Prediction of Complex Shear Modulus and Fracture Properties of Asphalt Binders with Oxidative Aging

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Sept 17, 2014

Outline

- Introduction
- Experiment Methods
  - Aging
  - Carbonyl area measurements
  - Frequency sweep and monotonic tests
- Test Results and Discussion
  - Crossover modulus and carbonyl area
  - Analysis of crossover modulus data
  - Evolution of crossover frequency ω_c
  - Predicted master curve of G* and δ and fracture properties
- Conclusion and Recommendations

Introduction

- Glover et al. (2009) indicated the most influential aspect of asphalt binder aging is oxidation.
- It is accepted that the binders become stiffer and more brittle with oxidation age, and finally induce damage.
- A better model for predicting asphalt binder mechanical properties from oxidation is needed.

* tirerack.com

Introduction

- Only limited work has been focused on predicting asphalt binder oxidation.
- The global aging model (Mirza and Witczak, 1995) which was used to predict asphalt aging in MEPDG may potentially induces lots of error, because it did not consider the individual aging path (Liu et al., 1996).

Introduction

- Herrington (1998) proposed a model which was fitted to oxidation rate data in terms of viscosity increase of unmodified binders under 2MPa air pressure at 60ºC, 70ºC, and 80ºC.

$$P = P_{f\infty}(1 - e^{-K_f t}) + K_s t$$

  - P is the change of logarithmic viscosity
  - k_f and k_s are rate constants of two reactions
  - Pf_∞ is the intercept.

Introduction

- Martin et al. (1990) found that the relationship between logarithmic viscosity and carbonyl area was linear.
- Xin et al (2011) proposed a similar two reaction model to predict carbonyl area as a function of aging temperature and time.

Introduction

- Farrar et al. (2013) collected four section cores that were constructed after four years to nine years from a hot mix asphalt comparative test site.
- It is found that there was approximately linear relationship between oxygen uptake and the inverse of the log of the crossover modulus, $1/\log(G_c^*)$, though the correlation was asphalt dependent

Introduction

- Liu et al. (1988) found there is a linear correlation between the oxygen content and the carbonyl content which is independent of aging temperature and aging pressure.

- So there may be a linear relationship between the carbonyl area (CA) and $1/\log(G_c^*)$

Introduction

- Farrar et al. also found that the linear relationship between $\log(\omega_c)$ and $\log(G_c^*)$ at each temperature.

- Christensen-Anderson (CA) model (1992) to predict the change in binder complex modulus and phase angle.

Introduction

- Pavement distresses are often related to cracking.
- The effect of oxidative aging on cracking potential needs to be addressed.
- Few studies have worked on how aging affects the fracture properties which are directly related to cracking.

Objectives

- Predict viscoelastic properties of asphalt binder with oxidative aging

- Determine fracture properties of asphalt binder with oxidative aging

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Aging

- Asphalt Binder:
  - IA PG58-22, MT PG70-28(SBS)
    LA PG76-22(SBS)

Temperature	Aging time, days
55° C	2,5,10,18, 26, 35, 45, 60, 90
70° C	1, 3, 6,10,15, 22, 30, 40
85° C	1, 3, 5, 8,13,18, 24, 30
100° C	1, 2, 4, 6, 8,11,14,17

≤1mm

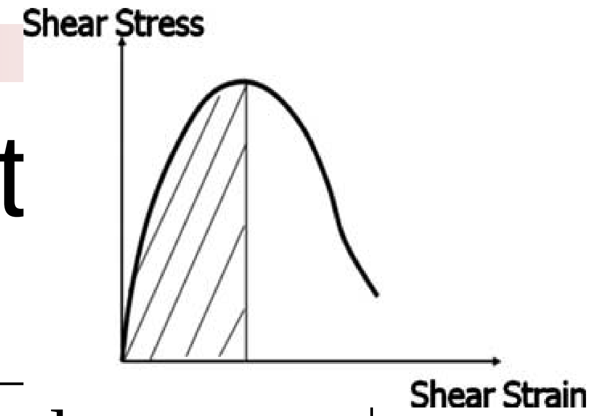
Carbonyl area measurements

- After aging durations, each sample was analyzed using FT-IR.
- The carbonyl area (CA) was determined by finding the area under the absorbance peaks from 1650-1820 cm^{-1}

Frequency sweep test

- 8mm diameter parallel plates
- Temperature: 5ºC, 15ºC, 25ºC, 35ºC, and 45ºC
- Angular frequency range: 0.1rad/s-100rad/s.

Monotonic test



- Aged binders (PG58-28)

Temperature	Aging time, days
70ºC	15, 22, 30, 40

- The shear rate are 0.025s^{-1}, 0.05s^{-1}, 0.1s^{-1} , and each shear rate was performed at 5ºC and 15ºC respectively.
- Shear strength and critical strain energy density (CSED) are determined
- Good correlation between CSED and cracking in field (Wen et al. 2010, 2013)

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Analysis

Carbonyl area (function of aging temperature and time) ← Arrhenius Equation

$$CA = CA_{tank} + M(1 - \exp(-k_f t)) + k_c t$$

$$k_f = A_f \exp(-E_{af}/RT)$$

$$k_c = A_c \exp(-E_{ac}/RT)$$

↓ linear

Inverse of log crossover modulus

↓ linear

Crossover frequency

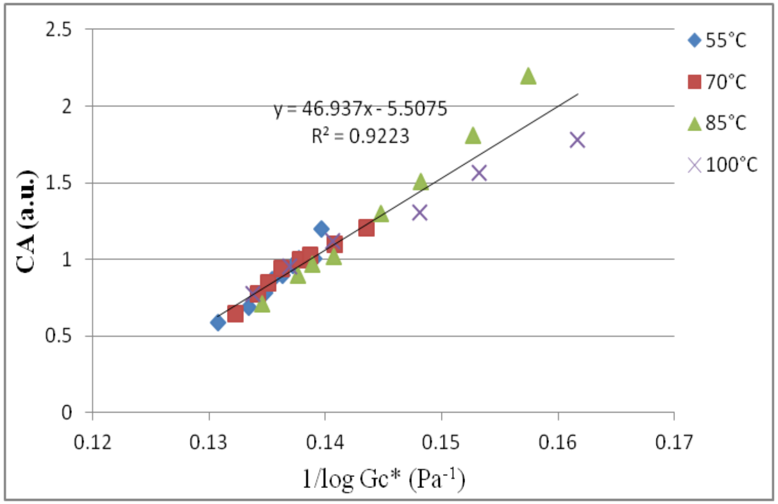
↓

G* and δ ←

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

$$\delta(\omega) = \frac{90}{\left[1+\left(\frac{\omega}{\omega_c}\right)^{\frac{\log 2}{R}}\right]}$$

The crossover modulus and carbonyl area



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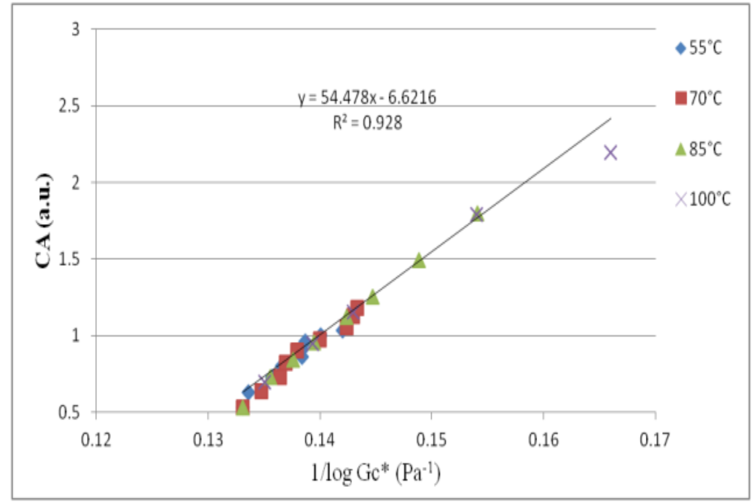

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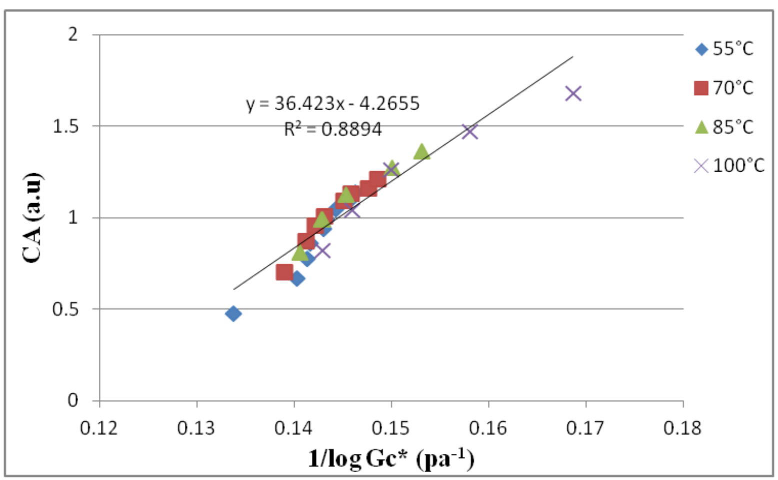
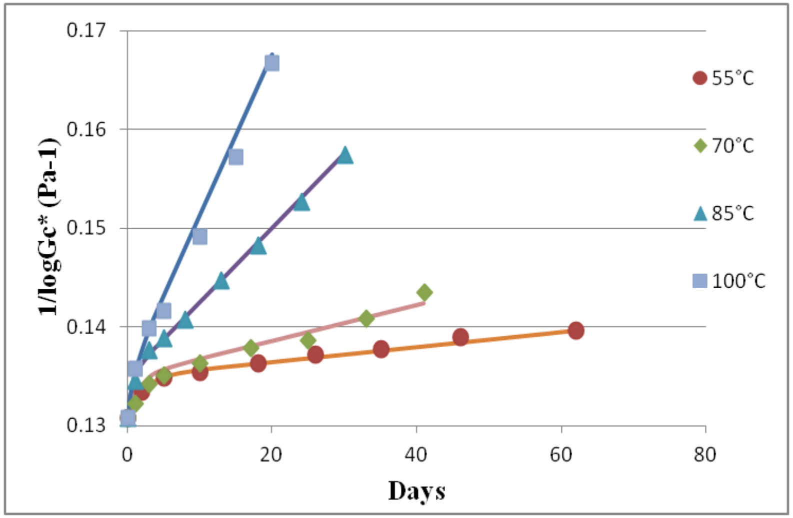


PG 76-22

Analysis of crossover modulus data



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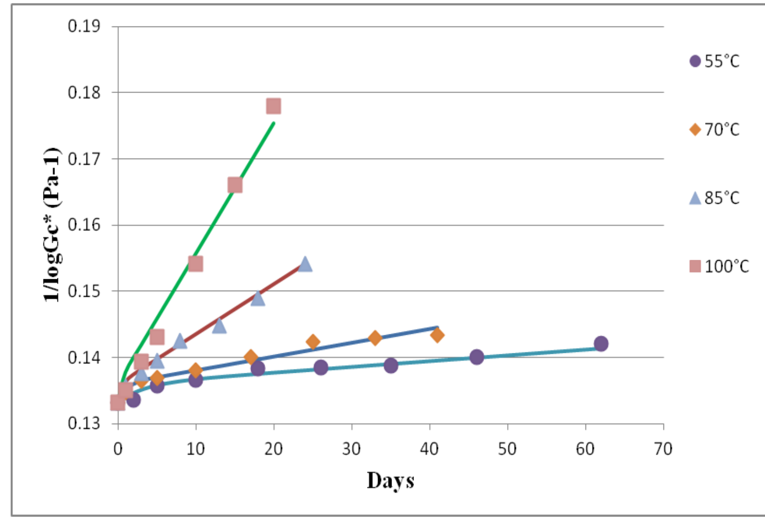

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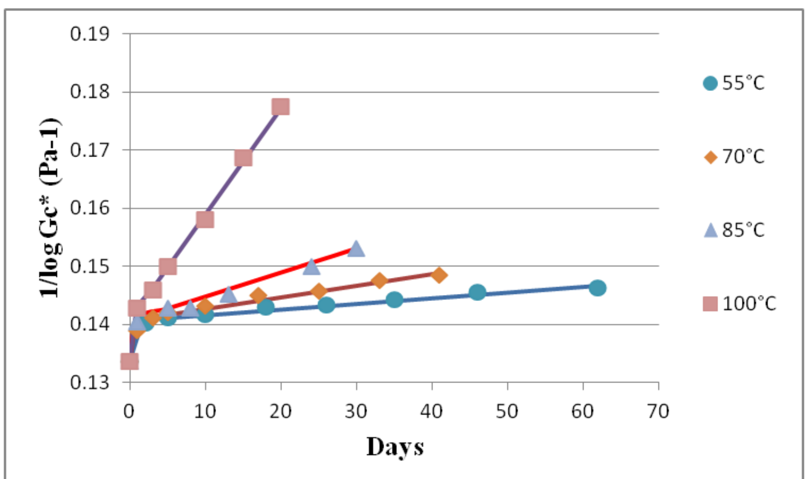
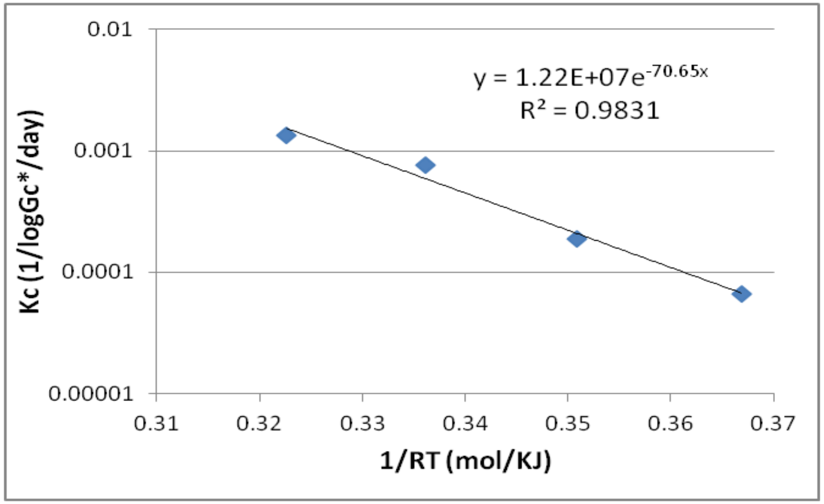


PG 76-22

Figure 1/log Gc* growth of PG binders at four temperature in air

Constant reaction values of PG binders



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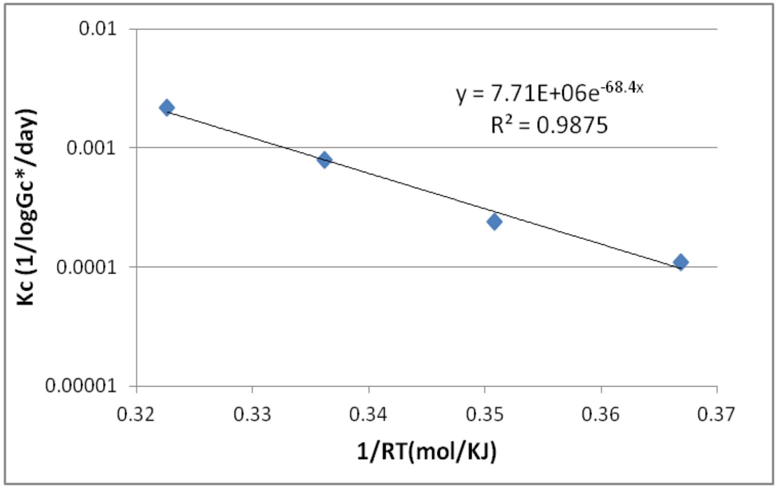

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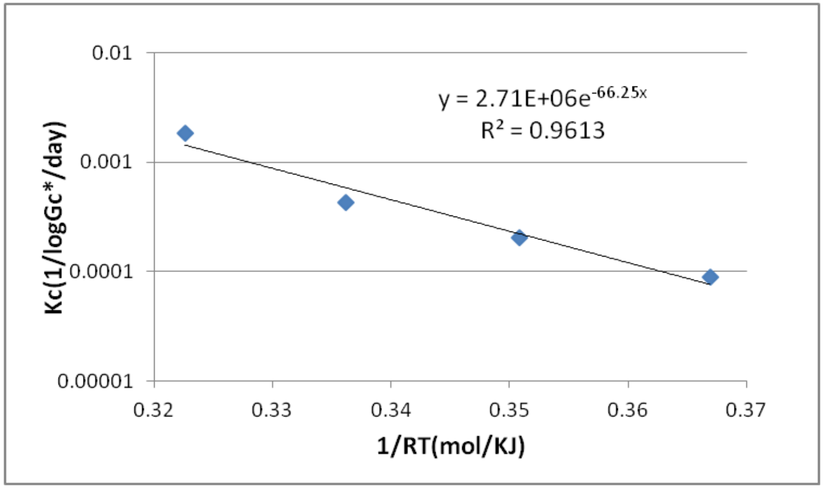


PG 76-22

$$\frac{1}{logG_c^*} = \frac{1}{logG_{c,tank}^*} + G_\infty(1 + e^{-K_f t}) + K_c t$$

$$K_f = A_f e^{(-\frac{E_{af}}{RT})}$$

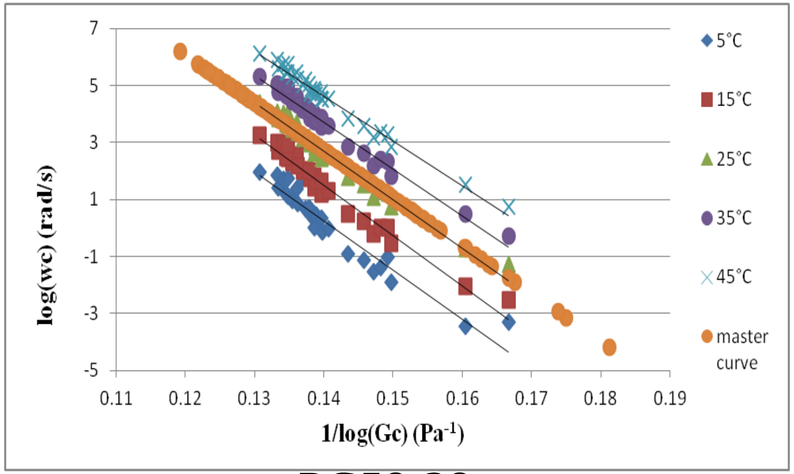
$$K_c = A_c e^{(-\frac{E_{ac}}{RT})}$$

$$G_\infty = \frac{1}{logG_{c,0}^*} - \frac{1}{logG_{c,tank}^*}$$

Table Optimized parameters of the three binders

Binders	$1/Gc^*_0$	A_f	E_{af}	A_c	E_{ac}
IA PG58-28	0.135	1.16e+06	40.50	1.97e+07	70.84
MT PG70-28	0.136	5.24e+05	51.20	7.86e+06	69.10
LA PG76-22	0.141	7.41e+04	29.24	2.19e+06	65.80

1/log(G_c*) master curve for the binders



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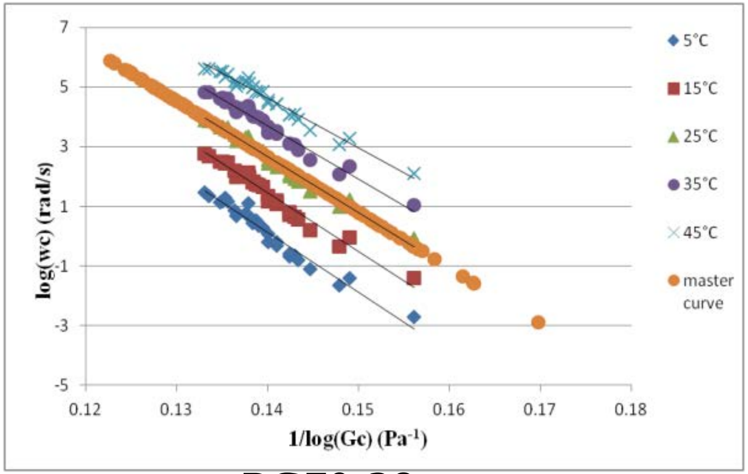

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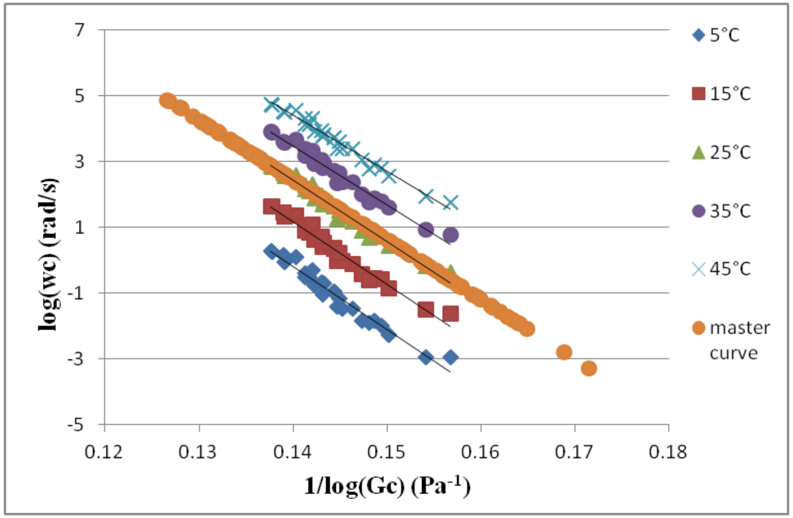
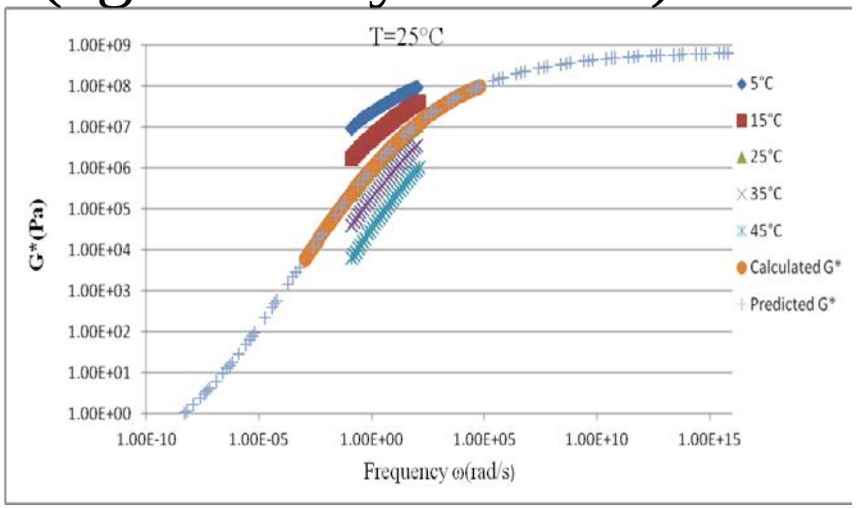
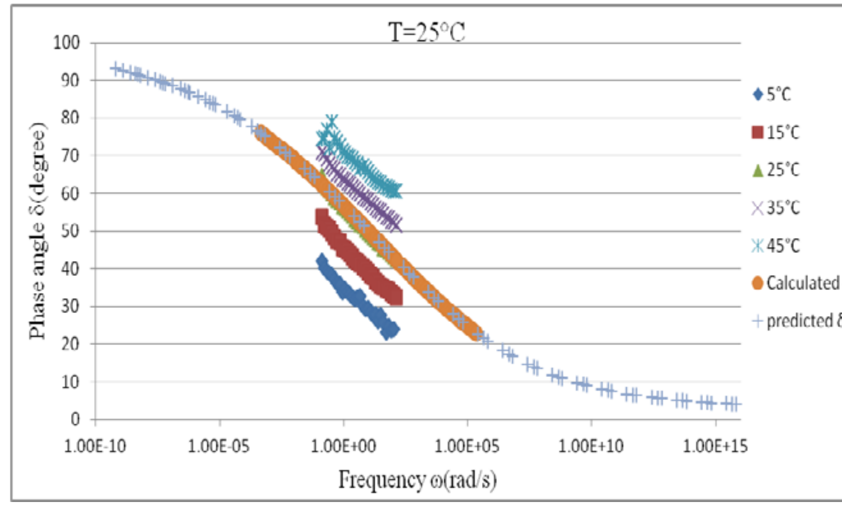


PG76-22

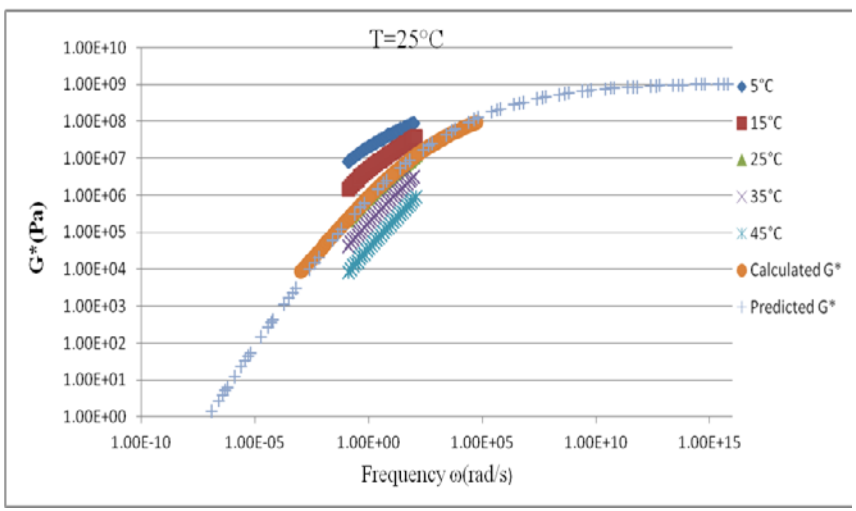
Predicted master curve of G* and δ (CA model) (aged 40days at 70C)



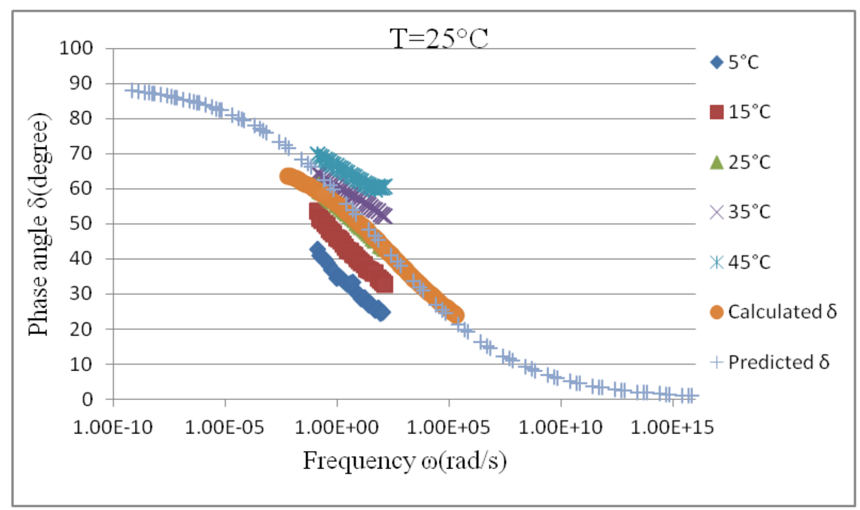
PG58-28 G*



PG58-28 δ

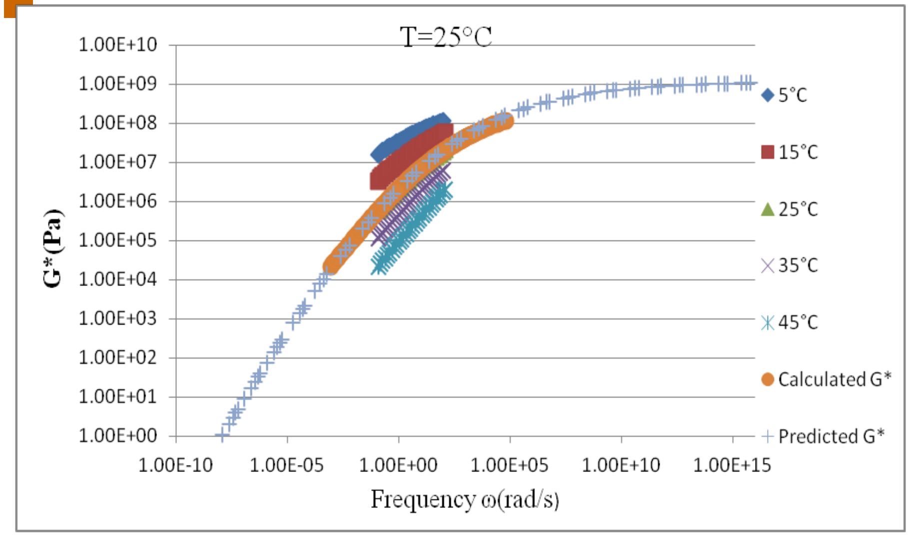


PG70-28 G*

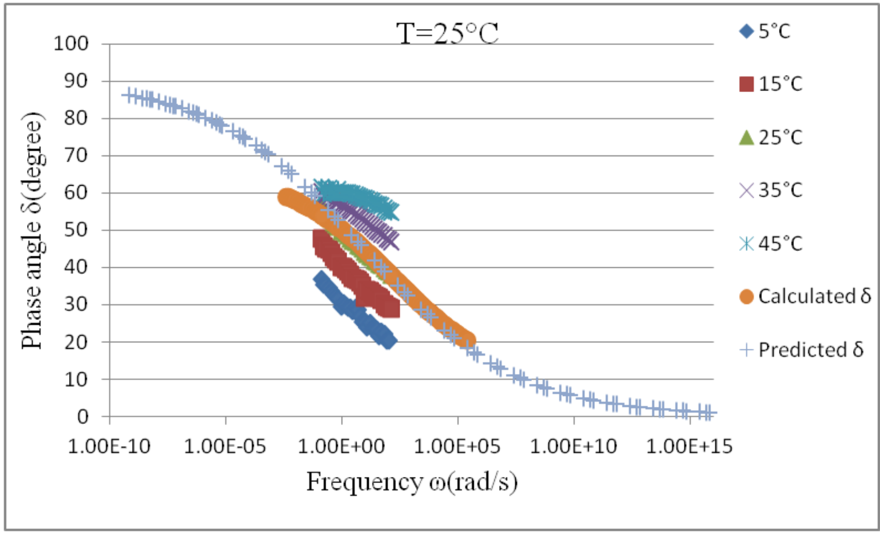


PG70-28 δ

Block 1



PG76-22 G*

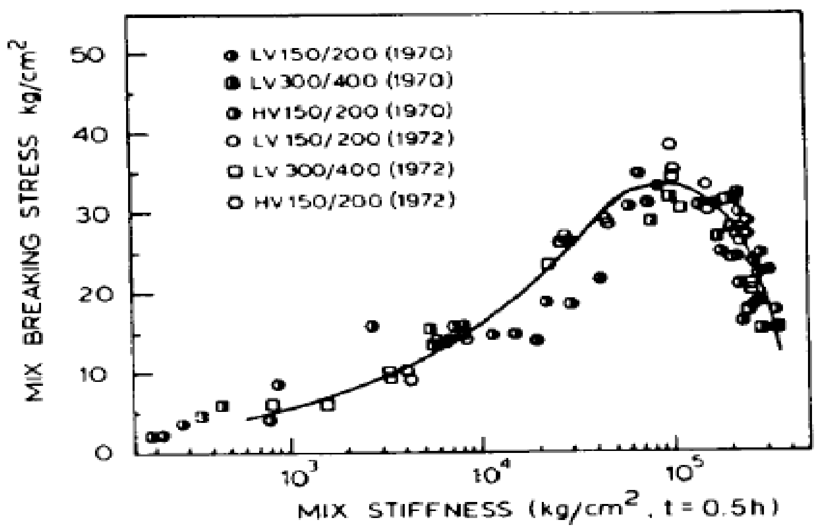


PG76-22 δ

- Predicted G* and δ of the three binders match well with the calculated G* and δ from the sigmoidal function
- The model can only accurately predict when the phase angle is between 10º and 60º. So there is little deviation between the predicted and calculated master curve when it approaches high temperatures or low frequencies.

Mixture stiffness and tensile strength

- Deme and Young (1987) found tensile strength of mixture is well correlated with mixture creep stiffness at a loading time of 1800s, i.e., S_{1800}
- The relation between mixture creep stiffness and tensile strength :



Tensile strength of mix is a function of mix stiffness.

$$S_t = \sum_{n=0}^{5} a_n \cdot (\log S_f)^n$$

Interconversion from complex shear modulus to shear relaxation modulus

- Generalized Maxwell model

$$G(t) = \sum_{i=1}^{n} g_i e^{-t/\lambda_i}$$

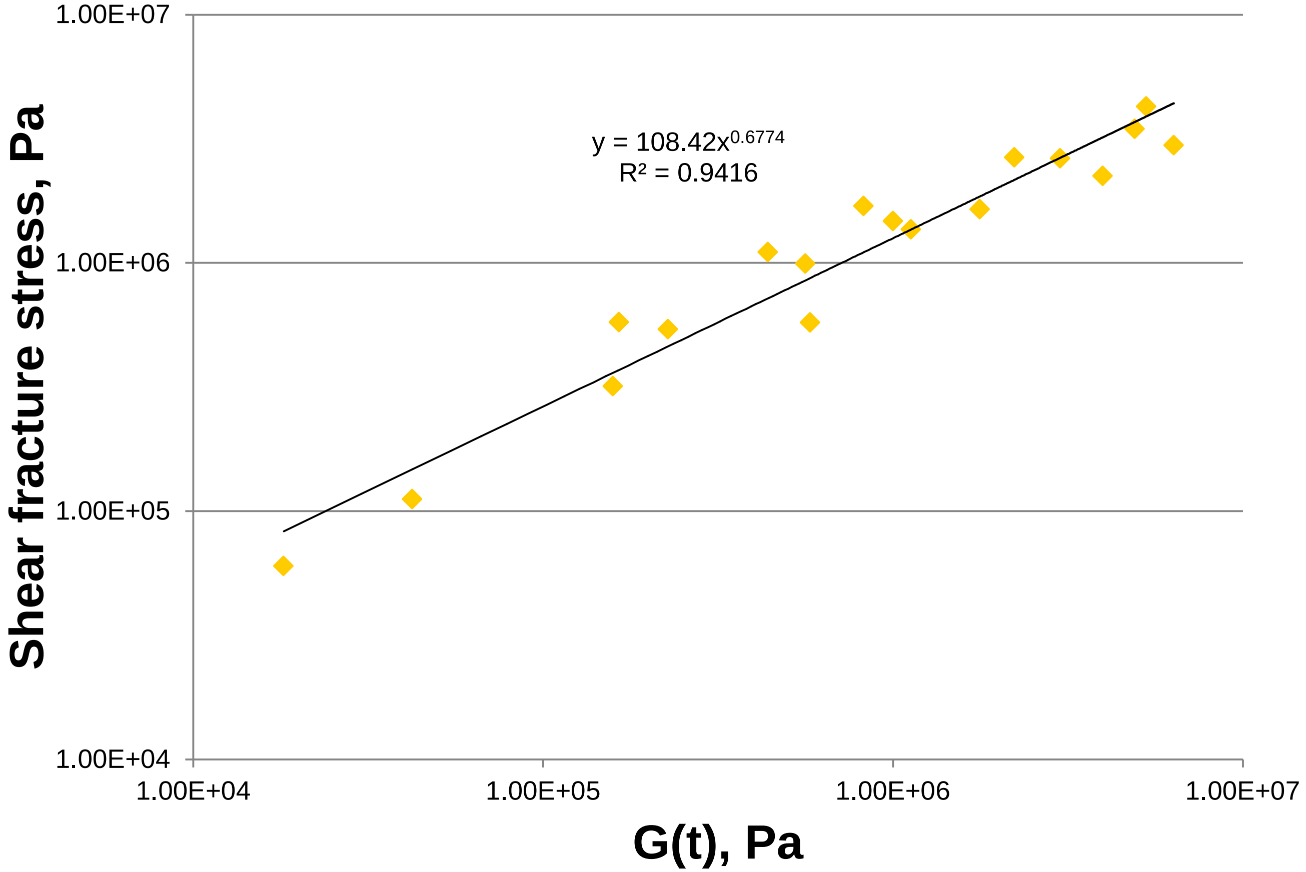
$$G'(\omega) = \sum_{1}^{n} g_i \frac{\omega^2\lambda_i^2}{1+\omega^2\lambda_i^2}$$

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

- Empirical conversion method developed by Ninomiya and Ferry (1959)

$$G(t) = G'(\omega) - 0.4G''(0.4\omega) + 0.014G''(10\omega)$$

Shear relaxation modulus and shear fracture stress



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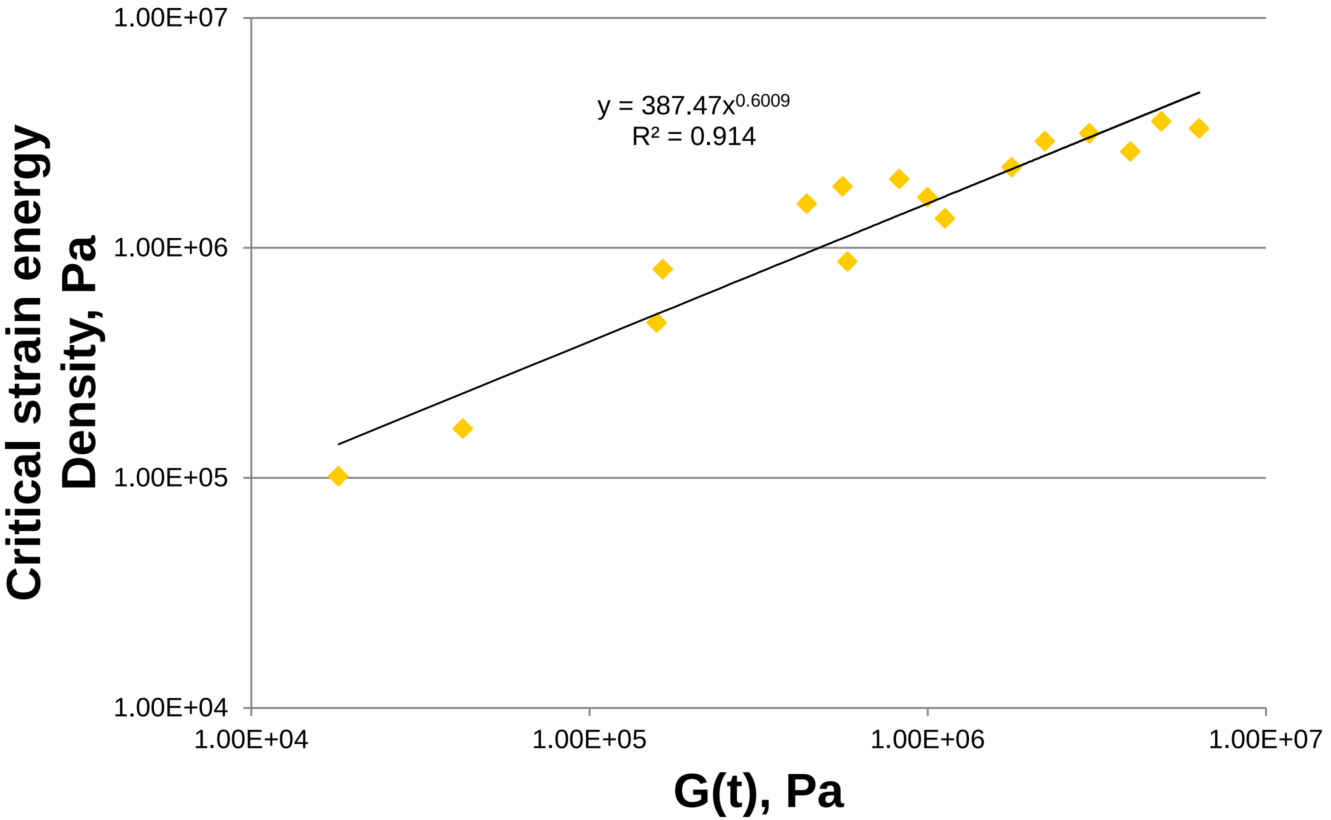
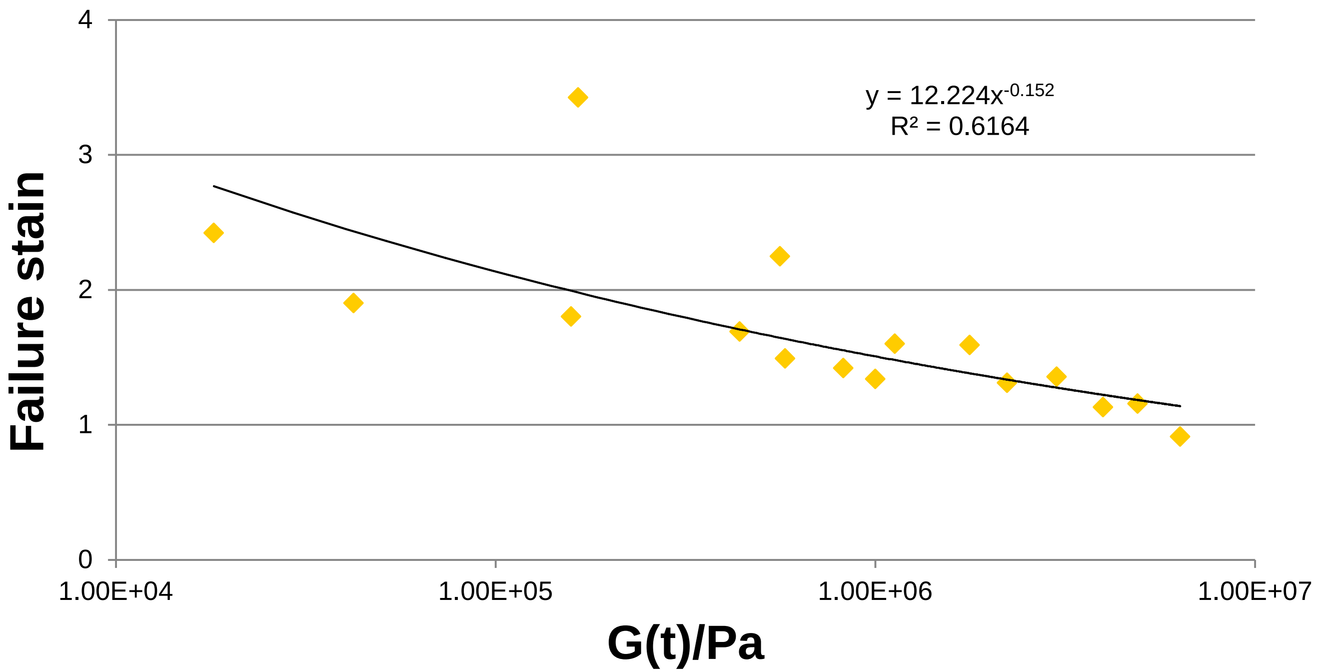
Shear relaxation modulus and critical strain energy density



PG58-28

Block 1

Shear relaxation modulus and Failure stain



PG58-28

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Conclusion

- The relationship between carbonyl area and the log of the crossover modulus are approximately linear although asphalt dependent.
- The inverse of log crossover modulus data showed correlations between the Arrhenius kinetics parameters, and predicted using the oxidation kinetics model as a function of aging time and temperature.

Conclusion

- The log crossover frequency and log crossover modulus are highly linearly correlated with aging time for both neat and modified binders.
- The CA model can be used to predict complex modulus and phase angle master curves, not only for neat binders, but also for modified binders.

Conclusions

- G* can be converted to shear relaxation modulus which can be related to the fracture properties of asphalt binders

Recommendations

- More binders should be included, including polymer modified binders
- Predict fracture properties of mixtures

Thank You!

Any questions?