Cracking of asphalt pavements and the development of specifications with rheological measurements

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ABSTRACT

The use of linear visco-elastic analysis methods for the characterization of asphalt binders has gained popularity since the wide introduction of rheometers in the early/mid 1990s. The use of the G.sin(delta) parameter for fatigue cracking has been suggested as lacking the validation with field performance. However, this parameter at the intermediate temperature results in a required rheological index for the asphalt binder. The rheological index can be considered to be related to the requirement for grading at an intermediate temperature and can be expressed as a function of delta(t), the difference between the low temperature grade specified and the temperature used for the intermediate grade requirement. The R-value as developed by Christensen and Anderson is related to the relaxation spectrum and this is related to many of the parameters that correlate to cracking. For example French workers have suggested that the standard deviation of the relaxation spectra was an important consideration. Other concepts such as the Glover-Rowe parameter, visco-elastic transition temperature (VET) and/or the use of phase angle to understand fatigue can all be related to this R-value. This paper discusses the development of the specification around the concept of R-value and how this is controlled within the current specifications and the interrelationships between this parameter and various cracking studies.*

Keywords: Durability, Fatigue Cracking, Performance based standards, Rheology

1. INTRODUCTION

Bituminous binders can be regarded over a certain range of temperatures and loading times/frequency as thermo-rheologically simple linear visco-elastic materials, provided that the load defined by either the stress or stain magnitude is kept with certain limits. Rheology has been used routinely for the specification of asphalt binders since the early 1990s following the work conducted during the Strategic Highway Research Program (SHRP). The choice of the parameters initially by the SHRP research team included a parameter which was related to the temperature dependency of the binder in the early versions of the specifications [1]. The model developed for asphalt binder in the SHRP program described the binder rheology using a skewed logistic function which included the definition of the R-value which is termed as the Rheological Index [2]. This rheological index describes the shape of the master and is effectively related to the relaxation spectra that would describe a particular asphalt binder [2]. The final specification adopted after SHRP included single point values, defined as the measurement of a visco-elastic frequency (or time) and temperature dependent value at a single frequency (or time) and temperature. The rheological parameters adopted in the initial version of the specification (at that time termed AASHTO MP1) were G*/sinδ (10 rads/sec) for the high temperature, G*.sinδ (10 rads/sec) for the intermediate temperature and S(t) and m(t), where t= 60 seconds, for the low temperature consideration. Each of these measurements defines a given rheological property of the binder in the linear visco-elastic region. The two pieces of equipment adopted, the dynamic shear rheometer (DSR) and the bending beam rheometer (BBR) were selected since at the range of stiffness values associated with the measurements, reasonable values of precision existed. The BBR was considered preferable for defining low temperature rheology over the DSR since often large errors due to compliance existed in the DSR measurements at the lower temperatures.

During the SHRP project a model for characterizing the relationship between stiffness (Complex Modulus (G*) or bending stiffness (S(t))) and loading time (expressed as frequency or time of loading) where proposed by Christensen and Anderson [3] (referred to as the Christensen-Anderson or CA model). The temperature dependency in this model was defined by Arrhenius and WLF parameters below and above the defining temperature with constant values assigned in the equations. This model was further refined by Marasteanu and Anderson [4] which led to the development of the CAM model. These models have been widely used over the past 20-years to characterize asphalt binders.

Interrelationships between the visco-elastic functions that can be obtained from fits to BBR data can be converted to equivalent DSR information and data can be combined from the two test types, assuming the aging and conditioning differences between the two test types are minimal. Given that these inter-conversions exist, it is possible to extract from data collected enhanced understanding of the behaviour of the bituminous binders. However, to achieve reliable results considerable detail has to be paid to the analysis techniques. Over the past 15-years numerical procedures have been developed and implemented in software to assist with this process [5].

The results from analysis of asphalts including a re-analysis of the SHRP core asphalts has been performed to enable recommendations to be made with; a) procedures for conducting time-temperature shifting, 2) the application of a model fit to master curves and 3) understanding the interrelationships.

2. EPERIMENTAL DATA AND ANALYSIS METHODS

The model defined by Jongepier and Kuilman [6] described the relaxation spectra by using a log-normal distribution. This work was further adopted by Ishai et al. [7] 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 mater curve in a Black space as noted by Ishai et al. [8] 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. [8] in that it provided the best correlation with the fatigue of asphalt mixes when considering a range of binder parameters, as shown in Figure 1. This was noted to be related to fatigue cracking of road pavements in France [8].

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 [2] and this led to the development of the model Christensen-Anderson model which defined the complex dynamic modulus, as follows:

$$G^*(\omega) = G_g\left[1+\left(\frac{\omega_o}{\omega}\right)^{(\log 2)/R}\right]^{-R/(\log 2)} \qquad (1)$$

where:

$G^*(\omega)$ = Complex shear modulus at frequency (ω)
G_g = Glassy modulus
ω_o = cross over frequency
ω = frequency of interest
R = Rheological Index

The *R* defined above was noted as being "directly proportional to the width of the relaxation spectra" by Christensen and Anderson [3] and consequently while it is somewhat differently formulated to the "S" used by Ishai et al. [7] a strong correlation between the two parameters exists since they both effectively describe the width of the relaxation spectra. Thus consequently, a similar relationship between R and fatigue cracking would be anticipated as obtained for "S" as shown in

Figure 2. The differences in the numbers this figure 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 [9] and Dickerson and Witt [10] 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 data obtained from these experiments to justify the significance of the meaning of the R value used in more recent work.

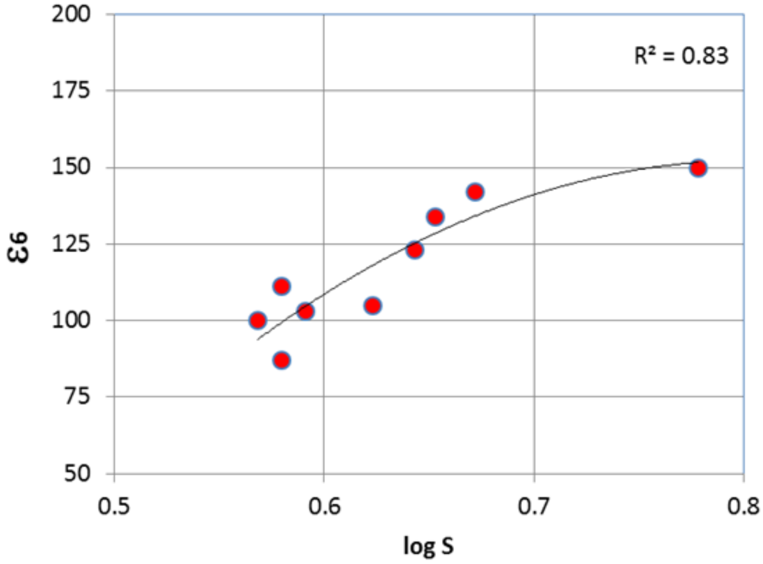

Figure 1: Correlation of strain level required for 1,000,000 load applications and log S (log standard deviation of relaxation spectra), data from Moutier et al. [8] representing original binder conditions

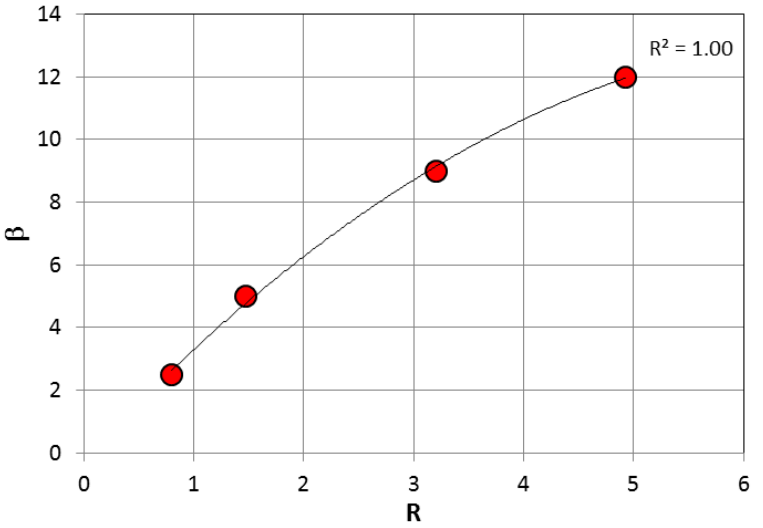

Figure 2: R in the CA model vs. β in the Jongepier and Kuilman Model (data from are binders 1, 9, 13 and 16 from Jongepier and Kuilman [6]

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 behaviour. Two types of shift are considered for asphalt materials; 1) adjustment for density considerations (Rouse [11]) and 2) adjustment for loading time and frequency. If density shifts are not implemented then significant errors can result when interpreting master curve data over a large range of temperatures [12]. The adjustment for loading time results in a horizontal shift to the isotherm being shifted to the reference isotherm follows the method defined by Gordon and Shaw [13].

To perform interconversions we have calculated the discrete relaxation and retardation spectra. The Generalized Maxwell Model is fitted to the data using the techniques developed by Baumgaertel and Winter [14]. The relaxation and retardation spectra analysis can also be applied to data from the bending beam rheometer enabling the inter-conversion to dynamic data [15]. The use of BBR data converted to dynamic data assist with the generation of mater curves in that it helps to define the properties in a stiffness range were rheometers have problems with strain resolution and producing reliable data using the 8mm geometry, typically used for the lower temperatures and higher stiffness range in DSR work. The inclusion of converted BBR data generally assists in better defining the time-temperature properties of a greater range than would be otherwise possible.

3. INTERMEDIATE TEMPERATURE CRITERIA

The intermediate temperature in the AASHTO M320 specification is G*.sinδ which is specified at a temperature which is related to the high and low PG grade temperatures in that specification. The original concept of this parameter is that the energy dissipated in fatigue cracking is the principle controlling parameter for pavement performance and this is directly proportional to the mixture loss modulus (E″ = E* .sinδ). When experiments are conducted at a single temperature and appropriate frequency of loading reasonable correlations are obtained between this binder parameter and mix performance. The intermediate temperature parameter specification value of 5,000 kPa results in DSR data being captured at a value above 100kPa which is suggested a lower bound value for applicability of the CA model for asphalt binders. Thus the data point from this test can be used with Equation 8 to estimate the R-value appropriate for a particular test result. More importantly, since both DSR and BBR data are run on PAV residue, the use of an intermediate temperature parameter combined with the low-temperature BBR data absolutely controls the rheology of bitumen in the PAV condition.

Recently, King et al. [16] proposed the use of the Glover-Rowe parameter which is based upon consideration to a functional model that describe the stress state in a low temperature ductility test and then expressing those parameters using linear-visco elastic G* and δ measured in the DSR. The parameter has also been related to a Δ(T) value from BBR testing defined as the difference in temperature between S=300 MPa and m = 0.300 at a loading time of 60 seconds. This temperature could be deduced from the interconversion of the BBR parameters to DSR parameters and development of the CAM model parameters, expressed to allow the deduction of temperature. However, this involves several steps and in many respects it is easier to deduce the G-R parameter from either DSR or a combination of DSR and BBR testing. This parameter can be expressed as follows:

$$\text{G-R} = \frac{G*(\cos\delta)^2}{\sin\delta} \qquad (2)$$

Damage onset and significant cracking are considered likely when the value for this parameter exceeds 180 and 450 respectively. The use this parameter was further explored by analysing data from a project at Newark Airport during which early life cracking had been noted [17, 18, 19] and enabled the explanation of early life durability issues.

While the G-R parameter was initially used for describing non-load associated cracking that typically occurs on airport pavements [16] it has been noted in in RAP mixtures it effectively captures the various damage levels [35]. Effectively, this parameter captures the ability of a develop stress via the use of the complex shear stiffness modulus and then relax stress through viscous dissipation captured via the phase angle.

The parameter called the G^*_{VET} and VET temperature (T_{VET}) have been gaining interest [21, 22]. VET is defined as the visco-elastic transition temperature, where the phase angle is 45° and G′= G″ defined at a specified frequency. Initially, the concept of this parameter was developed by French workers [38] who reported that this parameter was highly correlated to cracking in road pavements that were 7-years old. In this initial work the frequency of 7.8 Hz was used. Widyatmoko et al. [21] adopted the same approach but used a lower frequency of 0.4 Hz (2.51 rads). Widyatmoko et al. [22] published results from this approach which showed how the VET characteristic for two cases involving a 50PEN and 15PEN mixes. The 50PEN binder was used in SMA on four sites. The sites with and without cracking formed two distinctive groups when plotted in a graph of T_{VET} versus G^*_{VET}. In their second case a 15PEN binder is consider and the results for cracked locations showed high values for the VET temperatures and low values for the G* at that temperature. The authors noted that these materials which cracked were closer in behaviour to a semi blown 15PEN rather than a straight run material. Further it was noted that the data representing the cracked results had different ranges for the different binder grades. Those for the 50PEN cracked when T_{VET} was in the range 18 to 28°C whereas the 15PEN material cracked at a range from 33 to 35°C. It should be noted that the while the values of G* appear close, these are plotted on a linear scale, whereas for asphalt binders generally the variation in G* is considered on a log basis. The VET parameters have been shown to be interrelated to those obtained from the CA model and can be directly calculated [15]. Consequently, the VET parameters have been calculated for the SHRP core asphalts and compared to the data produced by Widyatmoko et al. [21, 22] as shown in Figure 3. The deviation in the G^*_{VET} of binder AAG from the other binders occurs because of the significant difference in rheological index of this binder. This clearly demonstrates how this parameter is dependent upon the rheological characteristics of the binder. It is interesting to note that the temperature of interest (T_{VET}) and the G^*_{VET} considers both the position of the master curve and the temperature susceptibility of the binder in the calculation. These parameters are entirely dependent upon the CA model and the Kaelble modified shift factor relationship.

The different ranges in stiffness and temperature that are obtained in the VET parameters result in different ranges for different binders. This diminishes the usefulness of the parameters as specification parameters.

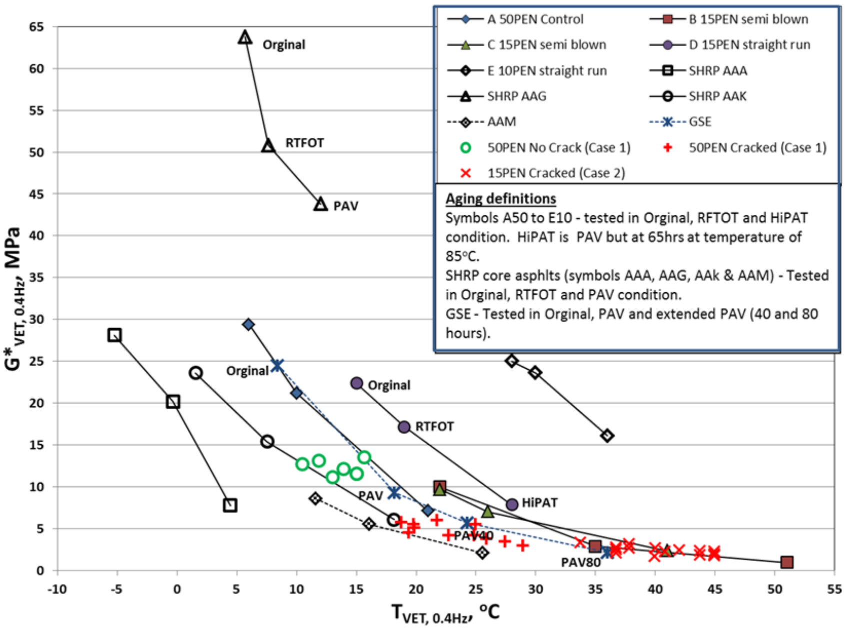

Figure 3: Use of VET parameters with data from testing of SHRP binders and Widyaymoko et al.

4. DISCUSSION

The analysis and presentation of properties in this paper has been developed using data collected within the linear visco-elastic region where the binder behaviour can be assumed to be thermo-rheologically simple in that time-temperature supposition applies. The analysis suggests that if the stiffness is with the range 100kPa to 1GPa then these assumptions are valid and furthermore the CA model with Kaelble shift factors is applicable to model the binder behaviour.

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 [42]. 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. [42] 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 Figure 4. If original or PAV properties are compared the r^2 values are 0.90 and 0.99 respectively.

The detailed analysis of the CA model parameters in the LVE region significantly extended the understanding of the cracking behaviour of parameters such as those described by the VET process or the G-R parameter method.

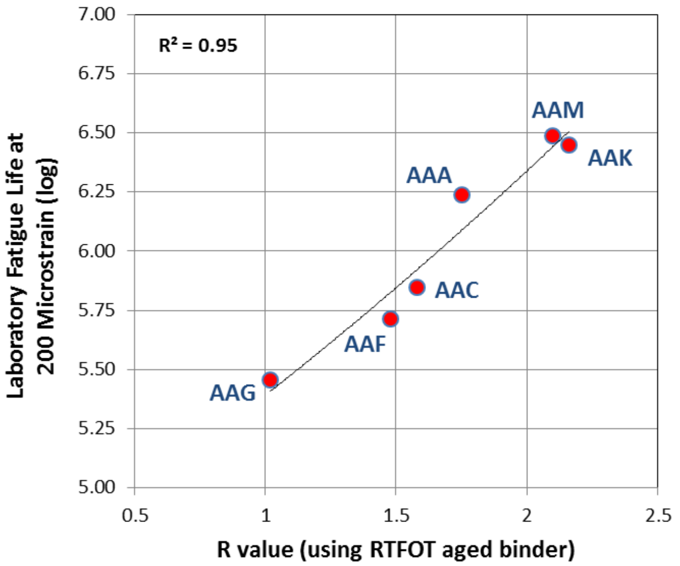

Figure 4: R-value as determined from tests results from Asphalt Institute vs. fatigue life from laboratory fatigue tests conducted as part of the SHRP A003A fatigue project [43]

5. CONCLUSIONS

The analysis presented in this paper enables conclusions to be made as follows:

1. Thermo-rheologically simple behaviour in the linear visco-elastic region and a CA model fit applies well to data in the stiffness range 100 kPa to 1e9 Pa. If data is kept within this range an acceptable root mean square error of less than 2.25%.
2. Analysis of the Glover-Rowe parameter from model parameters has been shown to relate to cracking in airfield pavements. The same parameter has been used by other researchers to assess the quality of RAP and rejuvenating agents. In addition, it has been shown elsewhere that the same concept can be applied to low temperature thermal cracking.
3. An evaluation of the VET approach used in Europe demonstrates that the property G^*_{VET} is an expression of the R value (rheological index) while the VET temperature is dependent upon the hardness of the binder as described by the position of the cross-over frequency and the temperature susceptibility parameters in the Kaelble fit to the shift parameters.
4. The importance of the rheological index, which is related to the distribution of relaxation times, in cracking performance has been recognized since the late 1980's and although it was not included as a standard parameter in the Superpave specifications (AASHTO M320) it is being effectively controlled by the adoption of two specification values for the PAV aged binder.
5. The importance of R can also be seen in the G-R parameter and is effectively monitored in countries using the VET approach.
6. The change in R and ω_c or the VET parameters could be used for assessment of the effectiveness of binder rejuvenation or the effects of aging.
7. The R value is highly correlated to fatigue performance. This can be demonstrated with data obtained from the SHRP program. However, some further analysis is needed due to differences in data collected at different times.
8. A search for new and better intermediate temperature parameters needs careful consideration of how changes to this parameter result in changes to the rheological index of the binder being specified. This in turn could affect cracking that occurs due to aging or other load or non-load associated mechanisms.
9. The analysis and concepts presented in this paper discussed how the linear properties of the binder can be used within the context of models and interrelationships that exist between the linear visco-elastic models to better understand those parameters being proposed for specifications.

While certain parameters have been discussed it should be noted that observations of performance in the field and pavement modelling may be needed to provide additional steps in linking parameters to performance. While the methods discussed in this paper appear to offer some promising future direction it should be noted that equal or better methods may always be available using alternate functions.

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REFERENCES

[1] R.S. McDaniel, R.B. Leahy, G.A. Huber, J.S, Moulthrop and T. Ferragut, "The Superpave Mix Design System: Anatomy of a Research Program," Final Report Prepared for National Cooperative Highway Research Program, Transportation Research Board of The National Academies, August 30, 2011.

[2] D.W. Christensen, "Mathematical Modeling of the Linear Viscoelastic Behavior of Asphalt Cements", PhD Thesis in Civil Engineering, Pennsylvania State University, 1992.

[3] D.W. Christensen and D.A. Anderson, "Interpretation of Dynamic mechanical Test Data for Paving Grade Asphalt Cements," Journal, Association of Asphalt Paving Technologists, Volume 61, 1992, pp. 67-116.

[4] M. Marasteanu and D.A. Anderson, "Improved model for bitumen rheological characterization," Eurobitume workshop on performance related properties for bitumen binder," Luxembourg, Paper no. 133, 1999.

[5] G.M. Rowe and M.J. Sharrock, "Development of Standard Techniques for the Calculation of Master Curves for Linear-Visco Elastic Materials," The 1st International Symposium on Binder Rheology and Pavement Performance, The University of Calgary, Alberta, Canada, August 14 - 15, 2000.

[6] R. Jongepier and B. Kuilman, "Characteristics of the Rheology of Bitumens, Proceedings of the Association of Asphalt Paving Technologists, Volume 38, 1969, pp. 98-122.

[7] I. Ishai, B. Brule, J.C. Vaniscote and G. Ramond, “Some Rheological and Physico-Chemical Aspects of Long-Term Asphalt Durability,” Proceedings, Association of Asphalt Paving Technologists Technical Sessions, Williamsburg, Virginia, 1988.

[8] F. Moutier, G. Ramond, C. Such and J. Bonnot, “Influence of the nature of asphalt cements on the fatigue strength of asphalt-aggregate mixtures under imposed strain,” Proceedings of the conference, “The United States Strategic Highway Research Program, Institution of Civil Engineers, Thomas Telford, London, 1990, pp. 229 to 240.

[9] G.R. Dobson, “On the Development of Rational Specifications for the Rheological Properties of Bitumens,” Journal of the Institute of Petroleum, Volume 58, No. 559, January 1972.

[10] E.J. Dickersen and H.P. Witt, “The Dynamic Shear Modulus of Paving Asphalts as a Function of Frequency,” Transactions of The Society of Rheology, 18:4, 591-606, 1974.

[11] P.E. Rouse, Jr., J. Chem. Phys., 21, 1272, 1953.

[12] G.M. Rowe, G. Baumgardner and M.J. Sharrock, “Application of Rheological Models to Modified Binders,” Presentation to the 48th Petersen Asphalt Research Conference, Western Research Institute, Laramie, WY, July 11-13 2011.

[13] G.V. Gordon and M.T. Shaw, "Computer Programs for Rheologists," Hanser/Gadner Publ., 1994.

[14] M. Baumgaertel and H.H. Winter, "Determination of discrete relaxation and retardation time spectra from dynamic mechanical data," Rheol Acta 28:511-519, 1989.

[15] G.M. Rowe, “Interrelationships in Rheology for Asphalt Binder Specifications,” Proceedings, 56th Annual Conference, Canadian Technical Asphalt Association, Winnipeg, MB, Canada. 2014. pp. 457-483.

[16] G.N. King, R.M. Anderson, D.I. Hanson and P.B. Blankenship, P.B., “Using Black Space Diagrams to Predict Age-Induced Cracking,” 7th Rilem International Conference on Cracking in Pavements, Delft NL, 2012, pp. 453-464

[17] G.M. Rowe, “Rheology considerations for recycled and recovered binder,” Pavement Performance Prediction Symposium - Binder Issues Affecting the Durability of RAP and WMA Pavements, Sponsored by Federal Highway Administration, Western Research Institute, University of Wyoming Conference Center, Laramie, Wyoming, July 12, 2012,

[18] G. King, G.M. Rowe and G. Reinke, “Newark Airport Runway: A Forensic Study Revisited,” Transportation Research Board, January 2013.

[19] G.M. Rowe, G. King and M. Anderson, “The Influence of Binder Rheology on the Cracking of Asphalt Mixes on Airport and Highway Projects,” Proceedings of 4th International Conference on Asphalt Materials, China, 2013.

[20] S.D. Mookhoek, “The effect of ageing on ravelling resistance,” HighRAC Workshop, TU Delft, Netherlands, June 2013.

[21] Widyatmoko, I, Elliott, R.C., Heslop, M.W., Williams, J.T., “Ageing Characteristics of Low Penetration Bitumens”, Performance and Durability of Bituminous and Hydraulic Materials in Pavements, ISBN 90 5809 3751, Zoorob, Collop & Brown (eds), 2002, pp. 13-24.

[22] I. Widyatmoko, R.C. Elliott and M.W. Heslop, “Mapping Crack Susceptibility of Bituminous Materials with Binder Durability,” Proceedings, Fifth RILEM International Conference on Cracking in Pavements – Mitigation, Risk Assessment and Prevention, University of Limoges, ENSIL (France), 5 – 8 May 2004, ISBN 2-912143-47-0.

[23] F. Migliori, G. Ramond, M. Ballié, M. Brûlé, B. Lombardi, J. Samanos, A. Ferraro, C. Such and S. Watkins, “Correlations between the thermal stress cracking of bituminous mixes and the binders’ rheological characteristics,” Eurobitume Workshop, Performance Related Properties for Bituminous Binders, Luxembourg, 1999.

[24] R.M. Anderson, G.N. King, D.I. Hanson, and P.B. Blankenship., “Evaluation of the Relationship between Asphalt Binder Properties and Non-load Related Cracking,” Journal of the Association of Asphalt Paving Technologists, V. 80, 2011, p. 615.

[25] G.M. Rowe, G. King and M. Anderson, “The Influence of Binder Rheology on the Cracking of Asphalt Mixes on Airport and Highway Projects,” Proceedings of 4th International Conference on Asphalt Materials, Guangzhou, China, 2013.

[26] G.M. Rowe, J. Barry and K. Crawford, K., “100% RAP Recycling in Indiana – Analysis of a HyRap Project, Ft. Wayne, IN.,” Presentation to Transportation Research Board Committee AFH60 Monday, January 13th, 2014.

[27] J.D. Ferry, “Viscoelastic Properties of Polymers,” John Wiley & Sons, 1980.

[28] J.A. Deacon, A.A. Tayebali, G.M. Rowe and C.L. Monismith, “Validation of SHRP A-003A Flexural Beam Fatigue Test,” Engineering Properties of Asphalt Mixtures and the Relationship to Performance, ASTM STP 1265, Gerald A. Huber and Dale S. Decker, Eds., American Society for Testing and Materials, Philadelphia, 1994.