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8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements

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Preface

A pavement is a complex structure composed of several layers made up of different types of heterogeneous materials. This multilayer system rests on a semi-infinite soil and is subjected to severe climate variations and heavy traffic loads. In their lifetime, pavements undergo degradation due to different mechanisms, of which cracking is among the most important. To appraise this type of degradation in mechanical analyses, boundary conditions applied to the pavement structure must be known. Moreover, the damage and the fracture behavior of all the material layers as well as interfaces must be understood.

Prior to 2000 and at the initiative of the Rilem Technical Committee (TC) 97-GCR (application of Geotextiles to Crack prevention in Roads) led by Louis Francken, a series of four international RILEM conferences on “Reflective Cracking” was held in Liege (RC1989) (RC1993), Maastricht (RC1996) and Ottawa (RC2000). The objective was to present up-to-date information on the rehabilitation of cracked roads with bituminous overlays which was the solution adopted worldwide to delay the cracking propagation in pavements (see the TC 157-PRC document).

To approach cracking problems in pavements in a more general sense, the scope of the conference was extended to other modes of cracking modes such as fatigue, aging, or top-down cracking. Then, a successful series of three conferences on “Cracking in Pavement” was held in Limoges (CP2004), Chicago (CP2008) and Delft (CP2012).

The purpose of the 8th Rilem international conference is to coordinate with the activities of the Rilem TC 241-MCD (2011–2016), which aims at developing a deeper fundamental understanding of the mechanisms responsible for cracking and debonding in asphalt concrete and composite (e.g., asphalt overlays placed on PCC or thin cement concrete overlay placed on asphalt layer) pavement systems. The objective of this event is to present the results of TC 241-MCD as well as the latest advances in research to analyze mechanical damage and its detection in multilayer systems. This will favor discussions between different research communities to help apply these advances to pavement structures. Eventually, the aim is to be able to better detect the initiation and the propagation of cracks in pavement and also to have tools that make possible the search for technical solutions able to prevent (or to limit) cracking in usual and emergeing structures.

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Part II Cracking in Asphalt Materials: Material Crack Characterization

Part I
Cracking in Asphalt Materials: Fundamental Bituminous Material Characteristics

Cracking and Linear Visco Elastic Binder Properties

Geoffrey M. Rowe, Mark J. Sharrock and Sérgio Raposo

Abstract The contribution of an asphalt binder to the cracking performance of a mixture is strongly influenced by information relating to the relaxation properties and stiffness. In the 1980s considerable interest existed in the relationship between the relaxation properties and cracking. The relaxation spectra can be captured by the R-value over a limited range of stiffness. This can be related to bottom up fatigue, durability and thermal cracking when the stiffness information is known. Analysis has been presented that demonstrates the interrelationship between parameters used in France, United Kingdom and the USA through linear visco-elastic modeling of a limited region of the master curve. This has been used in several studies recently and has been shown to be useful for judging material used in airfield, high RAP products and other additives in the asphalt market. The use of the linear visco-elastic methods can also lead to a better understanding of methods used to describe fracture—for example the Vialit pendulum test and the direct tension test. While these tests are conducted often in a non-linear region the data can be better explained when interpreting the stiffness results with a frame work developed by linear visco elastic considerations. The paper discusses some aspects of the techniques for development of master curves, interrelationships, linear visco-elastic properties and the relationships between the various parameters proposed for use in different countries.

Keywords Rheology · Relaxation · Cracking · Interrelationships

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1 Importance of Relaxation

In the late 1960s Jongepier and Kuilman (1969) described the relaxation spectra by using a log-normal distribution. This work was further adopted by Ishai et al. (1988) to describe standard deviation of relaxation spectra, "S". While the concept of relaxation spectra involves the consideration of complex mathematic techniques the parameters of interest can be derived similarly by inspection of the resulting master curve in a Black space as noted by Ishai et al. (1988) since it effectively describes the shape of a master curve of G* versus phase angle or frequency. The importance of this description was recognized by Moutier et al. (1990) in that it provided the best correlation with the fatigue of asphalt mixes when considering a range of binder parameters, as shown in Fig. 1a. This was noted to be related to fatigue cracking of road pavements in France.

In the derivation of the CA model the shape of the relaxation spectra was also considered to be skewed from the distribution assumed in the earlier work (Christensen 1992) and this led to the development of the Christensen-Anderson model which defined the complex dynamic modulus as a function of a cross-over frequency, glassy modulus and a rheological index (R).

The R defined above was noted as being "directly proportional to the width of the relaxation spectra" by Christensen and Anderson (1992) and consequently while it is somewhat differently formulated to the "S" used by Ishai et al. (1988) a unique relationship exists between "R" and "S" (Rowe 2015). Differences in the numerical values of "R" and "S" are chiefly due to (log 2) constant used in the CA model and to a minor extent the shape of assumed for the master curve. Other workers such as Dobson (1972) and Dickinson and Witt (1974) have also defined parameter which describes the shape of the master curve in a similar manner to R. The direct correlation between R and these other parameters allows use of the correlations and

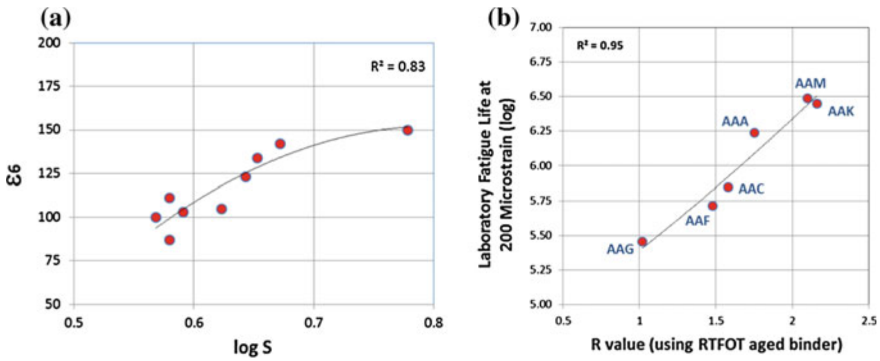

Fig. 1 **a** log S (standard deviation of relaxation spectra) versus strain required to fail a fatigue specimen in 10^6 load applications, **b** rheological index (relaxation parameter from CA model) versus life (log) at 200 micro-strain

data obtained from these experiments to justify the significance of the meaning of the R value used in more recent work.

Some important differences exist in the work developed in this paper compared to the original formulations of the CA model. In this work it has been assumed that temperature dependency is described by variable factors. This is generally a more accepted step in general rheology studies. The fixed values proposed in the SHRP work have not been used. Shift factors move the position of an isotherm with reference to a given temperature to another location on the time or frequency axis. Shifting to produce smooth master curves of stiffness applies when a material exhibits thermo-rheologically simple behavior. That is when isotherms of stiffness (expressed on log scales) are shifted either the log of time or frequency axis then they shall form a smooth curve. The same shift shall apply for all the visco-elastic parameters, e.g. G′, G″, G* and δ. Rowe (2015) has previously detailed the methods used to develop master curves from a combination of DSR and BBR data which involves interconversions from S(t) to G* and δ. The CA model is used with constraints on stiffness ranging from 10^5 to 10^9 Pa (Christensen 1992; Rowe 2014). Recently the relationship between the relaxation spectra H(τ) as defined by the CA has been shown in the form of a closed form arithmetic expression (Christensen et al. 1992).

With regard to the importance of this parameter to fatigue and cracking, the correlation of the R value from the recent testing described in this study can be compared to work conducted as part of the validation effort conducted for the mixture performance tests (Deacon et al. 1994). For mixture testing the preferred method adopted by the SHRP A003A team was the bending beam fatigue test. If we use the data within used by Deacon et al. (1994) and compare this with the R value for the RTFOT binder condition we obtain a very high correlation with performance. This example uses a Limestone aggregate which was given the code “RD” during the SHRP program. The performance is shown against the RTFOT ageing condition which has an r^2 value of 0.95, see Fig. 1b. If original or PAV properties are compared the r^2 values are 0.90 and 0.99 respectively. A similar high correlation is not evident with the values of R published at the time of the SHRP study and this may be a result of the determination of R including some different assumptions such as fixed parameters for the temperature susceptibility. This data set is consistent with the earlier work reported by French workers that longer fatigue life associated with traffic loading is obtained with higher values of R.

2 Stiffness Range to Describe Fracture Properties

When evaluating fatigue and fracture one of the major considerations is to consider the time of loading and temperature being used in the test. For many years it has been know that the fracture properties of asphalt binders and mixtures can be related to the binder stiffness (Heukelom 1966). While with newer materials the values of strength may vary (expressed as stress, strain or energy dissipated at an

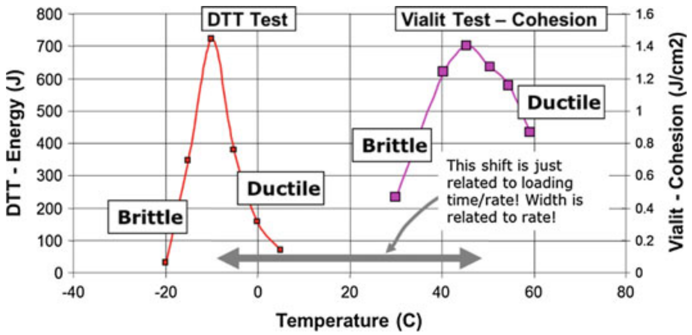

Fig. 2 Comparison of Direct Tension Test (energy under load vs. deformation curve) with Cohesion in Vialit test demonstrating difference in position of peak and width of curve produced

ultimate condition), the range of binder stiffness which typifies the brittle to ductile/flow fracture condition appears to be in the range 1 MPa to 1GPa (Rowe 2016).

The range of stiffness that can be described by the CA model cover this range adequately and thus the CA model provides a useful descriptive tool that can be related to both brittle and ductile fracture properties. The transitions that occur in typical "fracture" or "ultimate" tests can be related to this stiffness range. For example, while the peak temperatures obtained from the Vialit Pendulum Test (VPT) are significantly higher is has been demonstrated that similar ultimate property curves are obtained, which can be better understood if time/rate of loading is included in the calculations (Rowe 2014). For example the data shown in Fig. 2 shows a typical DTT result and a VPT compared to temperature. The differences in position on the temperature scale and the temperature ranges representing brittle to ductile/flow properties for the DTT data (which is much narrower) compared to that from the VPT data, can be directly related to the time of loading differences in the two tests.

If the stiffness of the binder is the controlling factor affecting the temperature spread then it can also be postulated that temperature spread can be considered to be related to the temperature susceptibility of the binder in some manner. This could be defined by an empirical measure or better understood by considering isochronal information which would be dependent upon the rheological fitting parameters. When polymer modified systems are compared to those for conventional binders a much more significant peak and temperature range are obtained. The differences in the results relate to the amount of energy needed to form the fracture surfaces and should be related to a slower rate of crack propagation associated with a tougher material. While this aspect has been traditionally considered for surface treatments with this type of test, conceptually it could be evaluated for asphalt mix performance.

3 Relationships with Cracking

Using stiffness information collected in the LVE region various authors have proposed different measures that relate to cracking (either cold temperature or durability cracking). For single event cold temperature cracking s value of S(60s) and m(60s) of 300 MPa and 0.300 have been used as criteria. These can be related to dynamic properties of G* = 111 MPa and δ = 26.2° (Rowe 2014). The Glove-Rowe parameter (G*cos δ^2/sin δ) has also been shown to relate to cracking (durability). Conceptually the G-R concept can also be used to capture single event cold temperature cracking (Rowe 2014). The visco-elastic transition (VET) concept has been promoted in the UK and it can be shown that these parameters can be calculated directly from the CA-Kaelble model fit parameters. A comparison of USA and UK binders are shown in Fig. 3 along with the values of the G-R parameter. The trend between these parameters is consistent with the various rheological parameters determined.

A further parameter which is currently showing increasing interest is the ΔTc as defined by the difference in critical temperature defined by the S(60s) = 300 MPa and m(60s) = 0.300. This parameter can be directly calculated from the CA-Kaelble model fit or easily deduced from BBR tests. It is strongly dependent upon the R value as are the other parameters discussed.

The parameters discussed above are all related to the stiffness and relaxation properties of the binder in the LVE region.

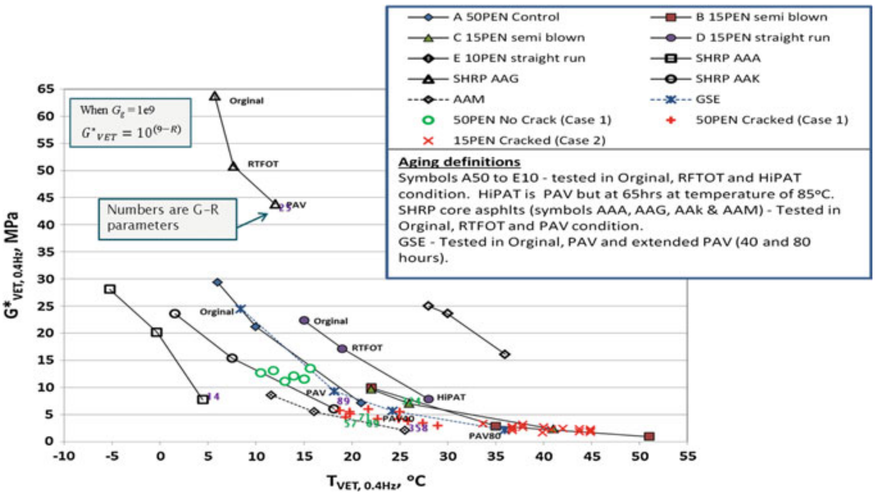

Fig. 3 Linear visco-elastic transition temperature parameters compared to G-R concept for various asphalt binders

4 Conclusions

Based upon the information presented in this paper and referenced work, we can conclude the following:

- Understanding the relaxation properties are critical for developing specifications that relate to cracking.
- The CA model rheological index (R) value is a good shape descriptor of the relaxation spectra as it relates to cracking.
- Fatigue and durability cracking are both related to the relaxation properties as defined by the R-value and the stiffness in the range $1e^5$ to $1e^9$ Pa.

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Evaluation of Fatigue Behavior of Aged Asphalt Mixtures Using the Simplified Viscoelastic Continuum Damage Model

Lucas F. de A.L. Babadopulos, Jorge B. Soares, Jorge Luis S. Ferreira and Luis Alberto H. Do Nascimento

Abstract Aging of asphalt mixtures might play an important role in pavement structural behavior. That should be evaluated using mechanical models. This work aims at identifying the effects of aging on linear viscoelastic and damage behavior of asphalt mixtures, properties that influence the fatigue life of asphalt pavements. That is performed by characterizing a Hot Mix Asphalt (HMA) at four different aging states. The aged materials were obtained by heating loose asphalt mixture in oven at two different temperatures (85 and 135 °C) and aging times (2 and 45 days). Prony series were fitted to complex modulus results. For damage characterization, the Simplified Viscoelastic Continuum Damage (S-VECD) model was adopted. Damage characteristic curves and G^R versus N_f failure envelopes were obtained from controlled crosshead tension-compression test results at 19 °C. It was concluded that aging produces materials that fail for less evolved damage states. However, depending on pavement conditions and layer geometry, and considering the HMA hardening, aging does not necessarily reduce the fatigue life.

Keywords Asphalt mixtures · Aging · Fatigue modeling · S-VECD

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1 Introduction

Asphalt pavement analysis adopts asphalt mixture properties obtained from specimens fabricated without long-term aging. Nevertheless, asphalt mixtures are known to age as time passes. Although Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV) tests are currently used for comparing unaged and aged asphalt binders, there is still no recommended method for considering changes in the constitutive behavior of asphalt mixtures due to aging. This work focuses in evaluating the change in fatigue life that asphalt mixtures can present upon aging.

2 Literature Review

Park et al. (1996) presented an application of Schapery's work potential theory that would later produce the S-VECD model, which describes the damage behavior of asphalt mixtures. AASHTO TP 107 (2014) presents test procedures and the calculation process that ends up with the damage characteristic curve (C vs. S curves) for a given material. Such curve relates material integrity (C) to damage accumulation (S), which is a function of the loading history (Underwood et al. 2012). Some of the fatigue failure criteria presented in the literature define a maximum acceptable percentage loss in modulus, usually 50 %. This criterion does not consider differences between the capabilities of materials to undergo damage. Other criteria are based on energy dissipation or on the phase angle trend, which is generally associated to the coalescence of microcracks into macrocracks (failure). In experiments, those criteria are observed to be mode-dependent, thus, not accessing material properties. Contributions by Sabouri and Kim (2014) allowed the combination of the phase angle drop criterion with a pseudo strain energy-based variable, producing a mode-independent failure criterion for fatigue. That variable is the averaged rate of release of the pseudo strain energy (per cycle), G^R, throughout the entire history of the test. Its relation with the number of cycles to failure (G^R vs. N_f curve) for a given asphalt mixture was found to be linear in log-log axis.

In order to simulate asphalt mixtures aging in the laboratory, one can use ovens, either with compacted samples (Walubita 2006; Baek et al. 2012) or with loose samples, prior to compaction (Partl et al. 2012, RILEM TC206 procedure). The main advantage of aging compacted samples is that compaction problems will not be observed after aging. However, this procedure leads to a heterogeneous aging of the sample. The main advantage in loose mixture aging is that a more homogeneous aged mixture is obtained, even though it is noticed that compaction is influenced by the aging state of the material (Babadopulos 2014).