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Gordon D. Airey,[1] Geoffrey M. Rowe,[2] Jo E. Sias,[3] Herve Di Benedetto,[4] Cedric Sauzeat,[4] and Eshan V. Dave[3]

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Black Space Rheological Assessment of Asphalt Material Behavior

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Reference

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ABSTRACT

Black Space diagrams representing rheological data of asphalt materials in the form of complex modulus (|G^*| or |E^*|) versus phase angle (δ) have been successfully used for interpretation of material behavior and performance. Previous studies have used Black Space for identification of testing geometry compliance errors when testing over multiple temperatures and loading times (frequencies), screening of the "thermo-rheological simplicity" of various binders and mixtures, and detailed evaluation of the performance balance in term of "stiffness" versus "relaxation" needs. This paper provides an overview of how Black Space can be further used to provide a greater understanding of the concepts of damage and healing and cracking susceptibility and fracture, and to also quantify the complex rheological response of alternative binders. In terms of the damage assessment, cyclic loading tests were analyzed using Black Space to identify additional physical phenomena such as nonlinearity, self-heating, and thixotropy. The cracking analysis has included thermal, fatigue, and durability cracking as well as the use of Black Space to access the performance of asphalt mixtures subjected to aging as well as rejuvenation and materials with recycled asphalt. Concepts such as the Glover-Rowe parameter that are based around Black Space and linked to other forms of rheological indices such as the low-temperature stiffness and relaxation rate parameters are introduced. The results in the paper show that Black Space provides a critical means of rheological characterization to investigate and evaluate the properties and performance of both binders and mixtures. This is particularly relevant at a time when there is a concerted move within the asphalt paving industry toward more sustainable solutions and increased demand for reuse and recycling of materials in asphalt mixtures.

Keywords

black space, rheology, cracking, damage, aging, rejuvenation, alternative binders

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Introduction

The linear viscoelastic (LVE) characterization of asphalt materials has been extensively used in material selection, mixture design, pavement design, and performance prediction. As a viscoelastic material, asphalt binder exhibits both elastic and viscous components of response and displays a temperature-, time-, and history-dependent relationship between applied stresses and resultant strains.[1,2] However, within the LVE region of response, the interrelation between stress and strain is influenced by temperature, loading history, and time alone, not by the magnitude of the stress (i.e., deformation at any time and temperature is directly proportional to the applied load).[3] In addition, as asphalt binder is responsible for the viscoelastic behavior of all asphalt materials, it plays a dominant role in defining many of the aspects of asphalt road performance such as strength and stiffness, permanent deformation, and cracking.

Various techniques and methodologies exist to measure the rheological (viscoelastic) properties of asphalt binders including dynamic mechanical analysis using oscillatory testing generally by means of a dynamic shear rheometer (DSR).[4–6] The principal viscoelastic parameters that are obtained from the DSR are the complex shear modulus (G^*) and the phase angle (δ). Absolute value of G^* ($|G^*|$) is defined as the ratio of maximum (shear) stress to maximum strain and provides a measure of the total resistance to deformation (stiffness) when the bitumen is subjected to shear loading. G^* contains elastic and viscous components that are defined as the storage modulus (G') and loss modulus (G''), respectively. These two components are related to the complex modulus and to each other through the phase (or loss) angle (δ), which is the phase, or time, lag between the applied shear stress and shear strain responses during a test. The phase angle is a measure of the viscoelastic balance of the material behavior, with extreme values of 90° corresponding to purely viscous response and 0° to purely elastic behavior, and provides an indication of the potential stress relaxation of the material. Between these two extremes, the material behavior can be considered viscoelastic in nature with a combination of viscous and elastic responses. Unlike oscillatory shear testing of binders, asphalt mixture complex modulus is typically measured in extensional mode through uniaxial loading on a cylindrical specimen; the outcome of this test is either one- or three-dimensional LVE characterization in the form of either complex modulus (E^*) or both E^* and ν^* (where ν^* is complex Poisson's ratio).

One of the primary techniques used in analyzing dynamic oscillatory data involves the construction of master curves using the interrelationship between temperature and frequency (time) to produce a continuous rheological parameter curve at a reduced frequency or time scale. The principle used to relate the equivalency between time and temperature and thereby produce a master curve is known as the time-temperature superposition principle or the method of reduced variables.[1] The production of a smooth, continuous master curve generally relies on the asphalt binder exhibiting simple rheological behavior, termed or classified as "thermorheological simplicity." An alternative to the production of master curves is to present the rheological data in the form of a Black Space diagram. Black Space provides a two-dimensional representation of the two fundamental characteristics of LVE response, namely the norm of complex modulus ($|G^*|$ or $|E^*|$) and the phase angle (δ), at each of the temperatures and loading frequencies at which these parameters are measured. This two-dimensional representation allows for easy visualization of a material's response in the context of its stiffness as well as relaxation capabilities and more importantly, the interplay between them at any given loading frequency or temperature.

Airey[7] demonstrated how Black Space could be used to not only represent the viscoelastic properties of different asphalt materials as an alternative to master curves and isochronal and isothermal plots, but also how to use Black Space to identify testing issues with the rheological data, performance issues with the rheological data, or both. Black Space was used to help identify compliance (testing) errors in rheological data associated with the inappropriate use of various DSR spindle geometries. Black Space diagrams were also shown to be an extremely powerful means of tracking the rheological changes in asphalt binders associated with both short- and long-term aging as well as means of studying the rheological properties of complex binders such as modified binders. Since then, the use of Black Space has been explored by a number of researchers.

This paper describes selected recent developments in the use of Black Space diagrams as a means of assessing the performance of distress mechanisms associated with asphalt materials in the following ways: the use of Black Space in aiding the interpretation and understanding of key areas consisting of damage and healing assessment of asphalt materials; the use of rheological parameters to assess cracking susceptibility; and finally, the rheological characterization of alternative binders are described with reference to prominent studies in each of these areas. It is important to note that the paper is not intended to be a comprehensive review of all the possible uses of Black Space in asphalt technology literature and is simply an overview of some key examples, specifically those focusing on newer techniques to leverage Black Space for improved asphalt material performance and increased level of sustainability.

Rheological Assessment of Global Damage and Healing

Black Space diagrams have been successfully used to provide a framework for the interpretation of experimental results from cyclic loading and fatigue tests.[8,9] Using Black Space, changes that induce complex modulus variations during loading can be investigated based on different physical phenomena including nonlinearity, self-heating, thixotropy, and damage. Some of these can be considered reversible and therefore produce biasing effects with respect to damage analysis.

NONLINEARITY EFFECTS

During fatigue tests, nonlinearity can be observed on the complex modulus at the beginning of cyclic loading where at a fixed temperature and frequency, the measured complex modulus depends on the applied axial strain amplitude. This alteration in complex modulus is instantaneous and reversible. This phenomenon can be studied independently from damage effects provided that the number of cycles remains low.

An example of nonlinearity effects on complex modulus is given in **figure 1** where the nonlinearity effect on asphalt mixtures was studied by means of cyclic loading tests where strain amplitude was increased and then decreased, linearly, from 10 μm/m to 110 μm/m. During the test, temperatures ranged from 8°C to 14°C and frequencies from 0.3 to 10 Hz.[10] Inside this narrow range, the nonlinearity direction determined on the Black Space diagram was not found to be constant, although variations were small.

THIXOTROPY AND LOCALIZED HEATING EFFECTS

Self-heating (as well as self-cooling during rest periods) will also affect the complex modulus during cyclic loading because of viscous behavior causing heat dissipation. Asphalt materials are thermosensitive; therefore, changes in complex modulus occur during loading because of self-heating temperature increases. During rest periods, the specimen temperature will tend to initially increase and then subsequently decrease. The change in complex modulus because of temperature variation is once again reversible.

Thixotropy effects on the complex modulus are observed during loading and resting and defined as a progressive decrease in modulus with time under loading and a gradual recovery when loading is removed at a constant temperature. A classical explanation for this phenomenon is the buildup or the destruction of a structural network in the material under loading and resting. During loading, stiffness tends to decrease, while during rest periods it increases up to an equilibrium value with the phenomenon being reversible. Finally, damage affects the complex modulus during loading with material cross-section reducing (microcracks) and a subsequent reduction in stiffness. With damage accumulation, microcracks may coalesce into a macrocrack resulting in the eventual material failure with this phenomenon being irreversible.

The evolution of complex modulus during cyclic loading and rest periods can be investigated in complex representations such as Black Space diagrams.[9] **Figure 2** represents an example of test results and an interpretation of the evolution of the effects of each of the phenomena described above. In Black Space, it is seen that each phenomenon presents a particular direction of complex modulus evolution. Before performing the continuous cyclic loading test, information on temperature-sensitivity may be obtained from classical complex modulus tests. If these tests include different strain amplitudes, nonlinearity effects can also be calculated.

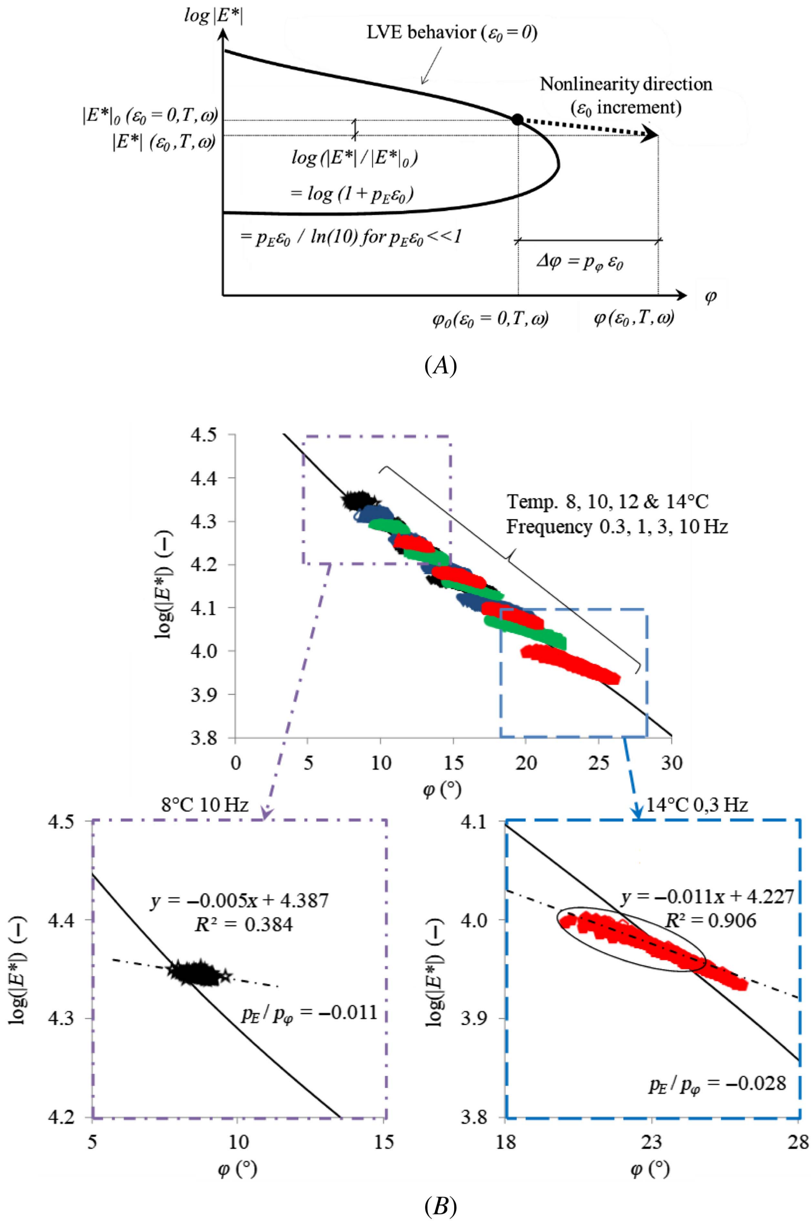


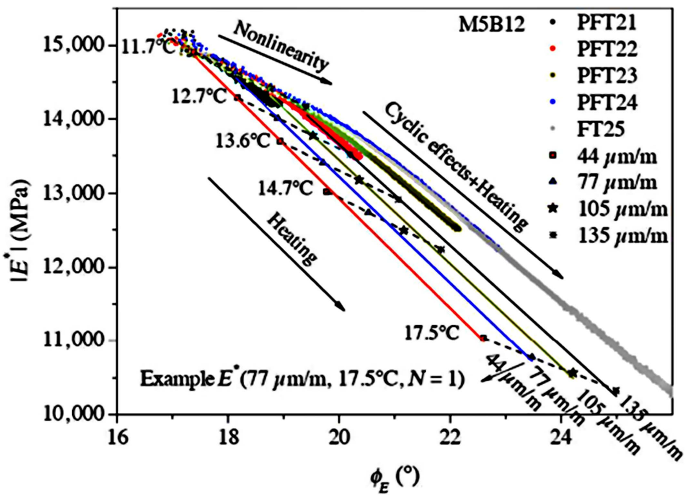
FIG. 1
(*A*) Scheme of nonlinearity direction in Black Space and definition of p_E and $p\phi$ coefficients used to quantify the effects of nonlinearity on complex modulus (norm and phase angle respectively) and (*B*) results obtained from nonlinearity tests (linear increase and decrease of the amplitude of strain-loading cycles from 10 to 110 μm/m) at different temperatures and frequencies.[10]

To observe damage, tests with loading and rest periods should be undertaken. After each rest period, the complex modulus can be compared with its initial value. Obviously, the comparison should consider the potential nonlinearity effects (strain amplitude) as well as temperature effects. Some cracks developed during loading could also heal during rest periods and make the damage evaluation false. However, the healing phenomenon is expected to occur more slowly than other reversible effects (temperature and thixotropy).

Babadopulos et al.[11] suggested that damage should have no effect (or negligible effect) on phase angle. Phase angle recovers quickly during rest periods, which indicates that its change is mainly because of reversible effects (temperature and thixotropy). Loading and rest periods tests were performed on bitumen to differentiate each of these effects as shown in **figure 3**, where after 10,000 cycles of loading at a 2 % shear-strain amplitude, specimens

FIG. 2

Directions of different phenomena on Black Space[9]: example of experimental results.

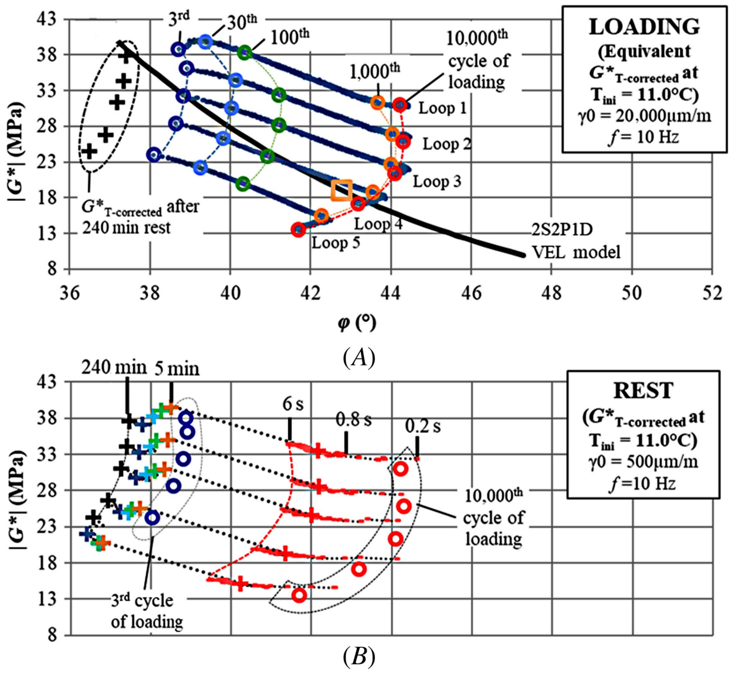


were provided with 4-h rest periods. During the rest periods, complex modulus was measured intermittently with 0.05 % strain amplitude cycles. To separate the different effects, data were corrected from temperature evolution effects and plotted in **figure 3** at a fixed temperature (T_{ini}) of 11°C.

The nonlinearity effect is visible between the complex modulus measured at low strain at the end of the rest periods and the complex modulus measured (after three cycles) at high amplitude at the beginning of the next loading period. The damage created by the loading periods can be seen as the difference between low-strain complex modulus measured at the end of the rest periods. Considering experimental fluctuations, phase angle

FIG. 3

Loading and rest periods test results corrected from temperature effects at $T_{ini} = 11$°C on bitumen represented in Black space: (*A*) equivalent complex shear modulus evolution during each loading period, measured at 2 % shear-strain amplitude and (*B*) complex modulus evolution, during each rest period of 4 h, measured at 0.05 % shear-strain amplitude (from Babadopulos et al.[11]).



can be considered as a constant while the norm of complex modulus decreases after each loop. The evolution during loading periods is because of damage but also thixotropy. After correcting for damage, the results from the Black Space diagram show the different directions of nonlinearity and thixotropy.

Rheological Assessment of Cracking Distress

In addition to the use of Black Space to assess asphalt material damage and healing and other physical phenomena, it is also possible to use these diagrams to identify critical limits associated with different forms of material cracking. Various rheological parameters can be defined and graphically displayed in Black space to allow critical and failure regions of cracking response to be identified and material changes with regard to aging and rejuvenation to be mapped.

THERMAL CRACKING – BENDING BEAM RHEOMETER DATA BLACK SPACE

The development of the *S* and *m* criteria for thermal cracking was validated by inspection of built pavements by Leahy, Harrigan, and Von Quintus.[12] Subsequently, Rowe[13] showed how the *S* and *m* criteria could then be translated to $|G^*|$ and phase angle using a transformation method by fitting a discrete spectrum to the bending beam rheometer (BBR) data and performing an interconversion to the dynamic properties.

Once the data are transformed, it is then possible to take the criteria and insert these into Black Space where the limiting criteria become a value of $|G^*|$ (111 MPa) and phase lag, δ (26.2°) at a frequency of 0.0167 radians/s (1/60 s), that correspond to the *S* and *m* values (at 60 s) as shown in **figure 4**. Thus, we observe that the *S* and *m* criteria are essentially the same as the specification of a modulus and phase angle in the Black space.

DURABILITY CRACKING – GLOVER-ROWE PARAMETER

One approach to assess the cracking resistance of asphalt materials, particularly durability cracking, is through the use of Black Space diagrams and a point parameter known as the Glover-Rowe (*G-R*) parameter. Based initially on the relationship between ductility and pavement performance and an understanding of the importance of the stress relaxation properties of the binder in an asphalt mixture, the *G-R* parameter can be used to evaluate the resistance of binder and asphalt mixtures to age-related cracking.[14–16] The *G-R* parameter for binders can be computed from measurements of complex modulus ($|G^*|$) and phase angle (δ) using a DSR at a frequency of 0.005 rad/s and 15°C using equation (1).

$$G - R = |G*|(\cos\,\delta)^2 / \sin\,\delta \tag{1}$$

By plotting the *G-R* parameter and including the limiting values associated with a warning of the probability of cracking (180 kPa) and presence of significant cracking (600 kPa) (values derived from field durability cracking evaluation[14]), it is possible to identify the effect of aging on the susceptibility of a binder to durability cracking as shown in **figure 5**.

Similarly, the same concept can also be considered for rejuvenation as shown in **figure 6** for two locations treated with a rejuvenator.[17]

Figure 6 also shows lines that represent the rheological index (*R*-value) as defined by the Christensen-Anderson (CA) model[18] with a glassy modulus (G_g) set as 1 GPa. However, this assumption that the value of G_g is equal to 1 GPa for all binders is most likely incorrect. Other works have shown that this value can vary considerably and also changes with temperature susceptibility of the binder.[19] Thus, the assumption that $R =$ 9-log G_c, where G_c is the crossover modulus is incorrect, and it has been suggested that it is better to simply use the value of G_c as a specification parameter rather than *R*. G_c has the advantage in that it lies in a similar stiffness range to the *G-R* value for most paving binders and effectively characterizes the shape of the master curve in the high stiffness region whereas the *G-R* value identifies the hardness of the binder. Other parameters being considered for specifications in the intermediate temperature/non-load related cracking region also include the phase angle

FIG. 4 Black Space data for BBR results interconverted to dynamic data (zero, low, medium, and high indicate level of field cracking).

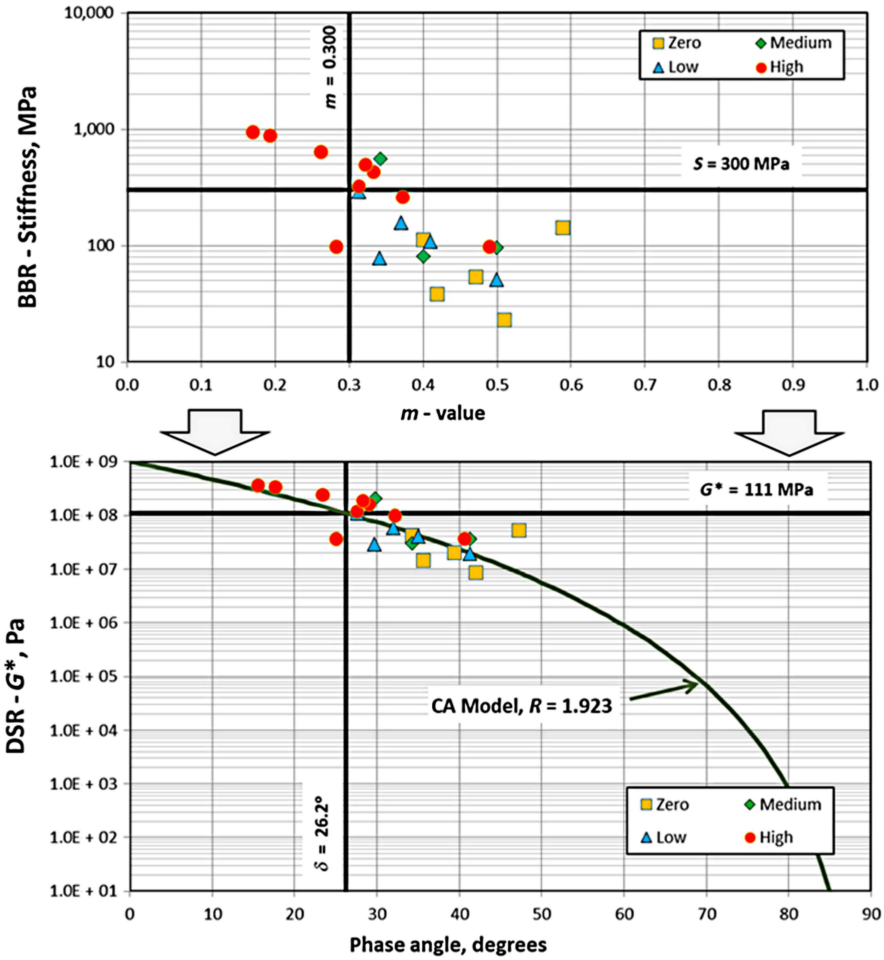


FIG. 5

Black Space diagram including *G-R* parameter limits. Different binders at different stages of aging.[17]

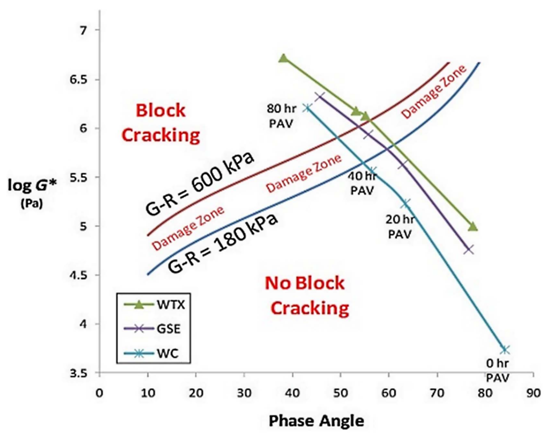
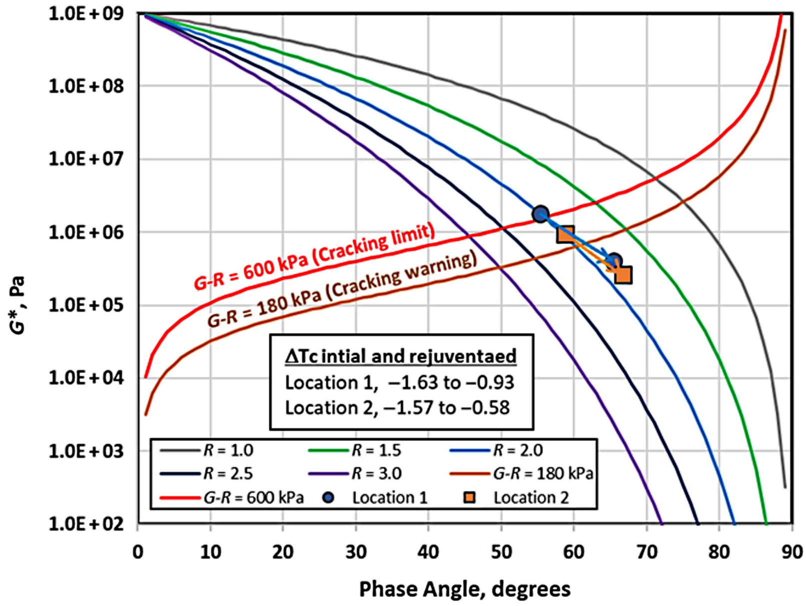


FIG. 6

Black Space diagram including *G-R* parameter limits. Treatment of binders with rejuvenators (other rheological indices, ΔT_c and *R*-values also shown).[17]



response at a stiffness of 8,967 kPa, $\delta_{G^* = 8.967\ \mathrm{GPa}}$.[20] It should be noted that this parameter, the *R*-value, the G_c and ΔT_c (shape parameter determined as the difference between the critical temperatures of $T_{stiffness\ (60\ s)}$ and $T_{m\text{-}value\ (60\ s)}$ from the BBR) all define the shape of the master curve in the intermediate temperature region, much in the same manner that the penetration index or penetration-viscosity number would characterize properties using empirical specification approaches.

By inspection of the data in **figure 6**, we note that at an *R*-value of 2, the value of $|G^*|$ is close to a value of 1 MPa at the critical region where the *G-R* parameter transitions from a "cracking warning" condition to a "cracking limit" condition. Several approaches exist for understanding the stiffness and relation properties in this stiffness range. Regardless, we note that it is important that both stiffness and relation properties are defined in this region. The advantage of the *G-R* parameter to other parameters is that as materials age, the relationship produced intersects with the *G-R* lines at nearly a right angle, indicating that the parameter is very sensitive to the changes in the properties that are occurring because of aging.

As discussed earlier, the rheological index (*R*-value) as defined by the CA model,[18] $\delta_{G^* = 8.967\ \mathrm{GPa}}$, G_c, and ΔT_c effectively define the shape of the master curve in the higher stiffness region ($|G^*| \geq 10^5$ Pa). The selection of a parameter for specification use should depend upon the ease of measurement (likely to significantly affect implementation) and the accuracy of testing as determined by interlaboratory studies (precision, repeatability, reproducibility, etc.). However, while the shape of the master curve is of considerable importance, the relative hardness (stiffness) is needed. This can be captured by the *G-R* parameter, which can be regarded as a "point" parameter. Other parameters that effectively capture the hardness of the material include the crossover frequency, ω_{cr}, (reference temperature must be specified) or the temperature at which the crossover modulus occurs, T_{cr} or T_{VET}, (frequency must be specified). However, these last two parameters cannot be easily plotted in Black Space, and the conceptual tie with performance is more difficult to visualize.

DURABILITY AND THERMAL CRACKING

As discussed earlier, a direct relationship exists between measurements conducted in the frequency and time domain provided that strains are kept within the LVE region. For asphalt binders, we have made use of inter-conversion technologies using the RHEA software and the computation of the calculated relaxation spectra fit to the data. The parameters for limiting cold-temperature thermal cracking ($S = 300$ MPa and $m = 0.300$) thus can be translated into values of $|G^*| = 111$ MPa and $\delta = 26.8°$ at a frequency of 0.0167 radians/s (1/60 s). This intercept of complex modulus and phase lag can be shown as a *G-R* relationship that has a value of 184 MPa, and this could be used as an alternate to the *S* and *m* values currently used as shown together with other Black Space parameters in **figure 7**.

In earlier work, Anderson et al.[16] showed that a good correlation between ΔTc and the *G-R* parameter existed. However, because one of the parameters is a shape parameter whereas the other is a point parameter, no correlation should be expected across the wide range of materials used in asphalt paving. Rowe[21] presented data that demonstrated that binders with different rheological types have significantly different behavior when comparing the *G-R* parameters to ΔTc. Specifically, elastomeric binders that are known to perform better with respect to cracking often have low values of ΔTc.

Zhang, Sias, and Dave[22] presented similar data in the format of *G-R* versus ΔTc that shows the relationships for different binders with *G-R* and ΔT_c parameters as shown in **figure 8**. In this study, the propensity to cracking of reclaimed asphalt pavement (RAP)-modified materials used in the northeastern USA was studied with binders after different aging conditions. The dashed lines represent the cracking-warning values, and the solid lines represent the cracking-limit values for the two parameters. Points in the bottom right quadrant of the plot are acceptable under both criteria whereas those in the top left quadrant would be sensitive to cracking using both criteria. The short-term conditioned binders (first point on each line) generally fall into the safe zone, which means that typically no cracking problems are expected. As the materials age, they move toward the upper left quadrant, indicating that there may be significant cracking problems based on the ΔT_c and *G-R* criteria.

FATIGUE CRACKING AND CRACKING PERFORMANCE LIMITS

In addition to representing the *G-R* parameter in Black Space and providing limits for the onset and failure associated with durability cracking, it is also possible to represent other non-load and load-related cracking

FIG. 7 Black Space representation of various parameters used to define cracking and deformation for binders.[17]

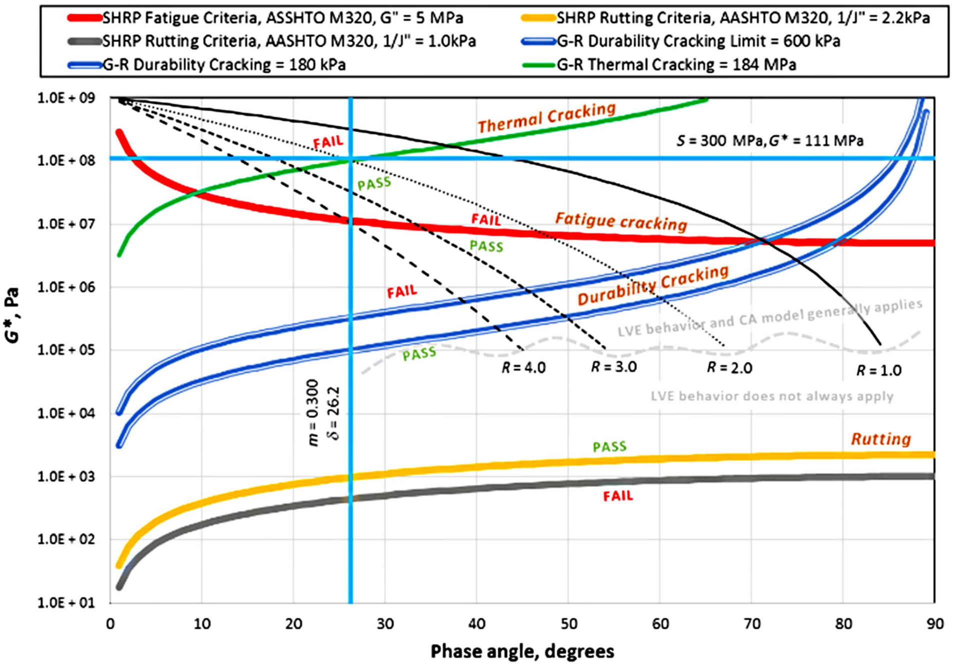
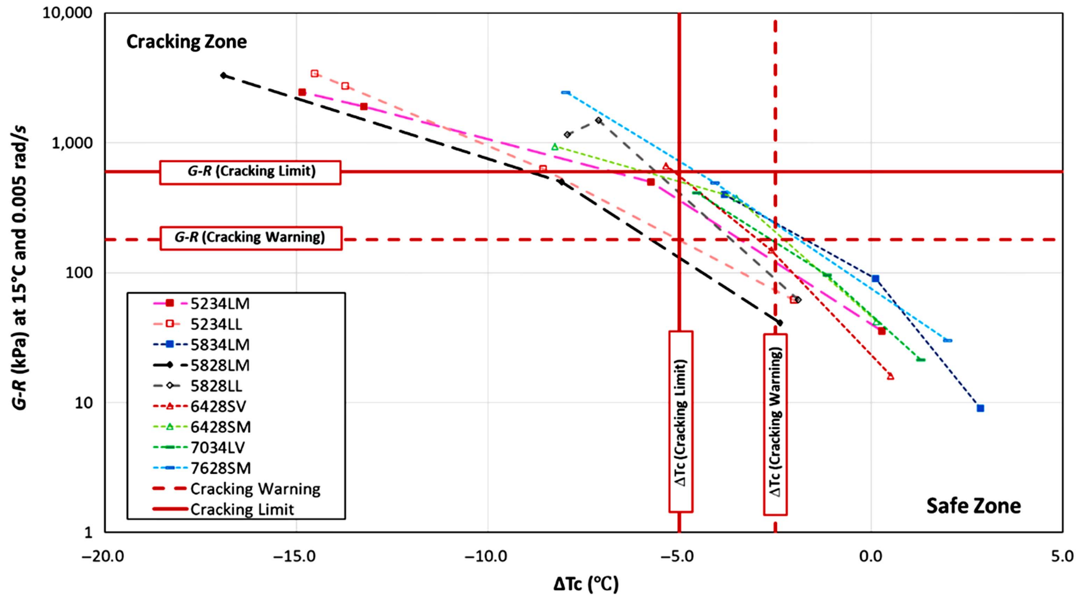


FIG. 8 Performance space diagram of *G-R* and ΔT_c parameters for balancing thermal and durability cracking performances of asphalt binders. (reproduced using data from Zhang, Sias, and Dave[22]).



and rutting limits. The Black Space diagram can depict pass and fail limits for rutting as well as forms of pavement cracking (durability, fatigue, and thermal) as shown earlier. It should be noted that at the stiffness values consistent with rutting, the binder is generally behaving in a different manner. For example, we know that as the stiffness drops below 10^5 Pa that the CA model loses its validity.[18]

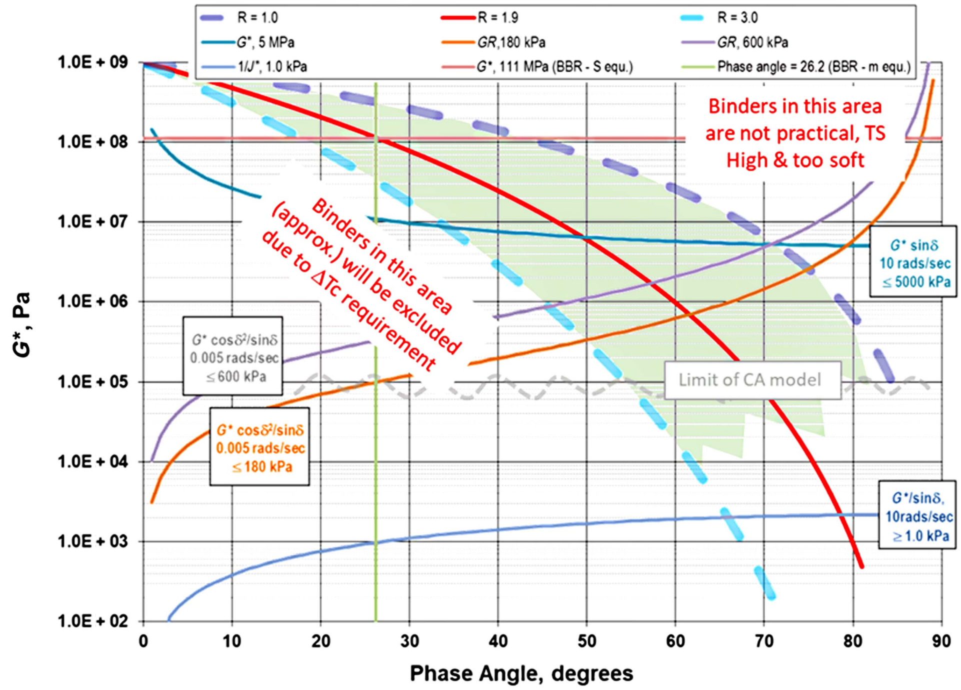
For conventional binders, ΔTc is strongly correlated with the *R*-value. Specifiers generally consider limits for ΔTc in specifications with values around −3.5 to −5. Values lower than this would represent binders that are excluded from specifications. The *R*-value of 1.92 corresponds approximately to a ΔTc value of 0. This value can vary to a small extent with changes in the glassy modulus and temperature susceptibility. An *R*-value of 3.0 is a practical limit related to a low (negative) value of ΔTc of around −5.0. This value of *R* is typical of an oxidized or aged binder and represents a temperature susceptibility defined by ΔT_c in the critical range.[17] A low *R*-value represents a binder that is not practical because the material will generally have a high temperature susceptibility. Thus, conventional asphalt binders will lie within the shaded area as shown in **figure 9**.

The specification of an *R*-value is problematic because this parameter is not easily determined and is a function of the analysis method.[17] However, if a constant value of 1 GPa is assumed for the glassy modulus, the control of the *R*-value can be directly correlated to the crossover modulus, G_c, (the value of $|G^*|$ at a phase angle of 45°), which can be easily measured for paving grade binders. This effectively allows both ΔTc and *G-R* to be controlled by Black Space parameters.

Thus, in summary for binders, the critical binder parameters associated with behavior in a Black Space plot, including those developed under the SHRP program, become the following:

- Thermal: *G-R*, 184 MPa measured at a slow frequency (1/60 s) 0.0167 rads/s at T_{min} + 10C or – $|G^*| <$ 111 MPa and $\delta >$ 26.2° at the same conditions.
- Fatigue (SHRP): $|G^*|\sin\delta$ measured at 10 rads/s at intermediate temperature – parameter as developed by SHRP researchers, which is under review.
- Durability: *G-R* parameter measured at 15°C and 0.005 rads/s with two criteria being considered (180 kPa and 600 kPa) and $Gc >$ 1 MPa, which effectively removes the need to specify ΔTc.

FIG. 9 Extending Black Space parameters with limits associated with ranges in ΔTc.



- Deformation: $|G^*| / \sin\delta$ ($1/J''$) as currently used – but now because of nonlinear effects, it is proposed that the multiple stress creep recovery test will be a better test C14

G-R CONCEPT FOR ASPHALT MIXTURES

Based on the binder *G-R* approach, Mensching, Rowe, and Daniel[23] developed the mixture Glover-Rowe ($G\text{-}R_m$) parameter using stiffness and phase angle measured on the asphalt mixture ($|E^*|$ and δ). However, determining a suitable temperature and frequency to calculate $G\text{-}R_m$ has required considerable research effort. Oshone et al.[24] used results from 81 asphalt mixtures to assess different temperature and frequency combinations (**fig. 10**). This work observed that most discrimination between mixtures in terms of $|E^*|$ and phase angle was observed at 15°C and 5rad/s and PGLT + 10 and 0.01666rad/s (where PGLT is the low-temperature performance grade parameter). AQ9 Subsequent research has further developed $G\text{-}R_m$ to use a commonly measured temperature-frequency combination of 20°C and 5 Hz.[25,26]

Oshone et al.[24] further conducted Pearson's correlation analysis on the $G\text{-}R_m$ parameter (15°C and 5 rad/s) from the 81 asphalt mixtures. As expected, the binder content and voids in mineral aggregate showed strong correlations where an increase in these parameters results in lowering of $G\text{-}R_m$. PGLT also showed a strong correlation where with lowering of PGLT, the $G\text{-}R_m$ reduces (in other words, a better PGLT lowers the value of $G\text{-}R_m$). Increasing nominal maximum aggregate size for mixtures increases $G\text{-}R_m$, and increasing amounts of RAP as well as PG high-temperature grade increases $G\text{-}R_m$ but with a smaller degree of correlation.

$G\text{-}R_m$ can be used to compare various mixtures (binder grades, recycled material content, etc.) and to evaluate and quantify changes in viscoelastic material properties with aging (e.g., **fig. 11**) or with rejuvenation. Kaseer et al.[27] used mixture Black Space and the $G\text{-}R_m$ parameter to evaluate various strategies for producing mixtures with higher RAP contents. Various recycling agents and use of a softer virgin binder were also evaluated at both short- and long-term aging conditions. Zhang, Sias, and Dave[22] used the $G\text{-}R_m$ to correlate laboratory conditioning methods with field-aging durations for a set of mixtures. Zhang[28] also developed a rheology-based mixture

FIG. 10 Discrimination between mixtures in terms of |*E**| and phase angle at different frequency and temperature combinations (reproduced using data from Oshone et al.[24]).

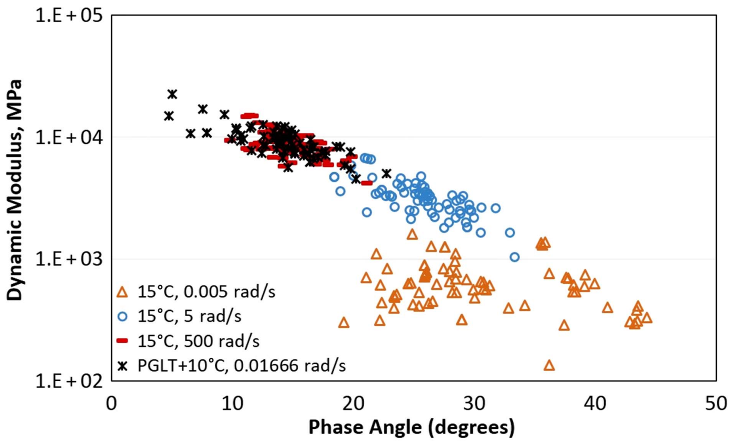
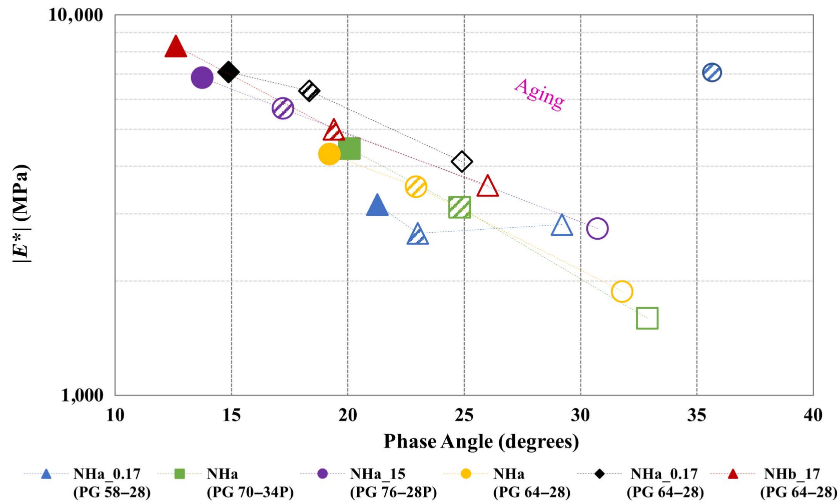


FIG. 11 Mixture *G-R* parameter evolution with aging (from Ogbo et al.[26]).



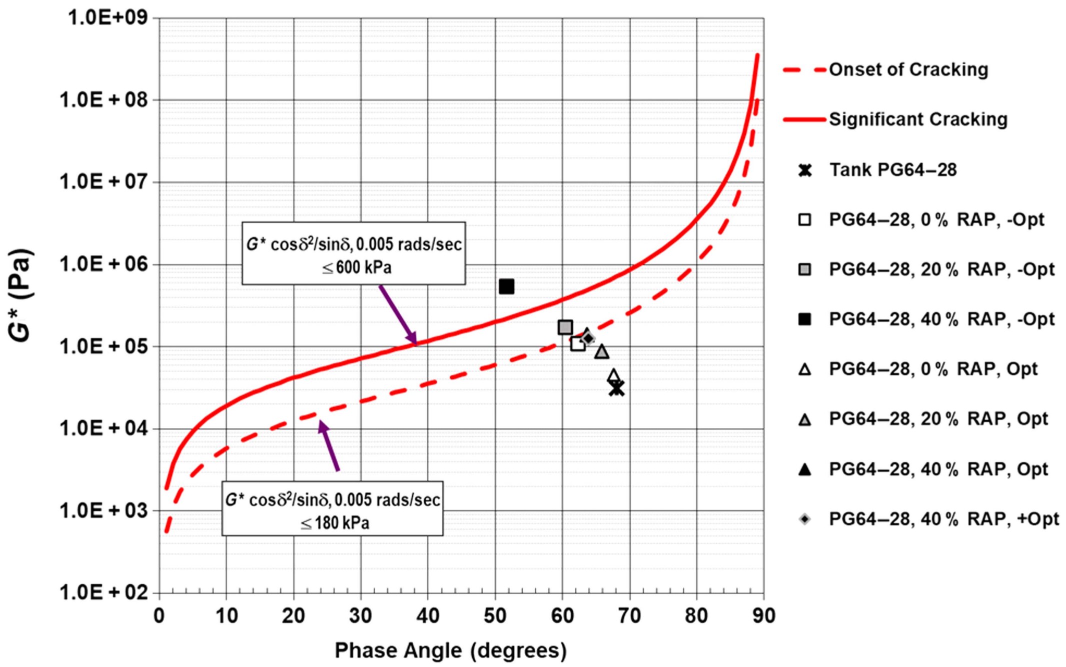
aging model using the $G\text{-}R_m$ parameter to evaluate cracking and aging susceptibility of mixtures with different binder grades and RAP content.

Master curve shape parameters obtained from fitting mixture |*E**| and phase angle master curves are also used to track and quantify the impact of aging and rejuvenation on the mixture viscoelastic properties.[29]

EVALUATING RECYCLED MATERIALS, AGING, AND REJUVENATION

Recycled asphalt content in asphalt binders and mixtures have prominent effects on their rheological properties. A study by Daniel et al.[30] extensively evaluated effects of RAP content on Black Space parameters. An example result from that research is presented in **figure 12** and shows the Black Space diagram (along with *G-R* parameter limits) for extracted and recovered binders from plant-produced mixtures as a function of RAP content (0, 20, and 40 % by total weight of mix) and binder amount (optimum, optimum −0.5 %, and optimum +0.5 %). Results for tank binder used in production are also shown in the figure for comparison. The results show that increasing

FIG. 12 Black Space diagram for asphalt binders extracted and recovered from asphalt mixtures with varying RAP amounts and binder contents (produced using data from Daniel et al.[30]).



the RAP amount and decreasing binder content led to significant increases in binder stiffness and loss of phase angle with higher RAP mixtures (40 % RAP) all in the "crack warning" region for the *G-R* parameter and the low-asphalt content mixture with high RAP amount past the cracking limit. The effect of lowering binder content on the *G-R* parameter can be attributed to decreases in asphalt binder film thickness and thus increased aging during mix production.

Data from the same study by Daniel et al.[30] also include assessment of *R*-value and crossover frequency for the binders extracted from asphalt mixtures with varying RAP amounts and binder contents. As expected, introduction of RAP in the mixture results in a significant reduction in crossover frequency. While RAP amount increases from 20 to 40 %, the *R*-value increases, with this effect being more pronounced for mixtures with a lower binder content.

Black Space and the *G-R* parameter can also be used to access both the aging and rejuvenating effects linked with binders associated with recycled asphalt pavements. Rahbar-Rastegar, Daniel, and Dave[31] used mixture Black Space to compare various laboratory conditioning protocols for mixtures and to evaluate how both $|E^*|$ and phase angle master curves change with aging.

Figure 13 shows an example of the evolution of the *G-R* parameter (measured on extracted and recovered binders) with mixture-aging conditions. In this study, Zhang, Sias, and Dave[22] used this analysis to determine the mixture-aging condition that corresponds to the standard 20-h pressure aging vessel aging on the virgin binder and also to evaluate the change in aging with depth using measurements from field cores.

The extent of virgin and RAP binder blending is presented in **figure 14** with short-term and long-term aging conditions (indicated by the rolling thin-film oven test and pressure aging vessel).[32] The Black Space diagram shows the effect of different degrees of binder activation, as a measure of virgin and RAP binder blending, and the shift toward the top left-hand corner with aging and in the opposite direction with rejuvenation.

FIG. 13 Evolution of *G-R* parameter with aging for virgin and extracted and recovered binders.[22]

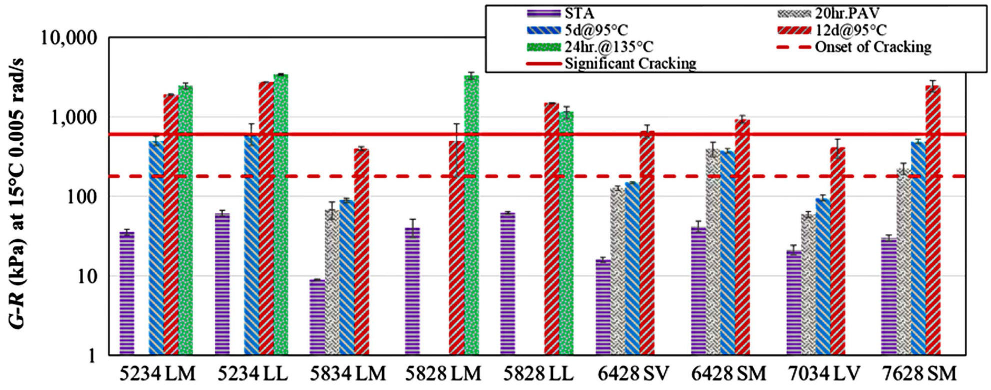
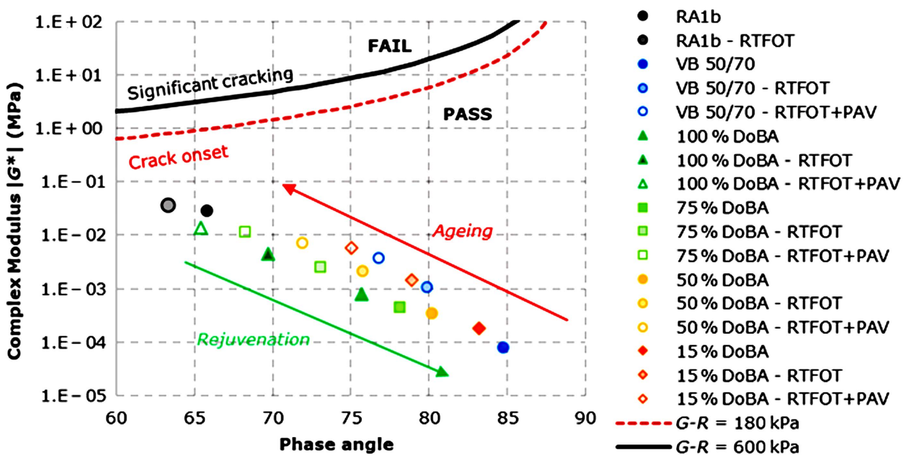


FIG. 14 *G-R* parameter for recycled binders showing aging and rejuvenating effects.[32]

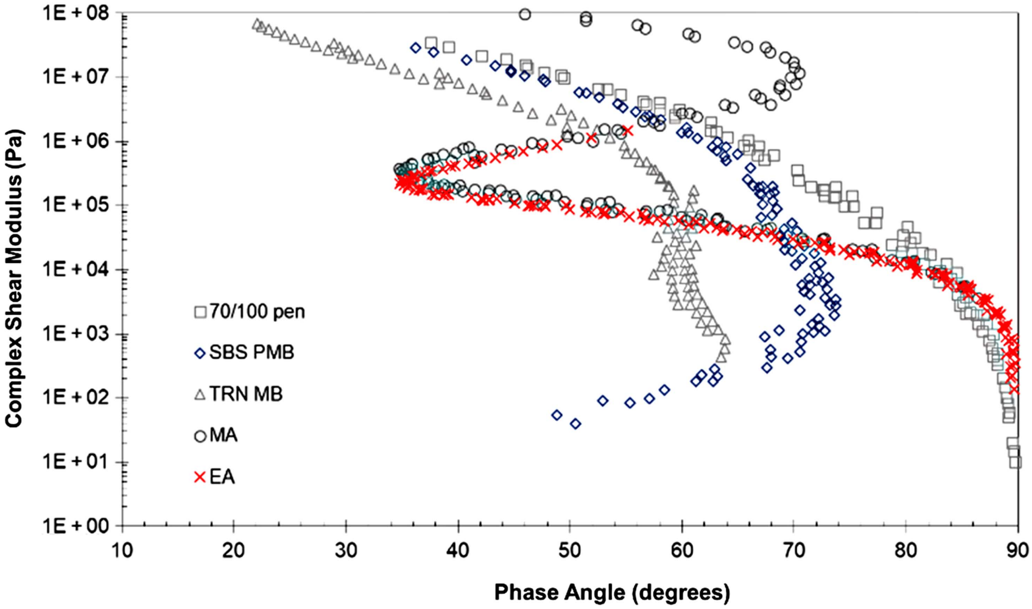


The effect of different types of recycling agents can also be compared using Black Space and the *G-R* parameter. Work by Bajaj et al.[33] showed how different types or categories of recycling agents produce primarily softening effects (reduction in |*G**| only) or rejuvenating effects (reduction in |*G**| and increase in phase angle). This study also evaluated the impact of different conditioning sequences on the rheological parameters of binders blended with RAP and recycling agents to examine how the interactions between the different materials impact rheological changes with aging.

Rheological Assessment of Alternative Binders

The techniques and approaches that have made use of Black Space have generally been applied to conventional asphalt materials. However, the move toward more sustainable solutions to minimize environmental impact has resulted in increased use of industrial byproducts and wastes in asphalt mixtures with the idea of partially replacing asphalt binders with bio-based materials or alternative binders. These synthetic binders or bio-based materials (also known as bio-binders or bio-oils) can be considered as renewable materials as compared to conventional asphalt binders that are derived from fossil fuels.[34–36]

FIG. 15 Black Space diagram of rheological data for different conventional (70/100 pen), polymer-modified (SBS PMB), tire rubber-modified (TRN MB), and synthetic binders (MA, EA) (after Airey et al.[44]).



Most of these renewable bio-based materials are of vegetative origin such as lignin, tall oil, pitch, wood resins, and plant sap.[35] Another widely used renewable material of vegetative origin is waste cooking oil, which is available in large quantities all over the world.[37,38] Further examples are bio-oils obtained from vegetable oils and biomass such as soy, linseed, and rapeseed. Other sources of bio-binders include algae,[39] wood residues,[40–42] and swine manure.[43]

Another aspect to be considered is the complexity of the treatment before the employment of these renewable materials. Most bio-based materials used for asphalt materials are obtained from raw materials through thermal treatments, chemical treatments, or both, such as pyrolysis, esterification, and hydrothermal liquefaction. These production techniques add an extra dimension to the rheological complexity of the final binder.

Black Space diagrams can be considered to provide rheological "fingerprints" for these different binders and have been used in figure 15 to provide a convenient method of comparing different categories of binders such as standard paving grade binders, modified binders, and synthetic polyacrylate binders.[34,44] The Black Space curves allow the unique rheological behavior of the polyacrylate binders to be illustrated without the need for more advanced rheological characterization involved with the generation of master curves.

Black Space diagrams have also been used for bio-binders produced using lignin and sawdust and produced using pyrolysis and hydrothermal liquefaction procedures at different operating conditions. Similar to the rheological behavior shown in figure 15, the rheological Black Space curves can be used to show the unique viscoelastic properties of these bio-based materials.

Concluding Remarks

The paper has described three broad applications of the use of Black Space diagrams in terms of the rheological assessment of asphalt binders and mixtures to aid interpretation and analysis of material and pavement performance. These three applications included global damage and healing assessment, rheological characterization for cracking behavior evaluation (including effects of recycled materials, aging, and rejuvenation), and rheological fingerprinting of alternative synthetic or bio-based sustainable asphalt binders.

In terms of cyclic loading and fatigue tests, Black Space diagrams have been used to evaluate the damage and healing changes in complex modulus and phase angle through the selection of strain amplitude sweep tests as well as combination loading and rest period cyclic tests. The results from these Black Space diagrams have enabled nonlinearity as well as the phenomena of self-heating and thixotrophy to be identified in addition to changes in complex modulus and phase angle because of damage and healing.

In terms of low-temperature (thermal) cracking, it is possible to transform the Superpave *S* (300 MPa) and *m* (0.3) criteria to a limited complex modulus (111 MPa) and phase angle (26.2°) set of criteria at a frequency of 0.0167 radians/s with these limits being used in Black Space to identify regions of high or low thermal-cracking susceptibility.

Black Space diagrams and a point parameter known as the *G-R* parameter have been successfully used to assess the durability (age-related) cracking resistance of asphalt materials. The *G-R* parameter, together with limiting values associated with a warning of the probability of cracking (180 kPa) and presence of significant cracking (600 kPa), can be presented in Black Space to monitor the susceptibility of asphalt binders to aging as well as the reverse effect of rejuvenation.

With the ability to transform the thermal cracking criteria of *S* and *m* to G^* and δ, it is also possible to link thermal cracking with durability cracking by defining a *G-R* value of 184 MPa for thermal cracking. Although not a direct correlation, it is also possible to link the *G-R* parameter and ΔTc to identify asphalt materials that have a greater or lower potential for significant cracking.

In addition to durability cracking, the Black Space diagram can also depict pass and fail limits for rutting as well as various forms of non-load and load-relating pavement cracking. It is also possible to establish relationships between ΔTc, *R*-value, and the *G-R* parameter and provide a shaded area in the Black Space diagram for conventional asphalt binders.

It is also possible to extend the *G-R* parameter to asphalt mixtures ($G\text{-}R_m$) with most measurements made at a temperature-frequency combination of 20°C and 5 Hz. The $G\text{-}R_m$ parameter can then be used to evaluate and quantify changes in viscoelastic material properties with aging or with rejuvenation. Black Space and the $G\text{-}R_m$ parameter are also used to assess the cracking and aging susceptibility of asphalt mixtures with different contents and types of RAP.

Finally, Black Space has been used to illustrate the complex rheological response of both synthetic binders and bio-binders with some of these binders showing useful combinations of high stiffness as well as good relaxation capabilities.

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