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Nová chrakteristika asfaltových pojiv

New Characterization of Asphalt Binders

Summary

Asphalt binders are rheologicaly complex materials that exhibit viscous flow, elastic recovery and or plastic deformations at various temperatures. Because of its viscoelastic nature, asphalt behavior depends on both temperature and time of loading, these two are related. The behavior at high temperature over a short period is equivalent to what occurs at lower temperatures over long durations. This is often referred as time-temperature shift or superposition concept of asphalt. Unfortunately, universal constitutive equations have not been developed yet for these materials. Rheological description of asphalt binders is rather empirical and is more less based on extensive material testing, providing hypothesis applied in practice. North American Performance Grade (PG) specifications are introduced and posibility of the 2nd and the 3rd generation of Europian standards are discussed.

Contents

1. Introduction

It is necessary to introduce new, more exact tests, based on better understanding of asphalt rheological properties as well as the utilization of modern equipment. Even though the new specifications are called performance related, only further development and correlation with the performance of pavements, built by using these specifications will make them really “performance related”. Because the pavement quality, largely, depends on the properties and quality of asphalt, it is necessary to control binder properties as well. The important asphalt properties can be divided as follows:

- mechanical properties
- adhesive properties
- durability

In this presentation, the attention is given to the mechanical properties only. There are indications that paving mixes relates to the mechanical properties of asphalt binder. From the conditions of asphalts in paving mixes the specification requirements can be derived. Many conventional methods of the characterization of asphalts such as determination of the softening point temperature, penetration measurements, and ductility test are not acceptable for a rational characterization of viscoelastic behavior. They are either completely empirical or do not provide information on the time dependence of asphalt properties. Therefore, by using these tests one is not able to model or calculate the stress and strain fields.

Mentioned asphalt specifications have undergone considerable development in past 15 years. However, the relationship between the test results and the performance of asphalt in the pavement is still in the process of investigation, and mostly through the experience of the asphalt technologist. The temperature susceptibility is described quite insufficiently. For instance, up to late eighties, the lowest testing temperature in binder specifications was 25 ^{o}C, in some cases 0 ^{o}C, in the U.S.. The performance of the same asphalt grade varied because gradation system based on viscosity and penetration was not able to revealed all the differences. Current situation was even worsening with the increasing usage of modifiers in North America dated in late 80’s. The specifications become obsolete and “new” Strategic Highway Research Program (SHRP) came in to use. The intent of developing new classification was to characterize asphalts by their performance on the road and during their lifetimes. Superpave with its PG grading system was developed as a part of the SHRP program. In order to better characterize materials and thanks to new methods of asphalt testing, PG system is continuously revised.

Asphalt properties are changing during the time. The asphalt binder characteristics are different from storage-transportation, application and or maintenance. Each stage is as important as others, moreover, all have different demands and priorities on asphalt binder behavior.

Asphalt binder has to be in liquid stage, during the storage and transportation. Good workability is essential for easier pumping and handling and can be achieved by the sufficient viscosity of the material. On the other hand, binder has to be stable with the minimum amount of segregation, for a period during the storage. Asphalt binder is heated to high temperatures during mixing with aggregates. Therefore, temperature susceptibility has to be taken into the consideration. Main purpose of the binder in asphalt mix is to hold aggregates of different sizes and types together. It is important, that all particles are properly covered by asphalt film and created a good adhesion between binder and aggregate. Overall, constructed pavement has to perform at given conditions, which are determined by temperature, traffic and other climatic conditions. Certain failures as fatigue and termal temperature cracking occur during the lifetime of the pavements. The asphalt aging, evaporation of the lighter oils and or chemical changes in asphalt binder itself, may aggravate these errors.

2. Superpave Asphalt Binder Specification

Both American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM) agencies are currently evaluating the Superpave binder specification and the test methods used to characterize asphalt in it. Requirements are introduced in Canada and in the United States; implementation is coordinated by the U.S. Federal Highway Administration (FHWA), supported by User – Producer groups. The emphasis is given to the relation of tests; specification highlights such tests, which measure physical properties that can be related directly to the field performance. Tests are conducted at temperatures, which are encountered by in-service pavements. Several tests, as Table 1 shows, were adopted, improved or developed in order to fulfill SHRP specification.

Table 1. SHRP tests methods and characteristic.

SHRP Test	Purpose
Rolling Thin Film Oven (RTFO) test	to replicate conditions during the asphalt production and storage
Pressure Aging Vessel (PAV)	to simulate aging during the service life
Dynamic Shear Rheometer (DSR)	to measure binder properties at high and intermediate service temperatures
Rotational Viscometer (RV)	to measure binder properties for technological purposes (mixing, construction)
Bending Beam Rheometer (BBR)	to measure binder properties at low service temperatures
Direct Tension Test (DTT)	to measure binder at low service temperatures

2.1. Superpave Binder Aging Procedures

Asphalt binder ages primarily due to two different mechanisms: volatilization of light oils present in the asphalt and oxidation by reacting with the oxygen in the environment. Superpave employs RTFO procedure to simulate this form of aging. After asphalt pavement is constructed, aging continues, but the oxidation mechanism dominates because of the relatively moderate temperatures of the environment. The Superpave specification uses PAV procedure to stimulate this in-service aging.

Rolling Thin Film Oven test

The RTFO procedure can be found in AASHTO as T240 or in ASTM under D2872. RTFO test simulates chemical changes during the technological phase – mixing with aggregate, paving and storing the asphalt mix. The method serves two purposes, one is to provide an aged asphalt binder that can be used for further testing of physical properties. The second is to determine the mass quantity of volatiles lost from the asphalt during the process. Maximum mass loss requirement is specified to guard against using an asphalt binder that would age excessively from volatilization during hot mixing and construction. The maximum mass loss requirement is calculated. The mass loss for any grade must not exceed 1.00 percent.

Pressure Aging Vessel

AASHTO PP1 and ASTM D6521 refer to Pressure Aging Vessel. It should be noted that binder samples aged in PAV have already been aged by the RTFO. Consequently, PAV residue represents binder that has been exposed to all of the environmental conditions to which binders are subjected during production and service. The PAV apparatus consists of the pressurized metal drum and a forced draft oven. Air pressure provided by a cylinder of clean, dry compressed air with a pressure regulator, release valve, and a slow-release bleed valve. The pressure vessel is designed to operate under the pressure and temperature conditions of the test (2070 kPa and either 90°, 100°, or 110°C). The vessel must accommodate at least 10 sample pans in a sample rack. The PAV exposes the binder to high pressure and temperature for 20 hours to simulate the effect of long term aging.

2.2. Superpave principle

The Superpave asphalt binder specification is intended to improve performance by limiting the potential for the asphalt binder to contribute toward permanent deformation, low temperature cracking and fatigue cracking in asphalt pavements. Three main causes of errors are derived from the material behavior at high, intermediate and low temperatures respectively. One of the older specifications adopted by Superpave are pumping and handling of asphalt and safety during the production. The following section describes each specified characteristic, in order in which they appear in the specification.

Permanent Deformation

The total response of asphalt binders to load consists of the elastic and viscous components. Pavement rutting or permanent deformation is accumulation of the viscous component of the responses to load repetitions mainly at high service temperature. The Superpave specification defines and places requirements on a rutting factor $\left|G^*\right|/\sin\delta$, which represents a measure of the high temperature stiffness or rutting resistance of the asphalt binder.

Sample is tested in dynamic shear mode, plate – plate geometry. Testing procedure is described in AASHTO TP5 or ASTM under P246. Two sizes of plates are being used according to different testing temperatures (4 ~ 80^{o}C). Sinusoidal oscillatory loading is applied to the specimen at frequency 10 rad/s. To minimize rutting, $\left|G^*\right|/\sin\delta$ must have a minimum value of 1.00 kPa for the original asphalt binder and 2.20 kPa for the aged binder.

Fatigue Cracking

$|G^*|$ and δ parameters are also used in specification to help control the fatigue of asphalt pavements. Since fatigue generally occurs at moderate pavement temperatures after the pavement has been in service for a period of time, the specification addresses these properties using binder aged in both the RTFO and PAV. The DSR is used to generate $|G^*|$ and δ. The fatigue cracking factor is $|G^*|\sin\delta$. Low values of $|G^*|$ and δ are considered desirable attributes from the standpoint of resistance to fatigue cracking.

The theory of Superpave predicts asphalt binder fatigue cracking when sample reaches maximum of 5000 kPa for $|G^*|\sin\delta$ in DSR at given temperature. ASTM records the testing procedure under the code P246.

Low temperature cracking

When the pavement temperature decreases asphalt concrete shrinks. Since friction against the lower pavement layers inhibits movement, tensile stresses builds up in the pavement. When these stresses exceed the tensile strength of the asphalt mix, a low temperature crack occurs. Superpave low temperature investigation can be measured at two different apparatuses. Both tests give critical temperatures at which asphalt binder cracks on the road.

Procedure for Bending beam rheometer is recorded under AASTHO TP1 or ASTM P245. This method uses thin asphalt beams in a three point loading test. The BBR is used to apply a small creep load to a binder beam specimen and measure the creep stiffness. If the creep stiffness is too high, the asphalt will behave in a brittle manner, and cracking is more likely to occur. To prevent this cracking, creep stiffness has a maximum limit of 300 MPa. A high m-value, which represents the slope of the stiffness curve, is desirable because as the temperature decreases and pavement contraction begins to occur the binder will respond as a material that is less stiff. A minimum m-value of 0.300 after 60 seconds of loading is required by the Superpave binder specification. Direct tension test used to serve as a complimentary test, for low temperature properties up to mid 90's. It was recommended to use DTT if the BBR stiffness of the measured sample stays between 300 and 600 MPa. During the past three years, improvements in the test method contribute to large spread of DTT among agencies.

2.3. Asphalt Binder Grade Selection

Performance graded binders are selected based on the climate in which the pavement will serve. It is assumed, that the physical property requirements are constant among all binder grades. The distinction among the various binder grades is specified as minimum and maximum temperatures at which the requirements must be met. Table 2 lists the current binder grades in AASHTO.

Table 2 Superpave Binder Grades

High Temperature Grades (^oC)	Low Temperature Grades (^oC)
PG 46	-34, -40, -46
PG 52	-10, -16, -22, -28, -34, -40, -46
PG 58	-16, -22, -28, -34, -40
PG 64	-10, -16, -22, -28, -34, -40
PG 70	-10, -16, -22, -28, -34, -40
PG 76	-10, -16, -22, -28, -34
PG 82	-10, -16, -22, -28, -34

The Superpave binder selection is the basic procedure for typical pavement loading conditions. Thanks to Superpave, transportation agencies have a great opportunity to choose their own grade according to local needs as traffic, climate or financial availability. It is proposed that slow transient and standing load applications higher maximum temperature grades should be used. For slow moving design loads, the binder should be selected one high temperature grade to the right (such as a PG 64 instead of a PG 58). For standing loads, the binder should be selected two high temperatures to the right.

3. Viscoelastic behavior

Material which is not quite liquid nor behaves as an elastic body may exhibit behavior which combines liquid like and solid like characteristics. During the sinusoidally oscillating strain experiments, the stress is neither in phase with the strain, what elastic theory predicts, nor 90^o out of phase as in viscous liquid. Therefore, two theories, with idealized materials combined together create a new hypothesis called viscoelastic. Most materials exhibits linear or nearly linear behavior under small stress levels while the same material may have a nonlinear behavior at high stress levels.

The material is said to be linearly viscoelastic – sinusoidal input has to give the sinusoidal output. Stress is proportional to strain at given time and linear superposition principle holds.

3.1. Oscillatory shear

Because of the nature of our materials, it is the oscillatory shear, which is the most common method how to measure moduli at variety of conditions. Temperatures, frequencies and strain, mostly influence behavior of asphalt binders and tests conducted in oscillatory shear fully meets given requirements.

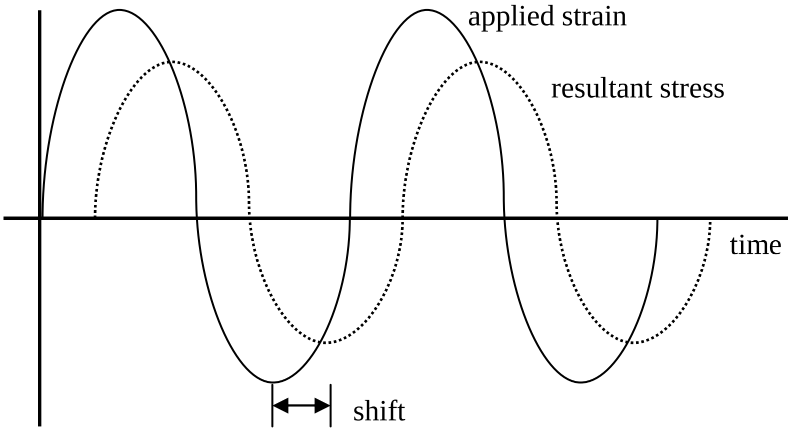
The strain and stress are functions of time and there are connected by a constitutive equation , where the linear viscoelastic material is in the simple shear , the constitutive equation has the form :

$$\sigma_{12}(t) = \int_{-\infty}^{t} G(t-t')\dot{\gamma}_{12}(t')dt'$$

where $\dot{\gamma}_{12}$ is the shear rate, $G(t-t')$ is the relaxation modulus and time goes from $-\infty$ up to the present time t.

According to the linear viscoelastic theory, when is the sample subjected to the sinusoidal shear strain $\gamma(t)$, which is defined by angular frequency ω and small amplitude γ_o, the stress will exhibit the same, but out of phase sinusoidal pattern as applied strain as depicted in figure 1.

Figure 1. Sinusoidal stress response to the of applied sinusoidal strain



The situation portrayed in the figure 1 can be described as follows:

For strain $\gamma(t)=\gamma_o \sin(\omega t)$ and rate of strain $\dot{\gamma}(t')=\omega\gamma_o \cos \omega t'$

After the substitution we received

$$\sigma_{12}(t)=\sigma_{21}(t)=\gamma_o\left[\omega\int_0^{\infty} G(t)\sin(\omega t)dt\right]\sin\omega t+\gamma_o\left[\omega\int_0^{\infty} G(t)\cos\omega t dt\right]\cos\omega t$$

The integrals in the brackets are functions of frequency only, thus equation can be rewritten as:

$$\sigma_{12}(t)=\sigma_{21}(t)=\gamma_o(G'\sin(\omega t)+G''\cos(\omega t))$$

where G', G'' are the shear storage and the shear loss moduli. The name of G' is derivative form the energy storage and release during the oscillatory deformation. The loss modulus G'' is associated with the dissipation and energy loss as a heat during the cycling. Using the trigonometric relationships, equation can be written as:

$$\sigma_{12}=\sigma_{21}=\sigma_o\sin(\omega t+\delta)=\sigma_o\cos\delta\sin\omega t+\sigma_o\sin\delta\cos\omega t$$

Here, $\sigma_o(\omega)$ is the stress amplitude and $\sigma(\omega)$ is the phase angle between stress and strain. By comparison, one obtains:

$$G'=(\sigma_o/\gamma_o)\cos\delta$$

$$G''=(\sigma_o/\gamma_o)\sin\delta$$

$$G''/G'=\tan\delta$$

The modulus can be expressed in the complex form:

$$G^*=G'+iG''$$

$$G^*=|G^*|e^{i\delta}$$

$$|G^*|=\sigma_o/\gamma_o=\sqrt{G'^2+G''^2}$$

Analogically, oscillatory experiments can be expressed in terms of a complex compliance. Relation between complex modulus and complex compliance is straight forward. Compliance expresses strain – stress ratio, the inverse value to the modulus.

$$|J^*|=1/G^*=J'+iJ''$$

where J' is the storage and loss J'' compliance

Various relationships between dynamic functions are thus obtained:

$$G' = \frac{J'}{J'^2 + J''^2} = \frac{1/J'}{1 + \tan^2 \delta}$$

$$G'' = \frac{J''}{J'^2 + J''^2} = \frac{1/J''}{1 + \left(\tan^2 \delta\right)^{-1}}$$

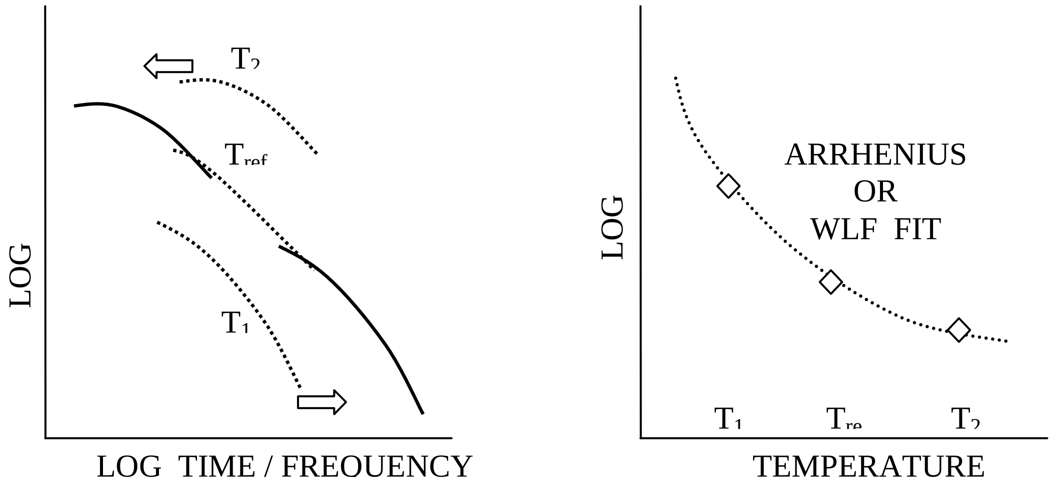
$$J' = \frac{G'}{G'^2 + G''^2} = \frac{1/G'}{1 + \tan^2 \delta}$$

$$J'' = \frac{G''}{G'^2 + G''^2} = \frac{1/G'}{1 + \left(\tan^2 \delta\right)^{-1}}$$

3.2. Time temperature superposition principle

All commercial rheometers can measure dynamic viscoelastic functions in a limited frequency region, which usually does not exceed three decades for given temperature. It is obvious from previous chapters that asphalt binder and asphalt concrete are subjected to wide range of frequencies. The principle of time temperature superposition (TTS) is well known for decades in polymer industry and provides us with a convenient way of extending the range of measured data. The procedure for the time-temperature superposition is straight forward. For high molecular weight materials such as asphalt binders the molecular structure freeze in and the molecular motion slows down. This stage is called glass transition temperature T_g. A series of oscillation experiments is performed over several decades of frequency at different temperatures above T_g of the material. The moduli are plotted against frequency on logarithmic axes. An arbitrary temperature, usually the one near the centre of the temperature range, is selected as a reference (T_{ref}). The data for the next highest temperature are then shifted to lower frequencies by a factor a_T, until there is correspondence between the overlapping regions of these and the reference curve. The process is repeated for each higher temperature in turn. Lower temperature data are similarly brought onto the reference curve by shifting to higher frequencies. Simultaneously, b_T horizontal shift is applied. The shift represents volume changes and can be measured by densitometer. The resulting plots of modulus against $a_T\omega$ are referred to as master curves of different moduli, Figure 2; where $a_T\omega$ is known as the reduced frequency. The loss and storage moduli (G’, G’’) and their ratio ($\tan\delta$), can all be shifted, by the same shifting factor (a_T must superpose all viscoelastic functions).

Figure 2 Schematically depicted time temperature superposition principle



References using TTS for asphalt binders are dated back to late sixties and seventies [1], but it was Goodrich [2], who popularized this method ten years later in North America. Since then, the idea of shifting of viscoelastic functions (e.g. G', G'') and its time/frequency dependency was adopted by many asphalt scientists, for others [3] the Black diagram is more acceptable. Materials, which obey the principle of TTS are said to be thermorheologically simple. TTS theory was found valid for most polymeric materials many examples are given by Ferry [4]. It has been shown that asphalt binders follow TTS principle as well.

In this presentation, data obtained by oscillations at different temperatures and frequencies, are used. The method shows the possibility to shift any dynamic mechanical data (e.g. G', G'') in a frequency/temperature domain.

3.3. The relaxation and retardation spectra

Theoretically, any transient viscoelastic data obtained by TTS can be expressed by discrete relaxation time spectrum. It allows prediction of linear stress responses and calculation of other viscoelastic functions as G(t), J(t), etc. . For infinite number of Maxwell elements, the discrete spectrum can be converted in to continuous relaxation spectrum H(λ), which can be defined on the interval $\{\lambda, \lambda + d\lambda\}$ [5,6]. Equation can be written as:

$$G(t) = G_e + \int_{-\infty}^{\infty} H e^{-t/\tau} d \ln \lambda$$

where, G_e is the equilibrium modulus (or plateau modulus) for viscoelastic solid. For viscous liquids, G_e approaches zero value.

The easiest way, how to determine the relaxation spectrum is to measure storage G' and loss G" moduli. The discrete relaxation time spectrum (g_i, λ_i) with i = 1,2,3...n approximates the dynamic moduli, G' and G".

$$G'(\omega) = G_e + \sum_{i=1}^{n} g_i \frac{(\omega\lambda_i)^2}{1+(\omega\lambda_i)^2}$$

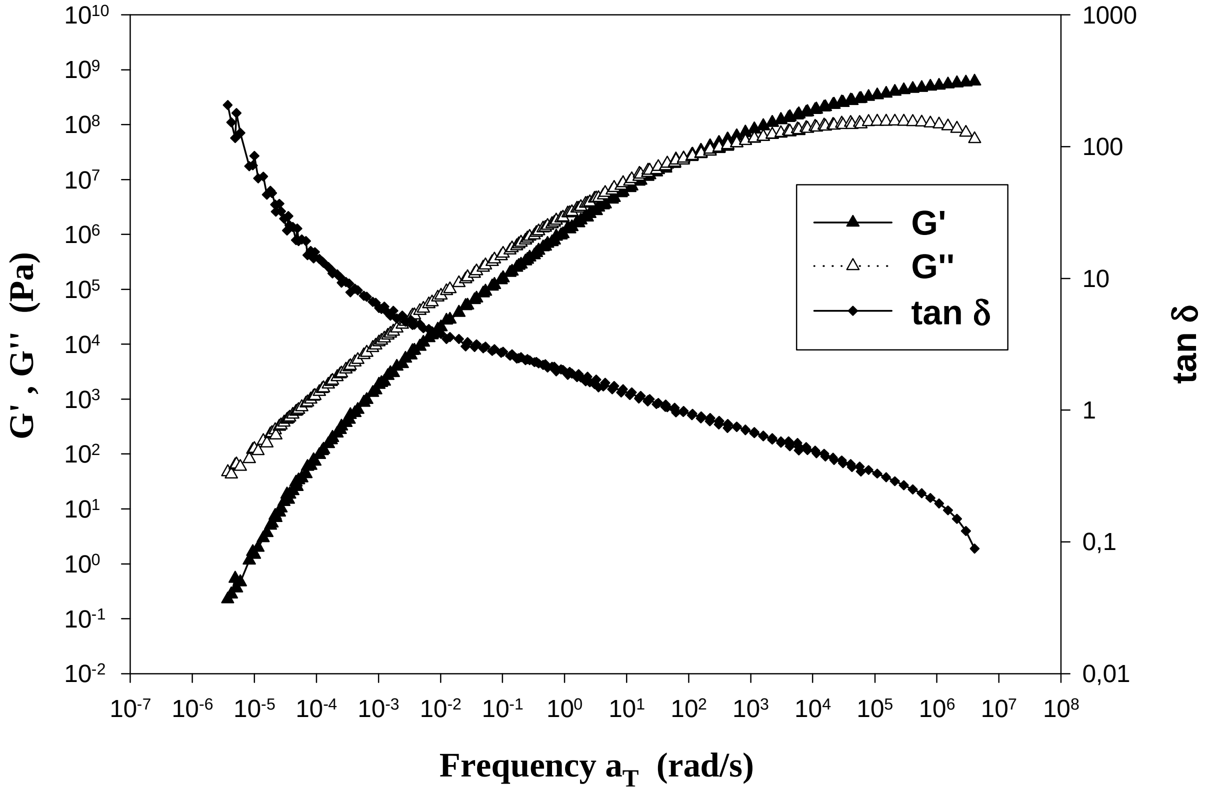
$$G''(\omega) = \sum_{i=1}^{n} g_i \frac{\omega\lambda_i}{1+(\omega\lambda_i)^2}$$

Baumgärtel and Winter have developed a robust numerical method which converts dynamic mechanical data from the frequency to the time domain and calculates the discrete spectrum. The advantage is in simultaneous fitting of G’ and G’’ during the spectra calculations.

4. Results

Following graphs show results based on the theory described in chapter 3. Dynamic data of asphalt binder are being plotted against reduced frequency and master curve of original measured data is created at reference temperature T_{ref}. of zero degrees Celsius, figure 3. This would provide material characteristic in vast frequency rage of 13 orders magnitude.

Figure 3. Master Curve of Asphalt Binder



In order to shift each recorded data set in to the desired position, vertical and horizontal shit is also plotted, figure 4. Using the relaxation and retardation spectra calculation, compliance J(t), figure 5, and relaxation modulus G(t) can be calculated with respect to time.

Figure 4. Vertical and horizontal shift factors for given master curve

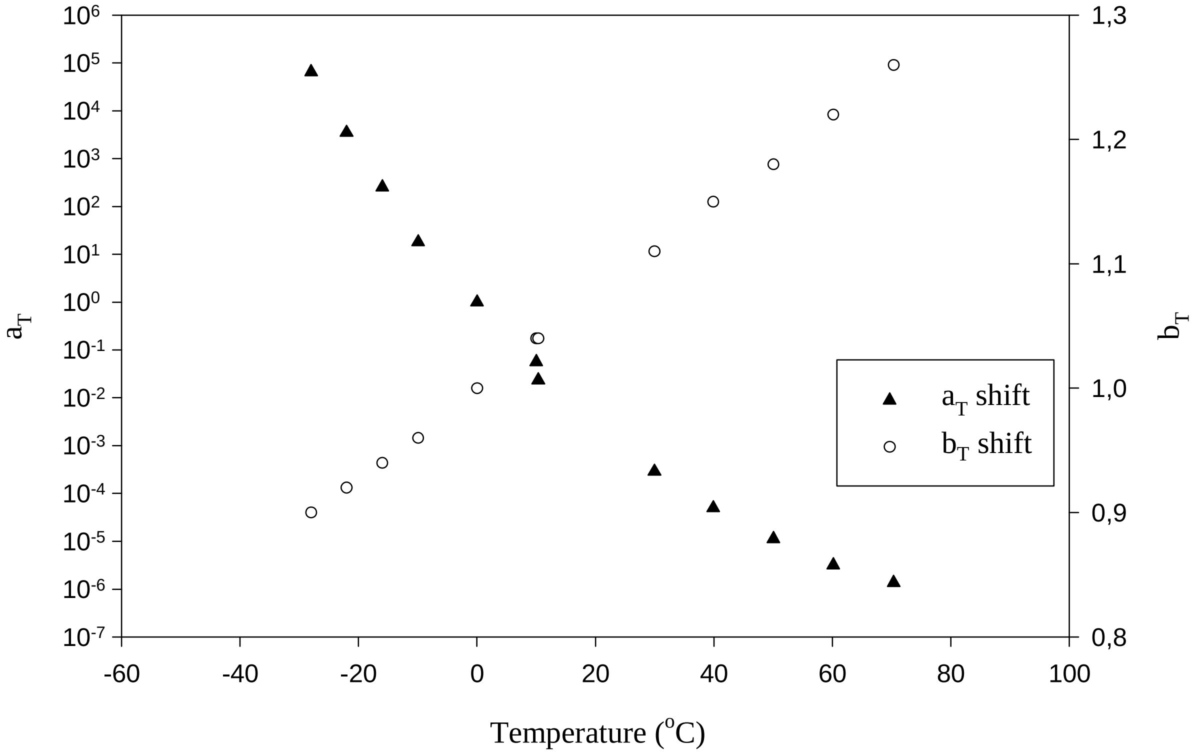
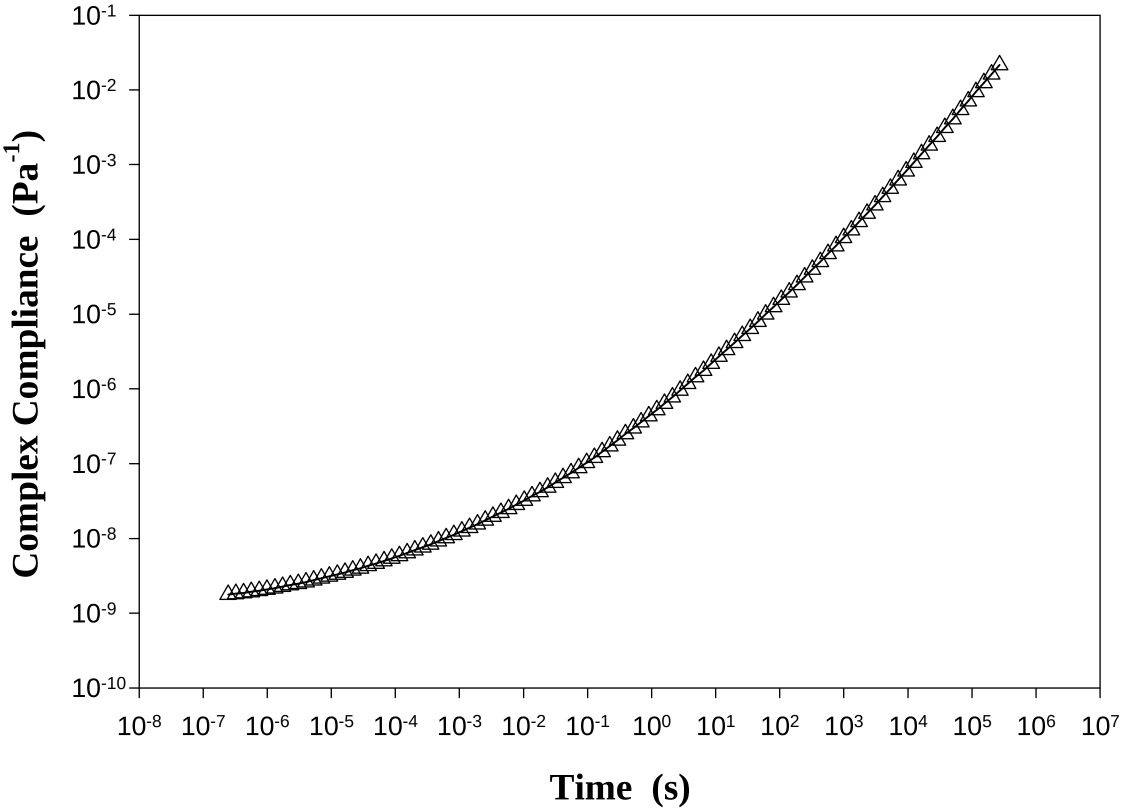


Figure 5. Complex compliance for given master curve



5. Conclusions

In order to be able to characterise the performance of an asphalt concrete, one should start from asphalt binder :

- parameters currently used threshold as $|G^*|/\sin\delta$ and $|G^*|\sin\delta$ should be reevaluated,
- list of relevant test methods to quantify the performance characteristics should be introduced,
- performance characteristics, a procedure described in chapters 3 and 4 gives important material characterization, with the potential of better time – temperature prediction
- additional (new) test methods as creep , repeated creep etc. may be necessary to better characterize bituminous materials,
- it is believed that low temperature characteristic of asphalt binders should be evaluated on asphalt concretes.

Next to this the asphalt industry also would like to have other/additional tests to prove the behaviour of Long Life Asphalt; e.g. tests for its ageing performance and its durability. A set of sophisticated performance tests is needed for the high performance mixes. With the new techniques they can improve their product by better material characterization.

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Curiculum Vitae

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More than a decade of professional experience and success in the research and study of asphalt binder technologies, asphalt concretes, technical support and laboratory operations. Dr. Vacin has a particular experience in asphalt binder rheology, modified binders properties and asphalt binder low temperature investigation. From 2003-2005, he served as a Research Assistant Professor in the department of Civil Engineering at the University of Waterloo and a member of the Centre of Pavement and Transportation Technology (CPATT), Canada. Mr. Vacin is a member of several scientific associations and author of numerous international publications. He is currently Associate Head at Department of Road Structures, Faculty of Civil Engineering, Czech Technical University in Prague.

Education:

1998–2003	University of Calgary (PhD.) ,Calgary, AB, Canada Department of Civil Engineering, Bituminous Materials Chair PhD. Program, thesis entitled: “Rheological Properties of Asphalt Binder, Mastic and Hot Mix Asphalt “, 2003
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Training Corses:

2005	Advanced Constitutive Modeling of Asphaltic Materials, College Park, MD, USA
2004	Merging Experiment with Theory in Rheology, Amherst, MA, USA
1999	Superpave Asphalt Mix Design and Construction, Lexington, KY, USA
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