HOT MIX ASPHALT – NUMERICAL CHARACTERIZATION AT HIGH TEMPERATURES

J. Zak[a], J. Stastna[b], L. Zanzotto[b], D. MacLeod[c]
[a] Department of Road Structures, Faculty of Civil Engineering, Czech Technical University, Prague, Czech Republic; josef.zak@fsv.cvut.cz
[b] Department of Civil Engineering, Schulich School of Engineering, University of Calgary, Calgary, Alberta, Canada;
[c] Husky Energy, 707 8th Ave. S.W., Box 6525, Calgary, Alberta, Canada;

ABSTRACT

This contribution deals with rheological modeling of Hot Mix Asphalt (HMA) tensile creep compliance. The properties of HMA are studied at reference temperature 58°C. The Maxwell, Gamma-stretch and Gamma-stretch 2 models are used to fit the data of tensile compliance D(t), in the studied material.

Keywords: paving mix; viscoelastic behaviour; dynamic testing; tensile compliance

1. INTRODUCTION

Material properties of HMA play an integral part in pavement performance. The properties of HMA are considered in the structural pavement design. That is the reason why the knowledge of input material properties and laboratory testing play an important role in pavement performance and thus an improvement of HMA or better knowledge of its properties lead to better pavement performance.
The classical theory of elasticity deals with mechanical properties of elastic solids, for which, in accordance to Hooke's law, stress is always directly proportional to strain in small deformations but independent of the rate of strain [3]. HMA is not an elastic homogenous solid, but its stress components are dependent on the rate of strain. This contribution deals with rheological characterization of HMA, especially with the tensile compliance function and its modeling.
The studied material was tested in tensile creep and small amplitude tensile oscillations.

2. TENSILE CREEP TEST-CREEP COMPLIANCE

In tensile creep test, a material originally kept in its equilibrium state is subjected suddenly to a constant stress and the strain is then monitored as a function of time. This is one of the most the most popular direct experimental techniques used to study the viscoelastic behaviour over the broad range of time.
In linear viscoelastic domain, the tensile creep experiment allows to introduce the tensile creep compliance function:

$$D(t) = \frac{\varepsilon(t)}{\sigma} \qquad (1)$$

where σ is the constant tensile stress and ε(t) is the tensile deformation function.
In this case, D(t), is independent of stress [5]. If the material behaviour is still in linear viscoelastic domain at a given constant temperature, we can conduct the creep test at higher or smaller stresses and obtain the same resulting tensile creep compliance function.
When testing HMA one can easily cross the boundary of the linear viscoelastic behavior. This is shown in Figure 1 displaying the tensile compliance function (at temperature of 58° C) for two stresses (40kPa and 80kPa). At applied stress of 40kPa the tested material seems to flow with a constant viscosity after about 100s. When the tensile stress is increased to 80kPa the similar flow is first observed and then the sharp increase of D(t) follows. Thus the viscosity is not certainly constant nor it changes linearly with time. Clearly the boundary of the linear viscoelastic behavior was crossed.

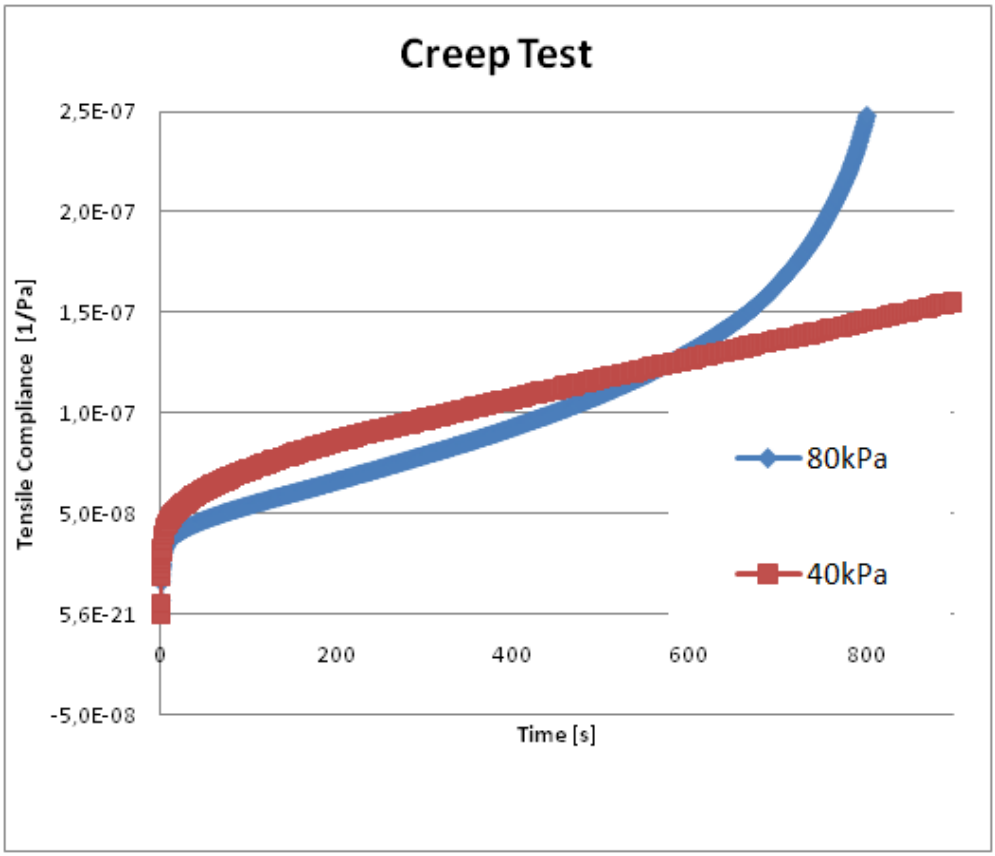

Figure 1: Creep test for HMA A

3. SMALL AMPLITUDE OSCILATIONS-TENSILE COMPLIANCE

The samples of HMA are quite often tested in small amplitude oscillation (sinusoidal) test. Such tests provide the relaxation and retardation spectra of the tested sample, in the linear viscoelastic domain, [8]. To achieve the most complete description of the material one has to perform the tests at several different temperatures and construct the master curves of the components of the complex tensile modulus (E* = E' + E''). The problem is that for a complete description of the tested material one usually needs more than ten Maxwell modes to achieve a good fit of the measured dynamic material functions (i.e. more than twenty parameters are needed). An example of such fit for tensile compliance using only five modes is given in Figure 2. Originally the data of tensile compliance, D(t), were obtained with the help of software IRIS [9] in which the master curves of E' and E'' were fitted to fifteen Maxwell modes. From the calculated spectra the tensile compliance was determined. The fit presented in Figure 2 was not very successful because only five Kelvin modes were used. The goal here was to decrease the number of parameters for the description of the tensile compliance. It is clear that to achieve this one has to change the fitting model of D(t).

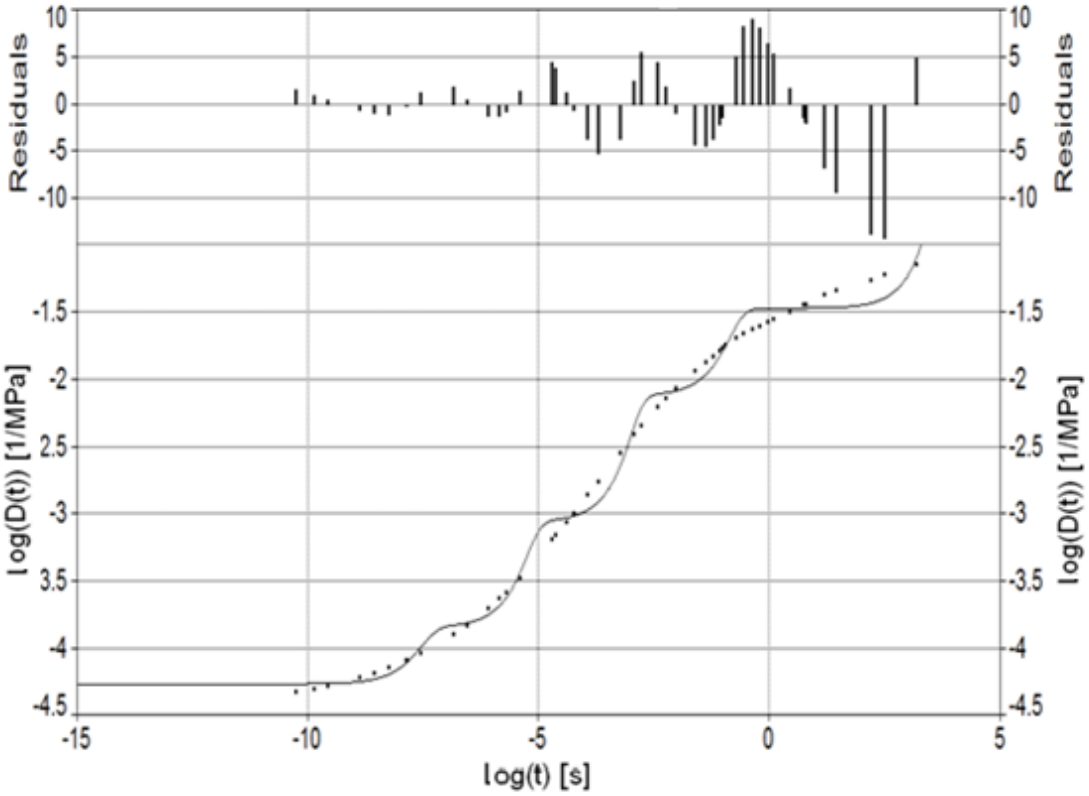

Figure 2: Correlation between D(t) HMA A and 5 Kelvin modes.

4. THE GAMMA-STRETCH MODEL OF TENSILE COMPLIANCE

The next model of D(t) taken into consideration was the Gamma-stretch model presented in [3]. This model assumes the constant viscosity, η, for the flow part of D(t). According to [3] the tensile compliance function can be written as follows

$$D(t) = D_g + D_D\left[1 - \frac{2(\sqrt{\alpha t})^{1+a}}{\Gamma(1+\frac{1}{a})} K_{1+\frac{1}{a}}\left(2 * \sqrt{(\alpha t)^a}\right)\right] + \frac{t}{\eta} \qquad (2)$$

Where $K_{1+1/a}$ is Macdonald's function [4] of order (1+1/a), Γ represents the gamma function, α is a reciprocal of time constant, D_g=D(0) is the glasslike tensile compliance, D_D is the delayed tensile compliance and η is the constant viscosity. The development of this creep compliance is described in [3].

This model requires only five parameters (D_g, D_D, α, a, η). From the Figure 3 it is obvious, that the Gamma-stretch model fit provides a quality fit of the tested linear viscoelastic data, function D(t). It is clear that for describing the tensile compliance of HMA under the applied tensile stress of 80kPa (Figure 2) the model (2) is not satisfactory because it can not describe the tertiary,[6], part of D(t). The possible "nonlinear" modification of (2) is given in the following paragraph.

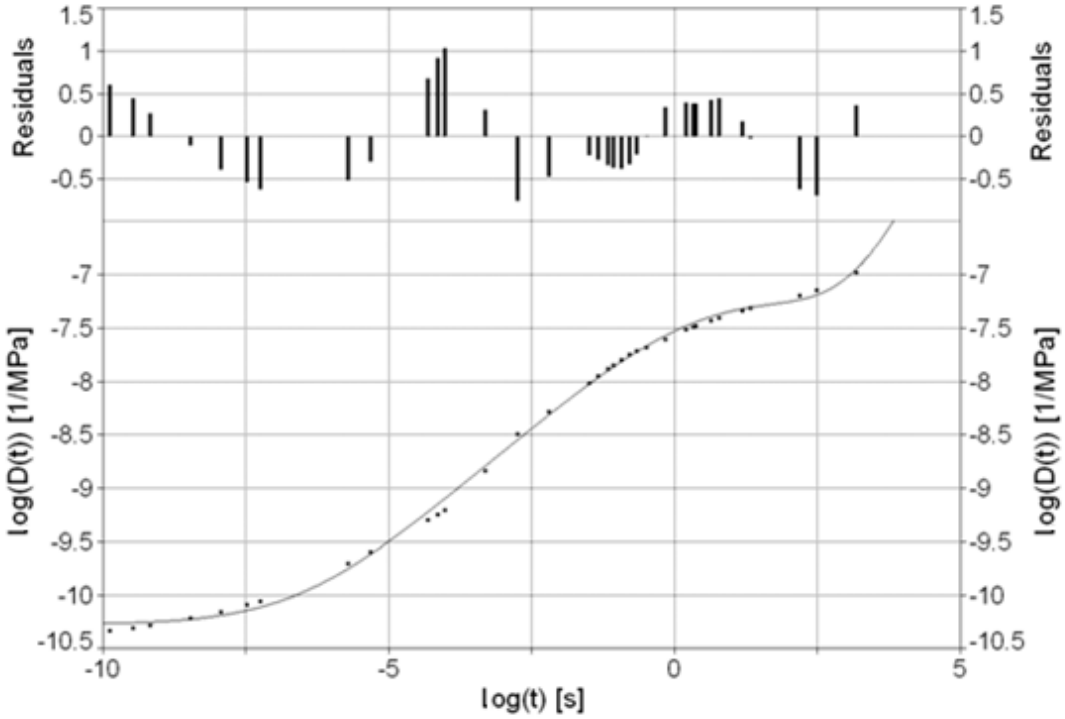

Figure 3: Correlation between D(t) HMA A and Gamma-stretch model

5. THE GAMMA-STRETCH 2 COMPLIANCE MODEL

To address the problems mentioned above, we looked for a modification of the Gammastretch model which would be able to:

- Minimize the residuals
- Improve the fit at long times
- Extend the usability of the model

Let us assume that η in (2) is not constant. The computed dynamic viscosity transformed to the time domain is illustrated in Figure 4. If we consider the similarities between E', E'', D'(t) and D''(t) of tested HMA and the properties of uncross-linked polymers of high molecular weight in [7], we can estimate the behaviour of viscosity at longer times and suggest the appropriate model of time dependent viscosity.

The real component η´ of the complex viscosity is related to the loss modulus by the equation (3):

$$\eta' = \frac{E''}{\omega} \tag{3}$$

As it is obvious from the above relation, in area where E'' is flat, η´ is inversely proportional to the frequency [7].

The equation used for fitting the course of viscosity was chosen so that it makes physical sense and is consistent with the behaviour of uncross-linked polymers of high molecular weight in [3].

$$\eta' = C_0 + \frac{C_\infty - C_0}{(1+(\beta\omega)^z)^b} \tag{4}$$

Where the C_0 represents viscosity for $\omega \to \infty$ i.e. $t \to 0$, C_∞ represents viscosity at long time, β is a time constant, and b is a power exponent. This viscosity model requires only four parameters (C_0, C_∞, β, b).

If we translate the frequency into the time domain in equation (4) and modify Equation (2), we obtain the model Gamma-stretch 2. The tensile creep compliance of the Gamma-stretch 2 model is then given as:

$$D(t) = D_g + D_D\left[1 - \frac{2(\sqrt{\alpha t})^{1+a}}{\Gamma(1+\frac{1}{a})} K_{1+\frac{1}{a}}\left(2\sqrt{(\alpha t)^a}\right)\right] + \frac{t}{C_0 + \frac{C_\infty - C_0}{\left(1+\left(\frac{2\pi\beta}{t}\right)^2\right)^b}} \tag{5}$$

The first estimates of parameters of viscosity in (5) can be obtained from (4) translated to the time domain, see Figure 4. Then the fit of the tensile compliance function can be improved, Figure 5.

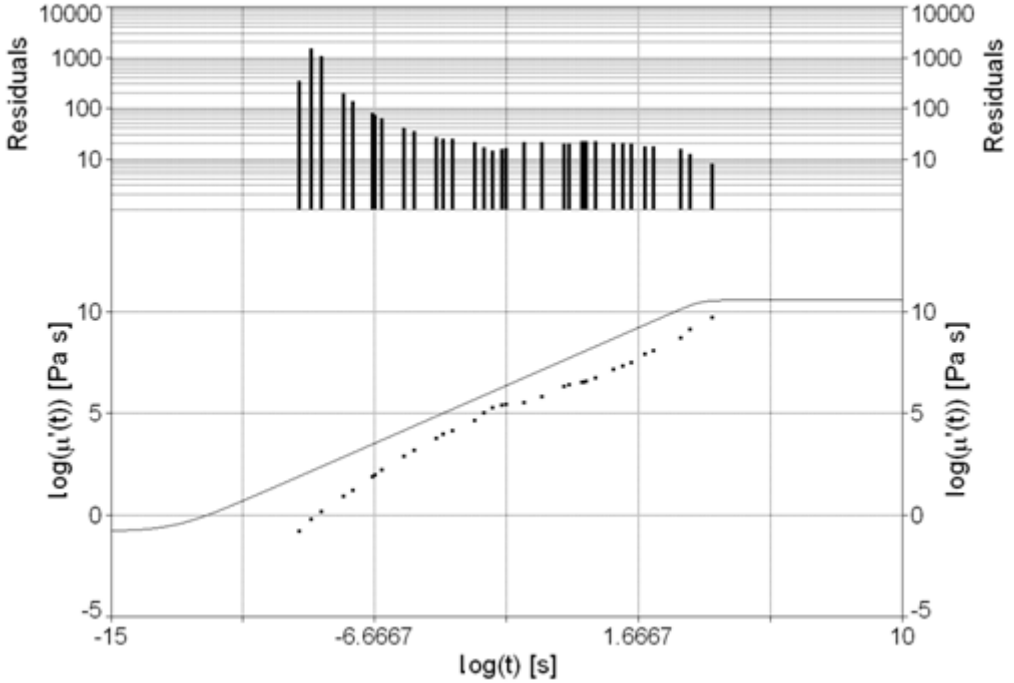

Figure 4: Character of viscosity model (3)

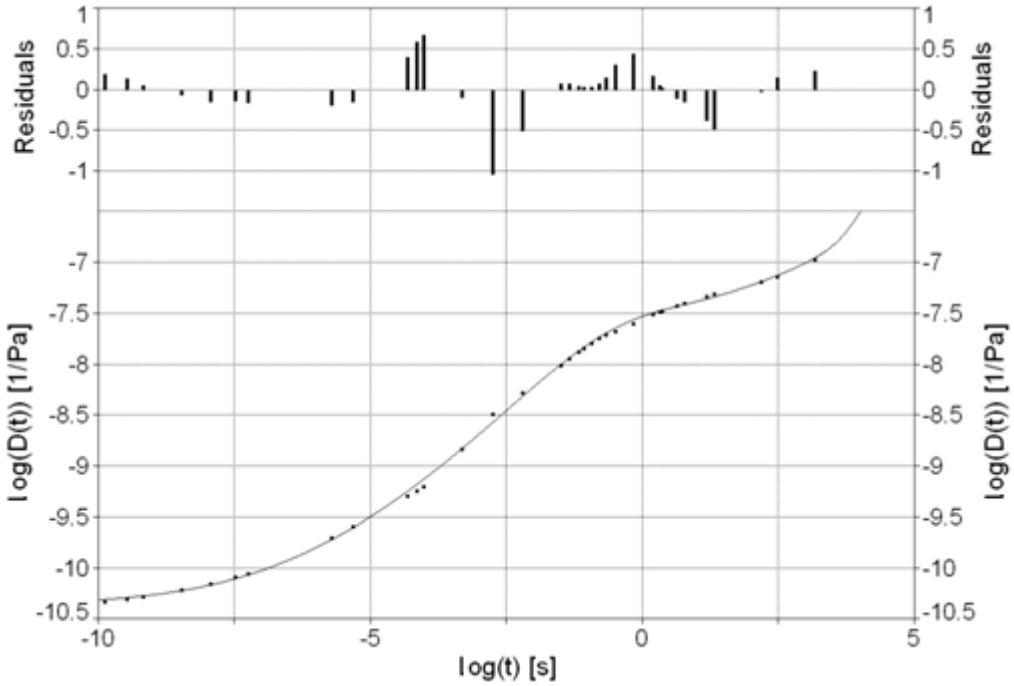

Figure 5: Correlation between D(t) HMA A and Gammastretch2 model

6. SUMMARY AND CONCLUSIONS

Hot mix asphalt is structurally complicated and non-homogeneous material. Despite its complicated structure it exhibits phenomenological viscoelastic properties similar to some polymeric materials. Based on such similarities the dynamic material functions of HMA can be determined in the linear viscoelastic domain. Thus from the obtained relaxation and retardation spectra all material functions (linear viscoelastic) can be calculated. In this contribution, the tensile compliance function D(t), of the studied HMA was studied and modeled. The classical (linear viscoelastic) description of HMA requires between ten and twenty modes (Maxwell/Kelvin). In an attempt to decrease the number of material parameters the two Gamma-stretch type models of D(t) were studied. It was shown that the model of D(t) with constant viscosity can describe the linear viscoelastic compliance of the studied HMA well. On the other hand it was also shown that the studied HMA can relatively easily cross the domain of linear viscoelastic behavior (depending on the temperature and the applied stress) and behave as a nonlinear viscoelastic material. In this case the first Gamma-stretch model would not be able to describe the experimental tensile compliance observed in the tensile test with high applied

stress. By assuming that the viscosity of HMA is not constant but it evolves in time the first model of D(t) was modified. With such modification the fit of linear viscoelastic D(t) was improved, especially at longer times. It has to be stressed that even this new Gamma-stretch model needs to be eventually modified when the complete tensile compliance (in the nonlinear domain) $D(t,\sigma)$ is to be satisfactory modeled.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Husky Energy Inc. for financial support and Mr. R. Wirth of the Department of Civil Engineering, University of Calgary, for his help in materials testing.
This paper has been supported by the research project SGS11/036/OHK1/1T/11 granted by the Czech Technical University in Prague.

REFERENCES

[1] Panda M., Mazumdar M. Utilization of reclaimed polyethylene in bituminous paving mixes. Journal of Materials in Civil Engineering, 2002, 14(6): 527-530.
[2] J.Zak, Wheel tracking test, Diploma thesis, Czech Technical University in Prague, 2011
[3] Giovanni Polacco, Jiri Stastna, Ludovit Zanzotto; Accumulated strain in polymer-modified asphalts; Rheo Acta 2008
[4] Gradshteyn L.S., Ryzhik L.M. Tables of Integrals, Series and Products. 1980, Academic, New York.
[5] Dealy J. M., Wissbrun K.F.; Melt rheology and its role in plastic processing Theory and application; Kluwer Academic Publishers; 1999
[6] Krishna P. Biligiri, Kamil E. Kaloush, Michael S. Mamlouk, Matthew W. Witczak; Rational Modeling of Tertiary Flow for Asphalt Mixtures; Journal of the Transportation Research Board; 2007
[7] Ferry J.D.; Viscoelastic Properties of Polymers 3rd edition; University of Wisconsin; 1980
[8] Baumgaerthel M., Winter H.H.; Determination of discrete relaxation an retardation time spectra from dynamic mechanical data; Department of Chemical Engineering, University of Massachusetts, Amherst (USA); 1989
[9] IRIS Development LLC. 2008, 14 Elm Street, Amhrest, MA 0100-2007, USA