HUET MODEL FOR OSCILLATORY AND STATIC LOADING OF ASPHALT BINDERS AT LOW TEMPERATURE

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ABSTRACT

One of the simplest continuous spectrum models used to characterize asphalt materials was proposed by Huet in 1963. The model was further expanded over the years (Huet-Sayegh, 2S2P1D) to better fit experimental data obtained over a wide range of temperatures. Huet model has expressions for both complex modulus and creep compliance, and therefore, it is possible to use, for example, asphalt binder Bending Beam Rheometer (BBR) creep compliance experimental data to predict Dynamic Shear Rheometer (DSR) complex modulus and vice versa.

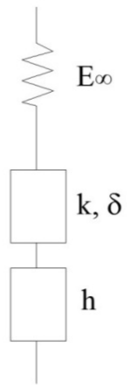
This idea is investigated using BBR and DSR experimental data obtained on a set of asphalt binders at low and intermediate temperatures. It is found that Huet parameters in time domain could be used to obtain reasonable G predictions, if additional restrictions are imposed on parameter k.*

Keywords: asphalt binder; continuous spectrum; creep; complex modulus

INTRODUCTION

One of the simplest continuous spectrum models used to investigate asphalt materials rheological properties was proposed by Huet in 1963. The model is composed of two parabolic elements, $J_1(t) = a*t^h$ and $J_2(t) = b*t^k$, plus a spring element (stiffness E_∞) combined in series as follows:

Figure 1. Huet model (1963)



A parabolic element has a continuous spectrum and the creep compliance, D(t), and complex modulus, E^*, function in the parabolic element can be expressed as:

$$D(t) = \delta \cdot \left(\frac{t}{\tau}\right)^k \quad (1)$$

$$E^*(i\omega\tau) = \frac{(i\omega\tau)^k}{\delta \cdot \Gamma(k+1)} \quad (2)$$

i = complex number (i^2=-1);
E^* = complex modulus;
h, k = exponents, $0 < k < h < 1$;
δ = dimensionless constant;
ω = 2π*frequency;
τ = characteristic time varying with temperature accounting for Time Temperature Superposition Principle (TTSP),
Γ = gamma function which can be expressed as follows:

$$\Gamma(n) = \int_0^\infty t^{n-1} e^{-t} dt \quad (3)$$

$$\Gamma(n+1) = n \cdot \Gamma(n) \quad (4)$$

n>0 or Real (n)>0

t =integration variable,
n = argument of the gamma function.

The Huet model has expressions for creep compliance, D(t), as well as for complex modulus, E*:

$$D(t) = \frac{1}{E_\infty}\left(1 + \delta \frac{(t/\tau)^k}{\Gamma(k+1)} + \frac{(t/\tau)^h}{\Gamma(h+1)}\right) \tag{5}$$

$$E^*(i\omega\tau) = \frac{E_\infty}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h}} \tag{6}$$

E_∞ = glassy modulus.

Parameter δ is a dimensionless number around 2, *k* is an exponent around 0.3, and *h* is an exponent between 0.3 and 0.8 for bituminous materials (Huet, 1999). Parameter *h* depends on asphalt binder aging condition; the smaller values are characteristic of aged, oxidized materials as a result of air blowing or weathering during production and service life (Huet, 1999).

From equation (2), the real and imaginary parts can be obtained using a methodology described in Cole et al. (1941) as follows:

$$E^{'}(i\omega\tau) = E_\infty \cdot \frac{\left(1 + \delta \cdot (\tau\omega)^{-k} \cdot \cos\left(\frac{\pi}{2} \cdot k\right) + (\tau\omega)^{-h} \cdot \cos\left(\frac{\pi}{2} \cdot h\right)\right)}{\left[\begin{array}{l} 1 + 2 \cdot \delta \cdot (\tau\omega)^{-k} \cdot \cos\left(\frac{\pi}{2} \cdot k\right) + 2 \cdot (\tau\omega)^{-h} \cdot \cos\left(\frac{\pi}{2} \cdot h\right) + \\ \delta^2 \cdot (\tau\omega)^{-2k} + (\tau\omega)^{-2h} + 2 \cdot \delta \cdot (\tau\omega)^{-k-h} \cdot \cos\left(\frac{\pi}{2} \cdot (k-h)\right) \end{array}\right]} \tag{7}$$

$$E''(i\omega\tau) = E_\infty \cdot \frac{\left(\delta \cdot (\tau\omega)^{-k} \cdot \sin\left(\frac{\pi}{2} \cdot k\right) + (\tau\omega)^{-h} \cdot \sin\left(\frac{\pi}{2} \cdot h\right)\right)}{\left[\begin{array}{l} 1 + 2 \cdot \delta \cdot (\tau\omega)^{-k} \cdot \cos\left(\frac{\pi}{2} \cdot k\right) + 2 \cdot (\tau\omega)^{-h} \cdot \cos\left(\frac{\pi}{2} \cdot h\right) + \\ \delta^2 \cdot (\tau\omega)^{-2k} + (\tau\omega)^{-2h} + 2 \cdot \delta \cdot (\tau\omega)^{-k-h} \cdot \cos\left(\frac{\pi}{2} \cdot (k-h)\right) \end{array}\right]} \tag{8}$$

Where:

$\varpi = 2 \cdot \pi \cdot f$ and *f* = frequency (Hz) (9)

The norm of the complex modulus, |*E**|, and phase angle, δ, are then obtained as:

$$|E^*| = \sqrt{E'(i\omega\tau)^2 + E''(i\omega\tau)^2} \tag{10}$$

$$\tan\delta = \frac{E''(i\omega\tau)}{E'(i\omega\tau)} \tag{11}$$

Since expressions (5) and (6) use the same parameters δ, h, k, and τ, theoretically, the BBR creep compliance experimental data can be used to predict the DSR complex modulus and vice versa, the DSR complex modulus experimental data can be used to predict creep compliance.

EXPERIMENTAL INVESTIGATION

DSR complex modulus tests (AASHTO T 313-05, 2006) and BBR creep tests (AASHTO T 313-06) were performed on two asphalt binders: PG58-28 (Citgo) and PG58-34 (MIF). DSR frequency sweep tests were performed at seven temperatures (-18ºC, -12ºC, -6ºC, 0ºC, 4ºC, 10ºC, and 16ºC) BBR creep tests were performed at two temperatures (-18º and -12ºC for PG -28, and -24º and -18ºC for PG—34). All tests were performed on pressure aging vessel (PAV) condition.

Examples of |G*| and δ master curves and black diagram curves generated from DSR experimental data are presented in Figures 2 and 3. Visual inspection of the experimental data indicates that there were no obvious experimental errors and that linear viscoelastic conditions were present.

Figure 2. |G| and δ master curves for Citgo binder (PG 58-28)*

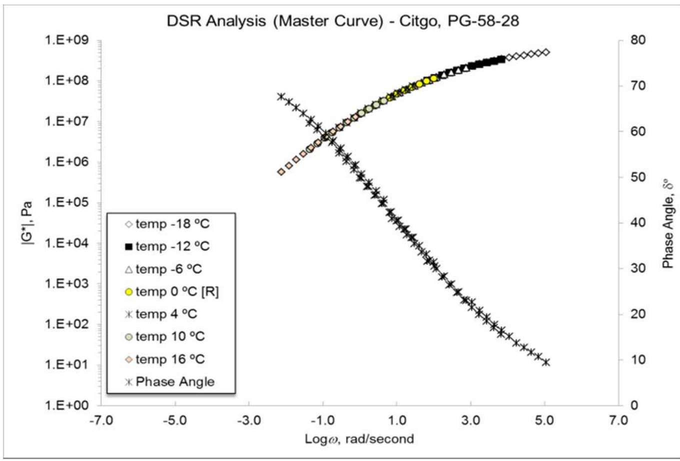
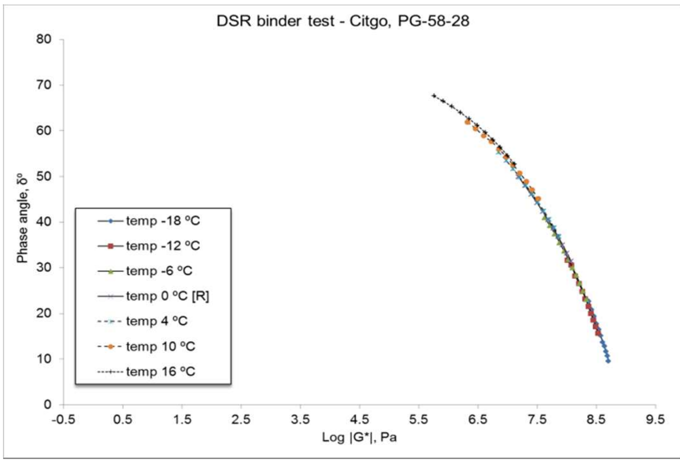


Figure 4. Black diagram curve for Citgo binder (PG 58-28)



Predicting asphalt binder creep compliance from asphalt binder complex modulus experimental data and vice versa

The model parameters obtained from fitting G* data at seven temperatures were used to predict the bending creep data. The values obtained using equation (5) matched very well the creep compliance data obtained with BBR at two temperatures, which is not surprising since the model parameters were obtained by fitting a large set of data.

The more challenging case is using Huet parameters obtained from fitting the relatively small set of creep compliance experimental data to predict complex modulus over a wide range of frequencies (or temperatures). When these parameters were used in equations (7) and (8) to calculate G' and G", uneven shapes of Cole-Cole plots (G" vs. G') were obtained, as shown in Figures 5 and 6. The figures show plots of the experimental DSR data, of Huet model predictions based on the model parameters obtained from fitting the DRS experimental data, and of Huet model predictions based on model parameters obtained from fitting the BBR experimental data.

Figure 5: Cole-Cole plot, Citgo binder

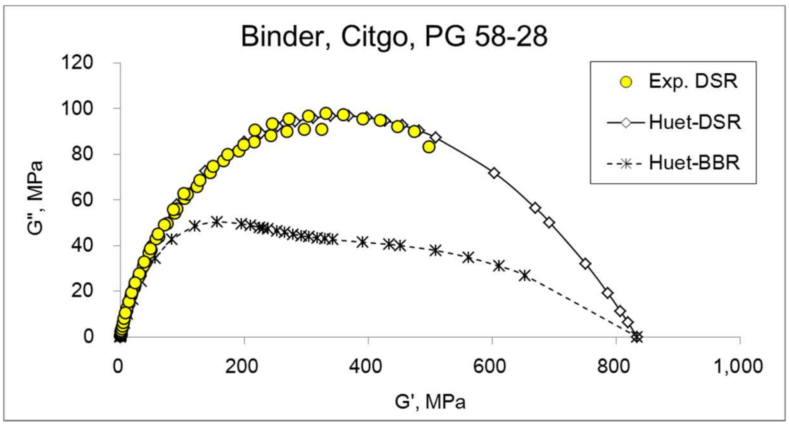
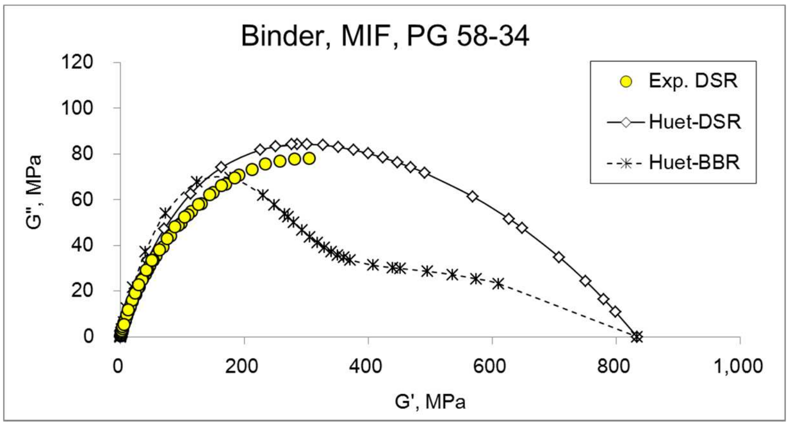


Figure 6: Cole-Cole plot, MIF binder



Based on several computation trials, it was determined that applying stricter limits in the calculation of *k* parameter could solve the problem. As a consequence, the following limits were placed for the two binders:

- Binder type Citgo (PG 58-28): 0.25 < *k*< 0.4
- Binder type MIF (PG 58-34): 0.20 < *k*< 0.4

By imposing these restrictions of the k parameter, slightly different values were obtained from fitting the BBR experimental data for the h and k parameters compared to the values obtained with no restrictions. Using these new values, Cole-Cole and black-diagram plots for two binder types were generated and examples are presented in Figures 7 to 9.

Figure 7: Cole-Cole using new parameters, Citgo binder

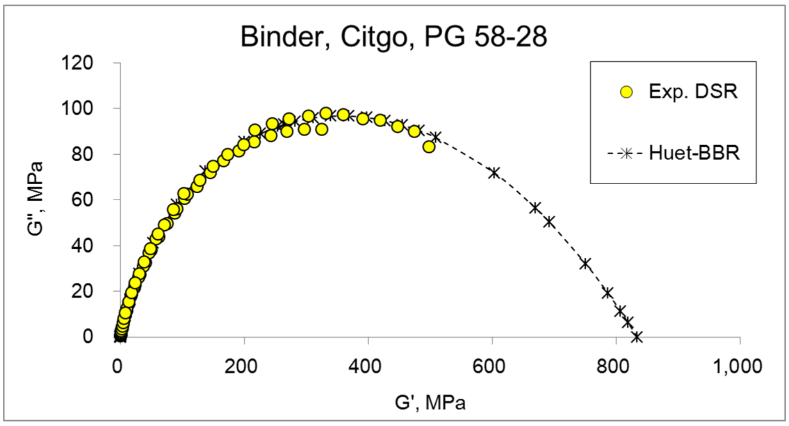


Figure 8: Cole-Cole using new parameters, MIF binder

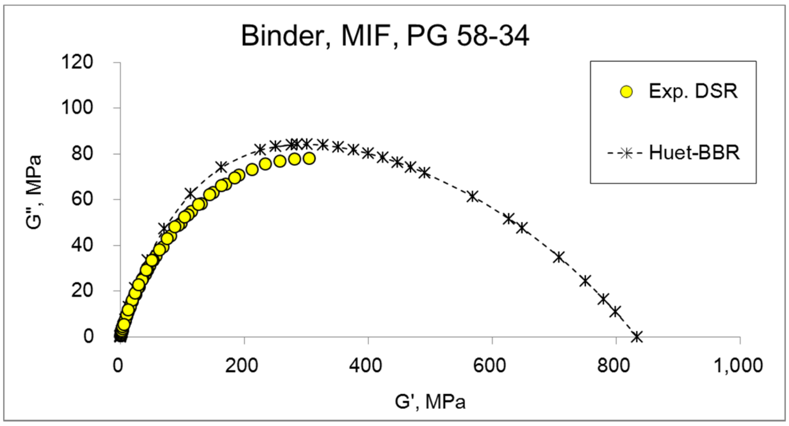
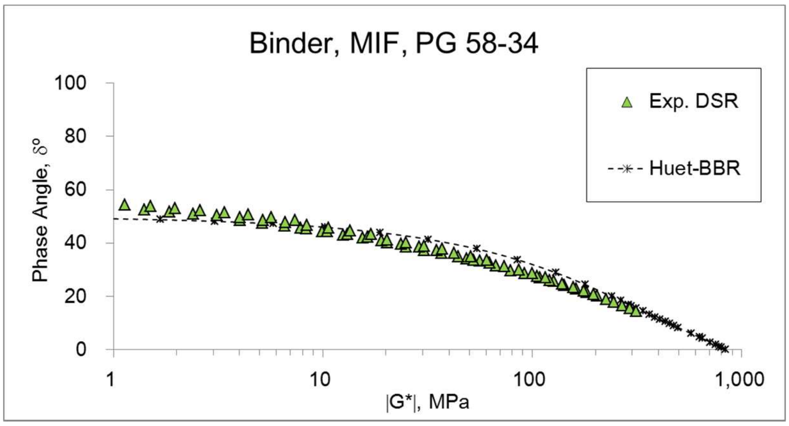


Figure 9: Black diagram plot of MIF binder

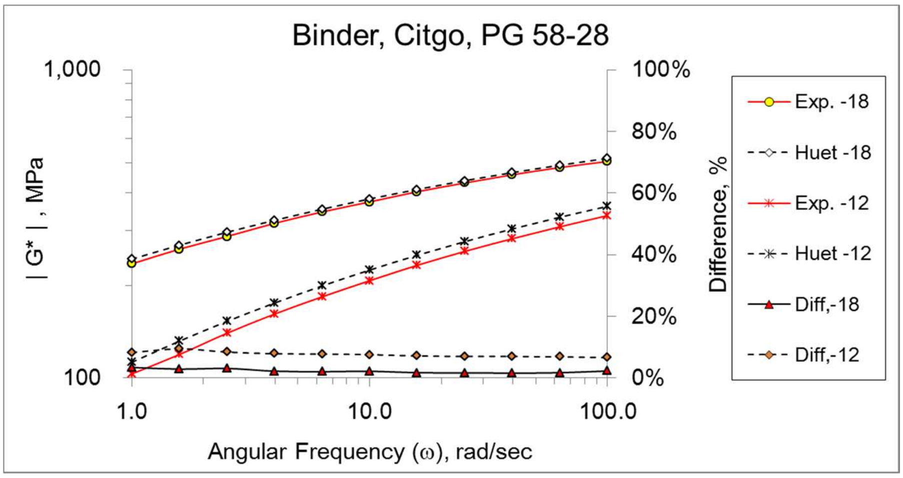


By imposing restriction on the k Huet model parameter, it appears that BBR creep data can be used with reasonable degree of success to predict the behavior of binders in the frequency domain. Direct comparison of the experimental and predicted norm of complex modulus is shown in figure 11 for Citgo binder.

CONCLUSIONS

In this paper, DSR complex modulus tests and BBR creep tests were performed on two asphalt binders in PAV condition. By fitting the Huet model expressions to the two sets of experimental data, it was found out that oscillatory data obtained over a wider range of temperatures could be successfully used to predict bending creep compliance. However, for the reverse scenario, it was found that Huet parameters obtained from creep experiments could be successfully used to predict complex modulus only if additional restrictions were imposed on parameter *k*. This indicates that additional work is required to understand the physical meaning of the Huet model parameters to determine a range of values that would not collapse the shape of Cole-Cole plots.

Figure 11: Binder experimental and predicted |G| for Citgo*



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