.5 |
| CRM-Emulsion | 1.80 (Emulsion) | 2.00 | CRM-EM1 | 17.5 |
| | | | CRM-EM2 | 18.9 |
| | | | CRM-EM3 | 18.9 |
| CRM-Foam | 3.00 (Foam) | 1.75 | CRM-FB1 | 9.6 |
| | | | CRM-FB2 | 14.1 |
| CRM-Cement | / | 3.00 | CRM-PC1 | 13.7 |
| | | | CRM-PC2 | 14.7 |

## 3. RESULTS AND ANALYSIS

The values of $E_0$ and $\phi$ measured on all tested specimens are shown in the Black diagram (Figure 1a). In this plot it can be noticed that $E_0$ varies from 17931 to 84 MPa and from 12694 to 1521 MPa, for HMA and CRM, respectively. Also, $\phi$ ranges from 5.6 to 43° and from 1.8 to 18°, for HMA and CRM, respectively. Although the results show that the complex modulus of all CRM specimens is clearly thermo- and frequency-dependent, the variability of both $E_0$ and $\phi$ values throughout the tested temperature and frequency ranges is limited, with respect to the variability which is typical of HMA specimens.

In order to highlight the differences in the LVE behaviour among the different CRM, the values of $E_1$ and $E_2$ are plotted in the Cole-Cole diagram (Figure 1b). In this plot it can be noticed that, as expected, CRM-EM and CRM-FB specimens showed a higher variability with temperature and frequency, with respect to CRM-PC.

It is remarked that such behaviour does not imply any form of blending between aged bitumen from RAP and fresh bitumen (emulsion residue or foamed bitumen). In particular, when bitumen emulsion is used, the bitumen droplets coalesce forming a continuous film that adheres to larger RAP particles or includes smaller RAR particles. However, the two bituminous phases are always at ambient temperature, which makes their physical blending quite difficult.

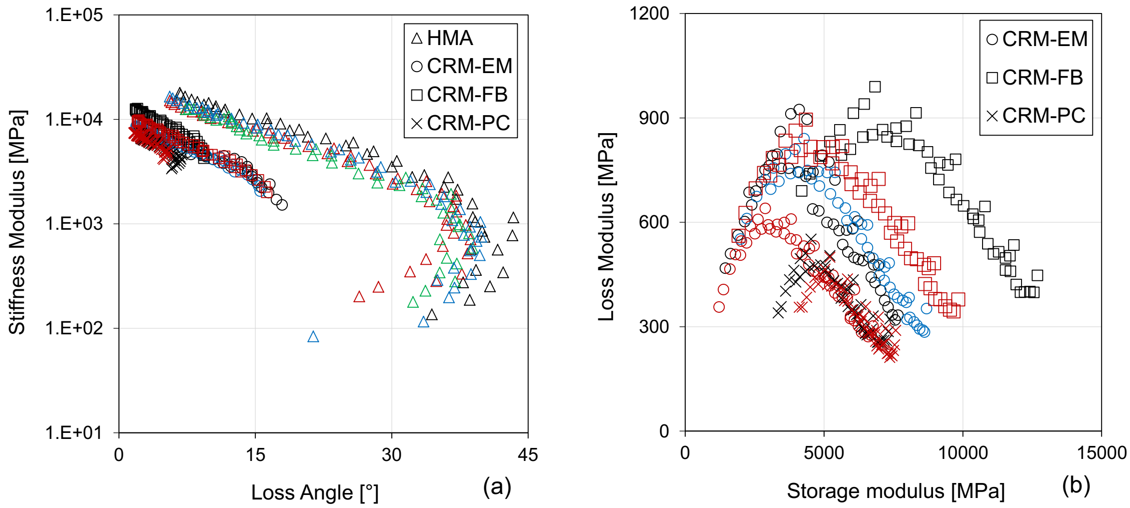


**FIGURE 1 The measured values of $E^*$: a) Black diagram; b) Cole-Cole diagram**

It is well known that, if the LVE behaviour of a material can be represented by a unique curve in the Black and Cole-Cole diagrams, validity of the time-temperature superposition principle (TTSP) is confirmed and the behaviour can be considered thermo-rhelogically simple.

For HMA specimens, some dispersion is present in the measured $E^*$ values, however the experiments confirm the validity of the TTSP (the small deviations may be due to the effect of aging). On the other hand, the behaviour of CRM should be analysed from a different perspective. In fact, for these mixtures, the simultaneous presence of aged binder (RAP), fresh binders (bitumen emulsion residue and foamed bitumen) and cement, makes the a-priori assumption of thermo-rheological simplicity difficult.

Notwithstanding the aforementioned issues, master curves of the stiffness modulus $E_0$ at the reference temperature $T_0 = 0$ °C were obtained for all tested specimens (Figure 2). In particular, the temperature shift factors were determined according to the closed form shifting (CFS) algorithm [19]. The CFS algorithm is based on the definition of an overlapping window between two successive isothermal curves: when the area between the two curves is zero the optimal shifting is obtained.

As it can be observed in Figure 2, validity the TTSP for $E_0$ is perfectly confirmed for all tested specimens. This suggests that the same rheological model could be used to simulate the LVE behaviour of HMA and CRM. The Huet-Sayegh (HS) model [20] was employed:

$$E^* = E_e + \frac{E_g - E_e}{1 + \delta(\mathrm{j}\omega\tau)^{-k} + (\mathrm{j}\omega\tau)^{-h}} \tag{2}$$

where $E_g$, $E_e$ are the glass and equilibrium moduli, respectively, $\delta$, $h$ and $k$ are dimensionless model parameters ($k < h < 1$), $\omega = 2\pi f$ is the angular frequency ($f$ is the testing frequency in Hz) and $\tau$ is the characteristic time. In particular, $\tau$ is a function of the testing temperature $T$:

$$\tau(T) = a(T)\tau_0 \tag{3}$$

where $a(T)$ are the temperature shift factors calculated using the CFS algorithm and $\tau_0$ is the characteristic time at the reference temperature [19]. Lines representing the fitted HS model are superposed to the measured $E_0$ values in Figure 2. Table 2 lists the HS model parameter, and the parameters ($C_1$, $C_2$) that were used to fit the shift factors with the Williams-Landel-Ferry model [21].

As it can be observed in Figure 2a, the behaviour of all HMA specimens can be simulated using identical values of $h$ and $k$; the values of $\delta$ and $\log \tau_0$ are also very close. It can also be observed that $E_g$ values are correlated to the air voids content of the specimens reported in Table 1 (higher voids correspond to lower $E_g$).

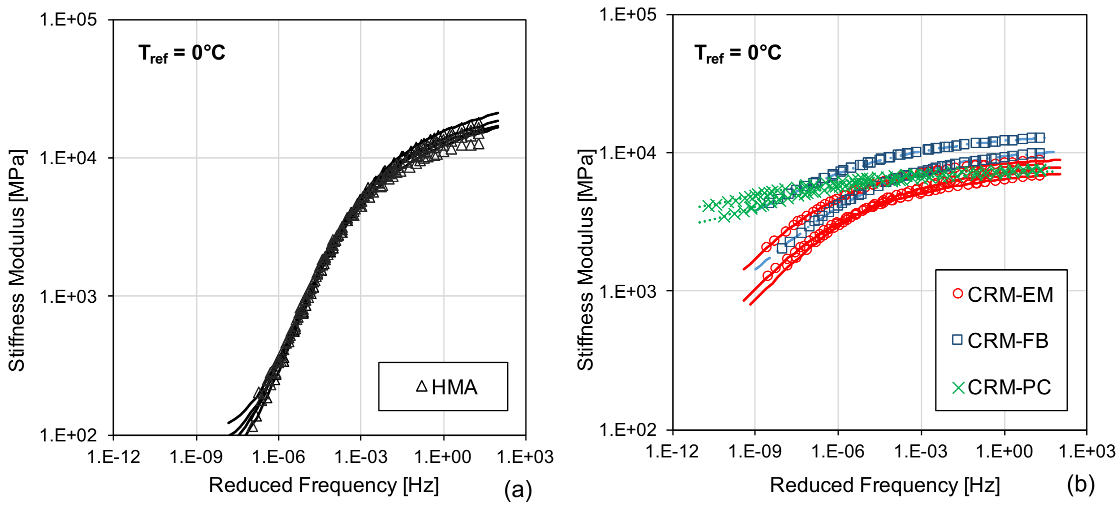


**FIGURE 2 Master curves of the stiffness modulus at 0°C: a) HMA; b) CRM**

**TABLE 2 Huet-Sayegh and WLF model parameters ($T_{ref}$ = 0°C)**

| Specimen ID | $E_g$ [MPa] | $E_e$ [MPa] | $k$ [-] | $h$ [-] | $\delta$ [-] | $\log \tau_0$ [-] | $C_1$ [-] | $C_2$ [°C] |
|---|---|---|---|---|---|---|---|---|
| HMA1 | 30000 | 50 | 0.16 | 0.55 | 2.13 | 1.49 | 19.9 | 116.1 |
| HMA2 | 23000 | 100 | | | 2.00 | 1.80 | | |
| HMA3 | 24000 | 75 | | | 2.48 | 1.76 | | |
| HMA4 | 26000 | 60 | | | 2.22 | 1.72 | | |
| CRM-EM1 | 9500 | 200 | 0.09 | 0.30 | 1.02 | 4.77 | 23.1 | 109.7 |
| CRM-EM2 | 8500 | 80 | | | 1.22 | 5.65 | | |
| CRM-EM3 | 10000 | 150 | | | 0.86 | 6.16 | | |
| CRM-FB1 | 15000 | 1000 | 0.08 | 0.22 | 0.78 | 6.05 | 32.3 | 174.1 |
| CRM-FB2 | 11300 | 20 | | | 0.35 | 4.46 | | |
| CRM-PC1 | 8200 | 2500 | 0.07 | 0.29 | 0.89 | 7.43 | 25.7 | 87.0 |
| CRM-PC1 | 8800 | 3200 | | | 1.26 | 8.17 | | |

Figure 2b shows that the HS model also simulates correctly $E_0$ measured on CRM specimens. Similar to HMA, unique values of the parameters $h$ and $k$ were estimated for each CRM and both parameters are significantly lower with respect to HMA. As expected, the CRM-PC specimens are characterised by the highest values of $E_e$. The estimated values of $E_g$ are quite dispersed, but this is not surprising since the CRM were produce on site using FDR and dispersion is also present in their volumetric properties (Table 1). It is worth noting that $\tau_0$ gives a consistent ranking of the relaxation ability of the different materials. Specifically, $\tau_0$ of CRM-EM and CRM-PC is about 4 to 5 orders of magnitude higher with respect to HMA, and about two order of magnitude lower than CRM-PC.

Figure 3 reports the master curves of the loss angle, along with the fitted HS models. The model simulates well the pattern described by the experimental data and the observed differences are generally less than 3°. In Figure 3b, it can also be noted that, for all CRM, the HS model systematically underestimates the loss angle. This suggests that in these materials a non-negligible part of energy dissipation is due to physical mechanisms which are not captured by the HS model. Possible explanations could be non-linearity or frictional dissipation due to aggregate-to-aggregate contact (in CRM, the aggregate particles are not completely covered by bitumen). However, additional testing is necessary to investigate the dissipation mechanisms taking place inside CRM.

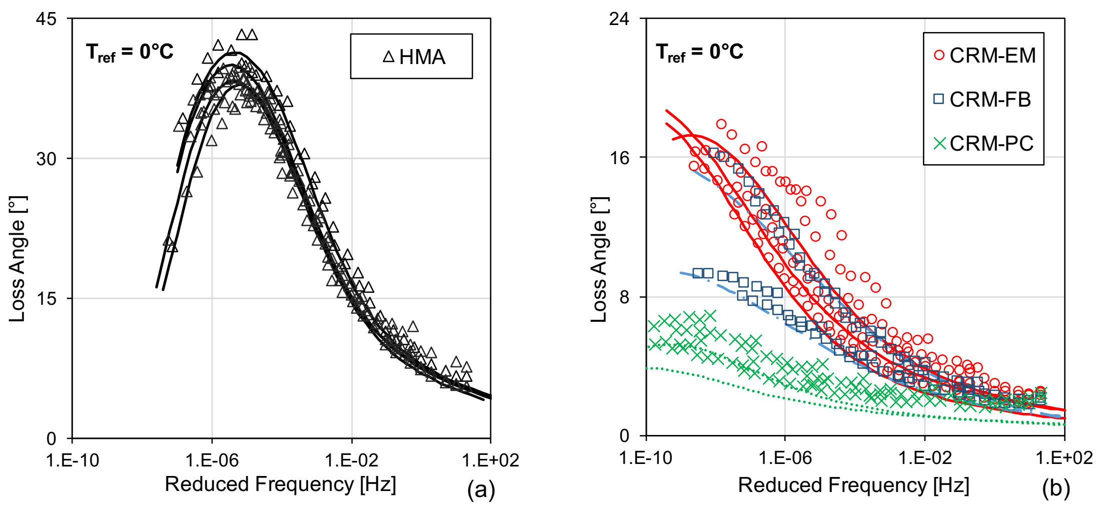


**FIGURE 3 Master curves of the loss angle at 0°C: a) HMA; b) CRM**

## 4. CONCLUSIONS

Based on the experimental results and analysis it is possible to conclude that the time-temperature superposition principle can be applied to analyse the LVE behaviour of CRM produced with bitumen emulsion and cement, foamed bitumen and cement and only with cement.

As regards the application of the Huet-Sayegh model it is possible to conclude that:

- The model can be used to simulate the LVE behaviour of CRM, obtaining an excellent fitting, in particular with the stiffness modulus data;
- The parameters of the model can be related to the physical and volumetric properties of both HMA and CRM specimens;
- The model underestimates the loss angle of CRM, probably because it can only capture linear and viscous dissipation mechanisms.

**REFERENCES**


[1] Grilli A., Cardone F. and Bocci E. Mechanical Behaviour of Cement-Bitumen Treated Materials Containing Different Amounts of Reclaimed Asphalt, European Journal of Environmental and Civil Engineering, On-line version, pp. 1-16. 2016.

[2] Thompson M. R., Garcia L. and Carpenter S. H. Cold In-Place Recycling and Full Depth Recycling with Asphalt Products (CIR&FDR), Illinois Center for Transportation (ICT), Rantoul, IL, USA. 2009.

[3] Salomon A., Newcomb E. Cold In-Place Recycling Literature Review and Preliminary Mixture Design Procedure, Minnesota Department of Transportation, Office of Research Services, Minnesota, USA. 2000.

[4] Yuan D., Nazarian S., Hoyos L.R. and Puppala A. J. Evaluation and Mix Design of Cement-Treated Base Materials with High Content of Reclaimed Asphalt Pavement, Transportation Research Record, 2212, pp. 110-119. 2011.

[5] Abdo J., Serfass J. and Pellevoisin P. Pavement Cold In-Place Recycling with Hydraulic Binders: the State of the Art in France, Road Materials and Pavement Design, 14(3), pp. 638-665. 2013.

[6] Asphalt Academy. Technical guideline (TG2): Bitumen Stabilized Materials (2nd ed.). CSIR Built Environment, Pretoria: Asphalt Academy. 2009.

[7] Pérez I., Medina L. and Del Val M. A. Mechanical Properties ond Behaviour of in Situ Materials which Are Stabilized with Bitumen Emulsion, Road Materials and Pavement Design, 14(2), pp. 221-238. 2013.

[8] Godenzoni C., Graziani A. and Perraton D. Complex Modulus Characterisation of Cold-Recycled Mixtures with Foamed Bitumen and Different Contents of Reclaimed Asphalt. Road Materials and Pavement Design, 18(1), 130–150. 2016.

[9] Godenzoni C., Graziani A., Bocci E. and Bocci M. The Evolution of the Mechanical Behaviour of Cold Recycled Mixtures Stabilised with Cement and Bitumen: Field and Laboratory Study, Road Materials and Pavement Design, on line version, pp. 1-22, 2017.

[10] Graziani A., Godenzoni C., Cardone F., Bocci E. and Bocci M. An Application of the Michaelis-Menten Model to Analyse the Curing process of Cold-Recycled Bituminous Mixtures, International Journal of Pavement Research and Technology, 10(1), pp. 62-74. 2017.

[11] Fu P. and Harvey J. T. Temperature Sensitivity of Foamed Asphalt Mix Stiffness: Field and Lab Study, International Journal of Pavement Engineering, 8(2), 137–145. 2007.

[12] Kavussi A. and Modarres A. Laboratory Fatigue Models for Recycled Mixes with Bitumen Emulsion and Cement. Construction and Building Materials, 24, pp. 1920-1927. 2010.

[13] Grilli A., Graziani A., Bocci E. and Bocci M. Volumetric Properties and Influence of Water Content on the Compactability of Cold Recycled Mixtures, Materials and Structures, 49(10), pp. 4349-4362. 2016.

[14] Swiertz D. R. Method for Determination of Optimum Emulsion Content for Emulsion-Stabilized Full-Depth Reclamation with Field Study, Proceedings of the Transportation Research Board Annual Meeting, Washington DC, United States. 2015.

[15] Khosravifar S., Schwartz C. W. and Goulias D. G. Mechanistic Structural Properties of Foamed Asphalt Stabilized Base Materials. International Journal of Pavement Engineering, 16(1), pp. 27-38. 2015.

[16] Grilli A. and Bocci E. and Graziani A. Influence of Reclaimed Asphalt Content on the Mechanical Behaviour of Cement-Treated Mixtures, Road Materials and Pavement Design, 14(3), pp. 666-678. 2013.

[17] Stimilli A., Ferrotti G. and Graziani A. and Canestrari F. Performance Evaluation of a Cold-Recycled Mixture Containing High Percentage of Reclaimed Asphalt, Road Materials and Pavement Design, 14(sup1), 149–161. 2013.

[18] Godenzoni C., Graziani A., and Bocci, M. Influence of Reclaimed Asphalt Content on the Complex Modulus of Cement Bitumen Treated Materials, 6th International Conference Bituminous Mixtures and Pavements, Thessaloniki, Greece, pp. 589-596. 2015.

[19] Gergesova M., Zupanˇciˇc, B., Saprunov, I., and Emri, I. The closed form t-T-P shifting (CFS) algorithm. Journal of Rheology, 55(1), 1–16. 2011.

[20] Sayegh G. Viscoelastic properties of bituminous mixtures. International conference on structural design asphalt pavements, Washington D.C. 1967.

[21] Tschoegl, N., Knauss, W.G. and Emri, I. The effect of temperature and pressure on the mechanical properties of thermo- and/or piezorheologically simple polymeric materials in thermodynamic equilibrium – a critical review. Mechanics of Time-Dependent Materials. 2002.