South African Road Design System – Asphalt Models

Road Pavements Forum Feedback

20 November 2014

H L Theyse

Asphalt material models

- Resilient response model based on published models
  - Local adaptation using data from South African binders and mixes
- Damage models based on a new concept
  - Formulation and calibration based on data for South African binders and mixes
- Data and initial models sourced from CSIR
  - Benoit Verhaeghe
  - Joseph Anochie-Boateng
  - Johan O'Connell
  - Erik Denneman

Asphalt models

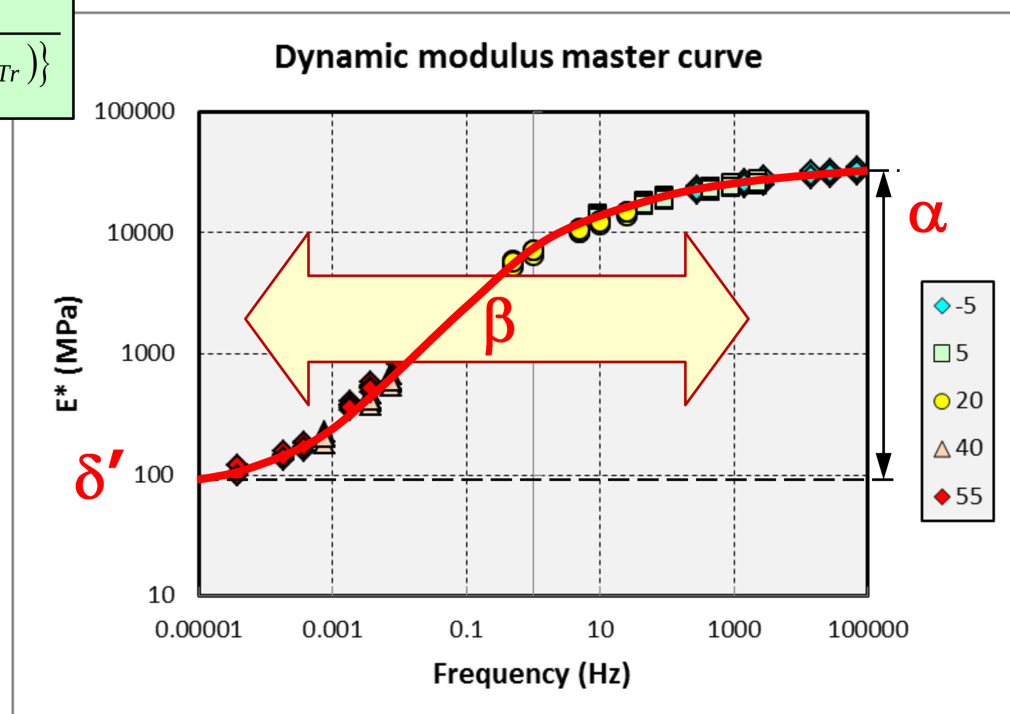
Resilient Response Models

Asphalt resilient response model

- Mimic visco-elastic behaviour with an implicit model
  - Temperature
  - Load-pulse duration
- Sigmoid dynamic modulus model

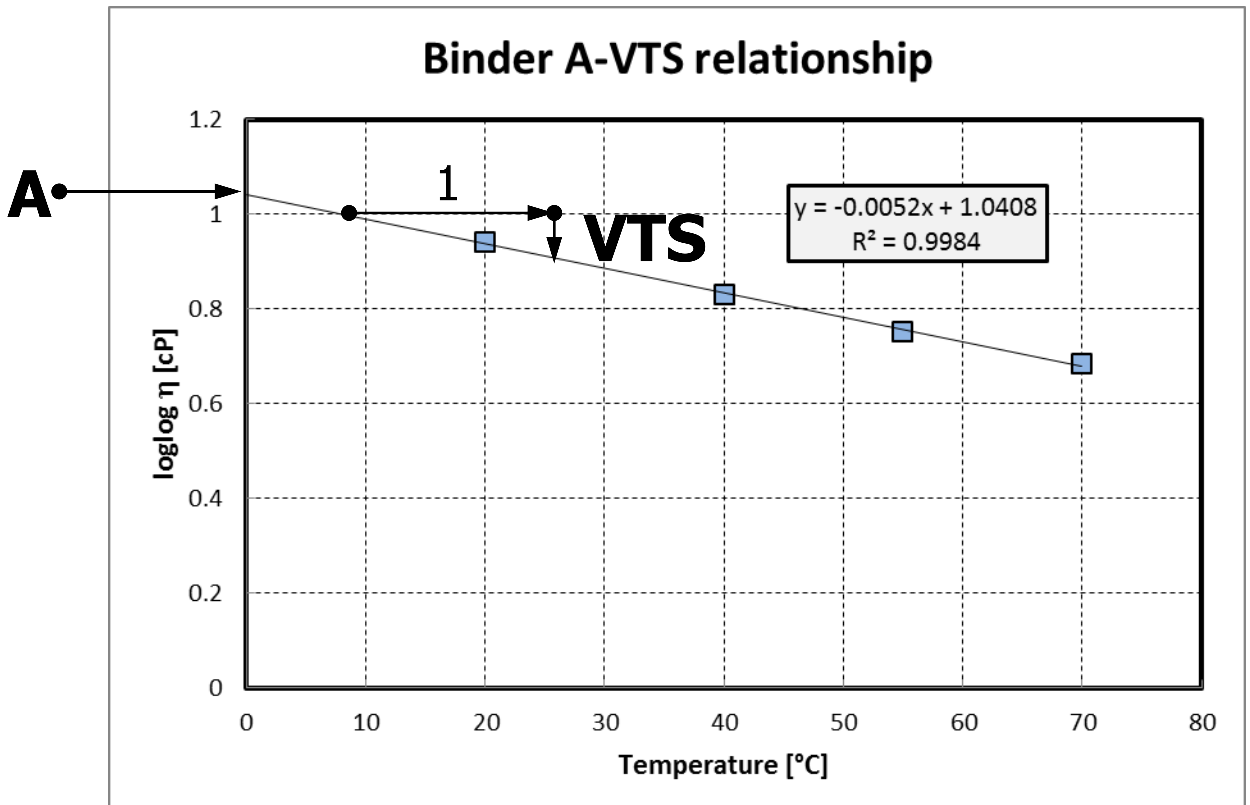
$$\log\left(E^*\right) = \delta' + \frac{\alpha}{1 + e^{\beta + \gamma\left\{\log t - \psi\left(\log \eta_T - \log \eta_{Tr}\right)\right\}}}$$

Symbol	Description
δ′	Minimum parameter
α	Range parameter
β	Location parameter
γ	Slope parameter
ψ	Shift parameter



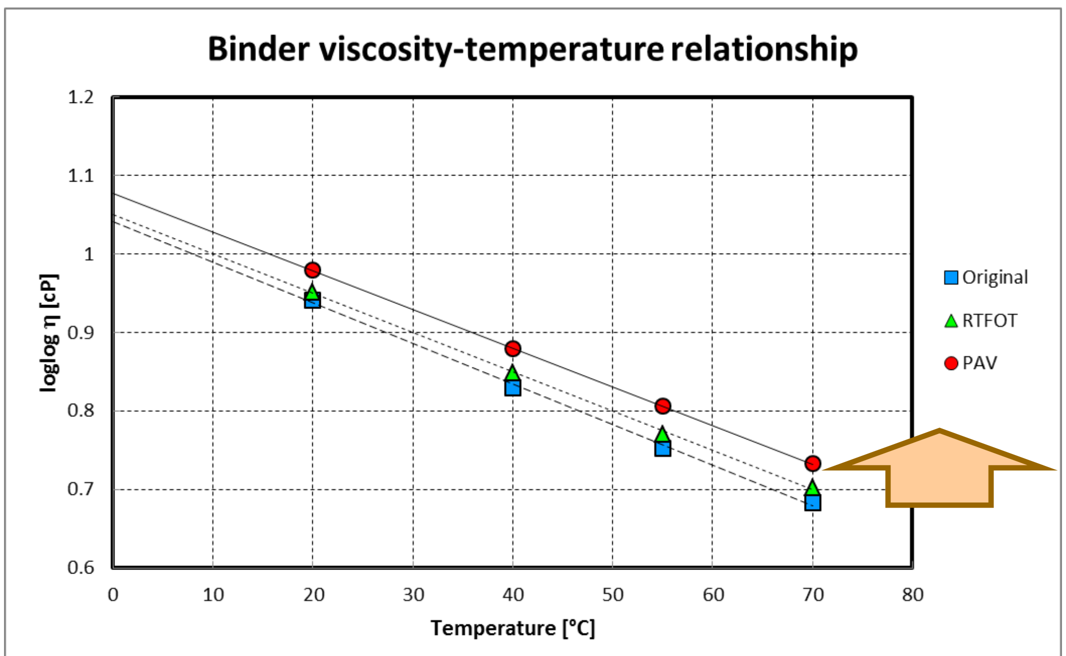
Asphalt resilient response model

- Binder effects enter through the binder model
  - Binder viscosity – temperature relationship derived from DSR test



Asphalt resilient response model

- Binder effects enter through the binder model
  - Binder viscosity – temperature relationship
- Binder ageing
  - Predominantly shifts the viscosity – temperature relationship



Asphalt resilient response model

- Binder effects enter through the binder model
  - Binder viscosity – temperature relationship
- Binder ageing
  - Shifts the viscosity – temperature relationship
- Dynamic modulus affected through
  - Location parameter

$$\beta = \beta_1 + \beta_2 \ln \eta_{Tr}$$

  - Adjusted load-pulse duration

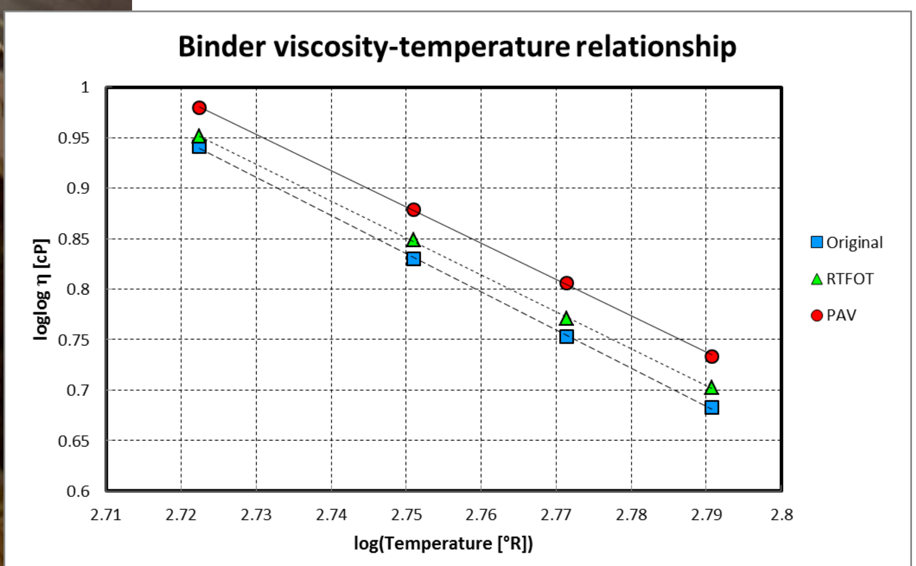
$$\log t - \psi \left(\log \eta_T - \log \eta_{Tr} \right)$$

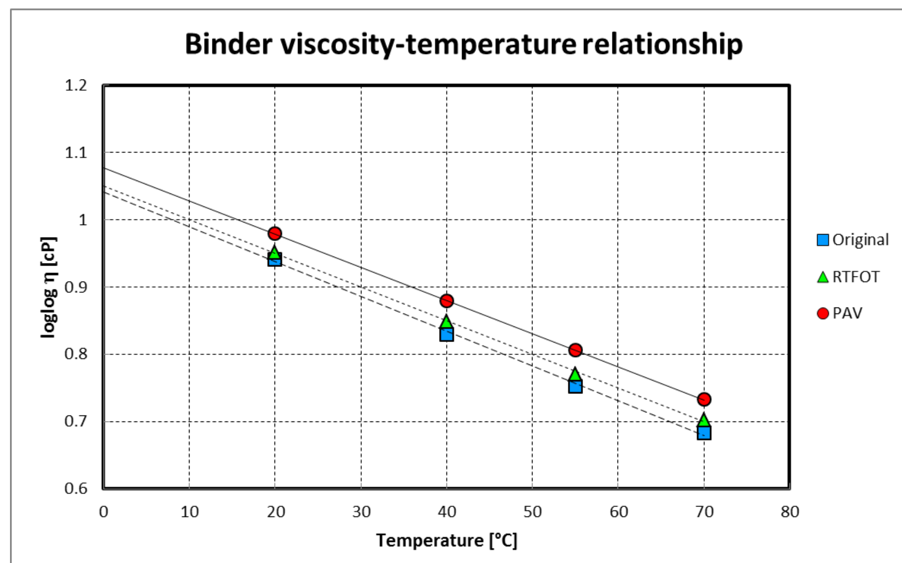
Binder model modifications

- Binder model
  - Intercept and slope of viscosity – temperature relationship
  - Converted to Celsius temperature scale
  - Converted to normal temperature scale
  - Allows negative temperatures

$$\log\log\eta_T = A - VTS\log T[°R]$$

$$\log\log\eta_T = A_C - VTS_C\left(T\right)$$

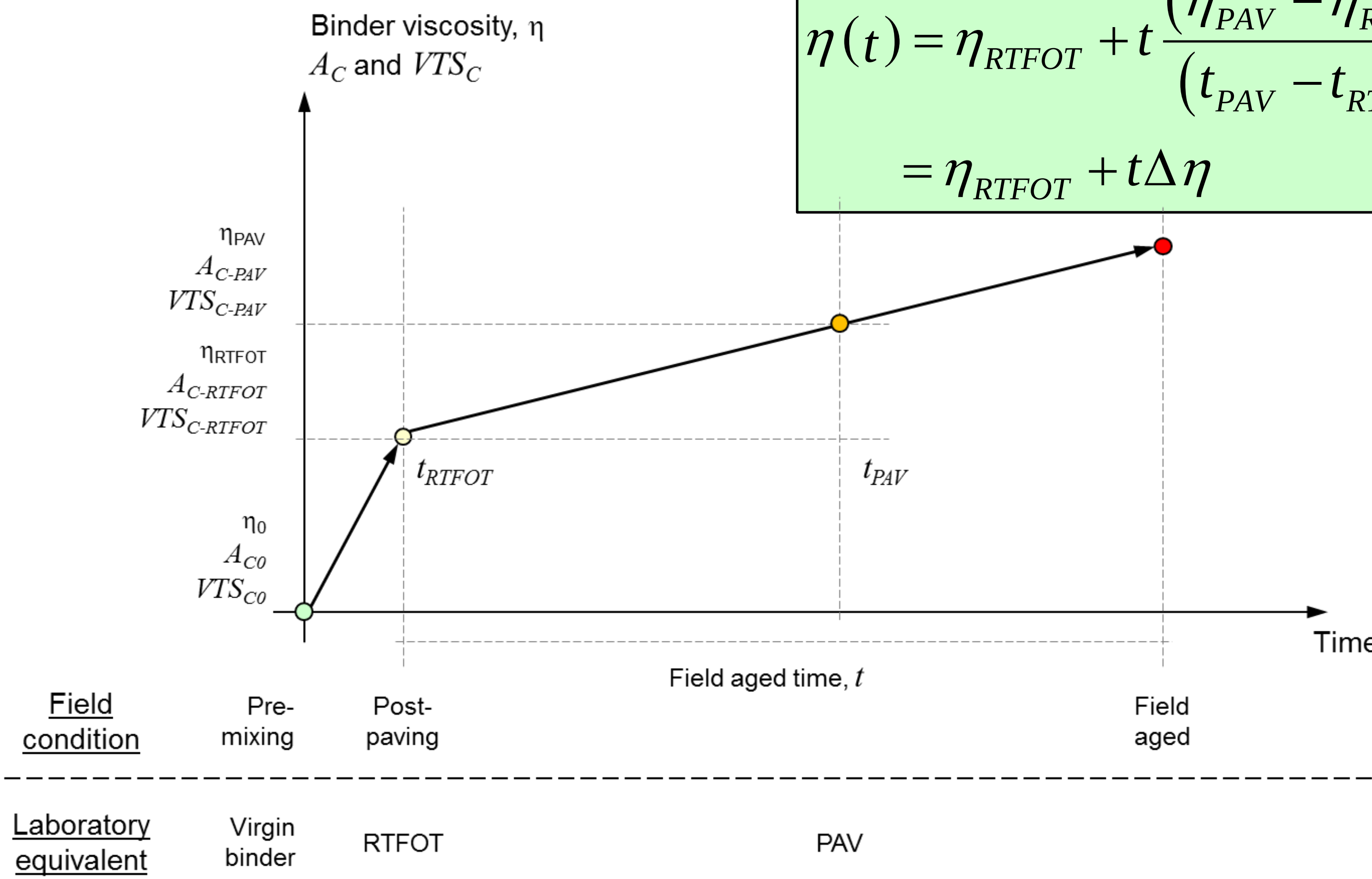




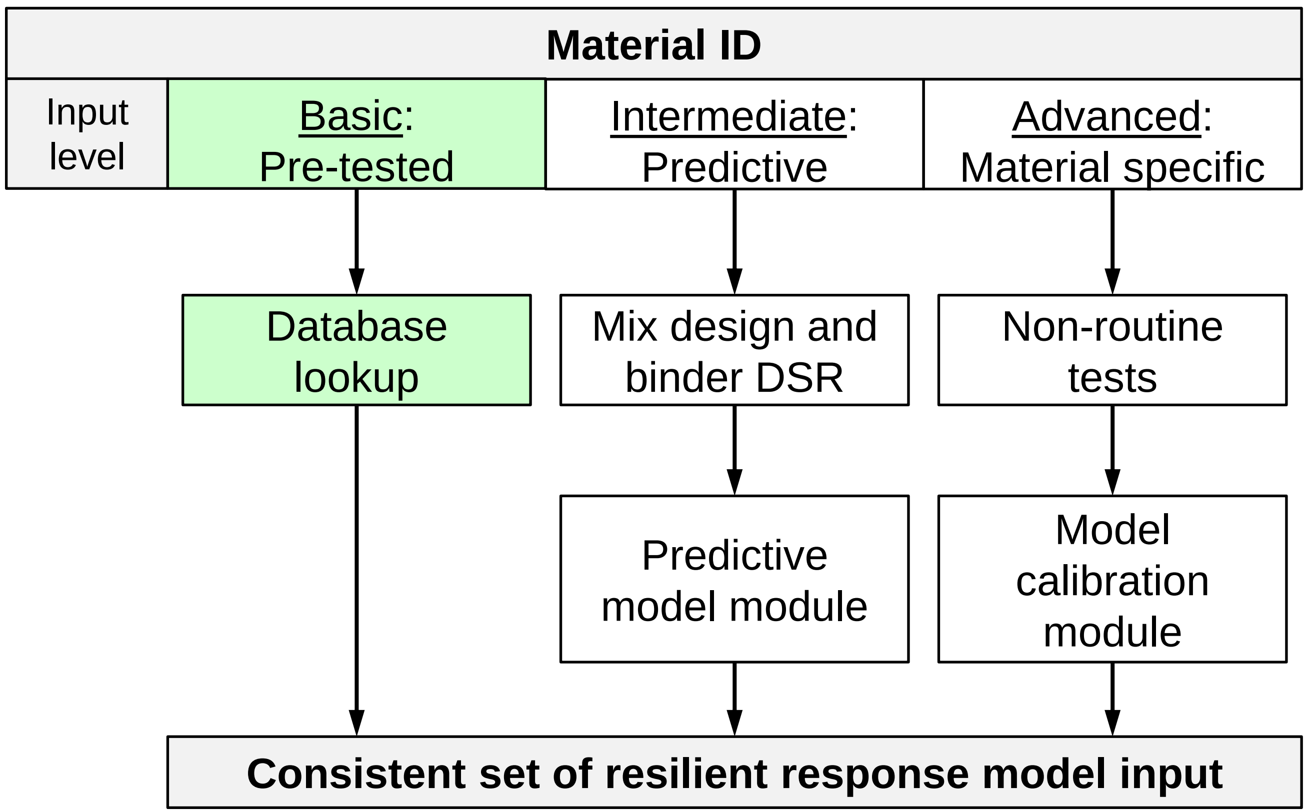
Extrapolation to field ageing

- Johan O'Connell model

$$\eta(t) = \eta_{RTFOT} + t\frac{(\eta_{PAV} - \eta_{RTFOT})}{(t_{PAV} - t_{RTFOT})}$$
$$= \eta_{RTFOT} + t\Delta\eta$$



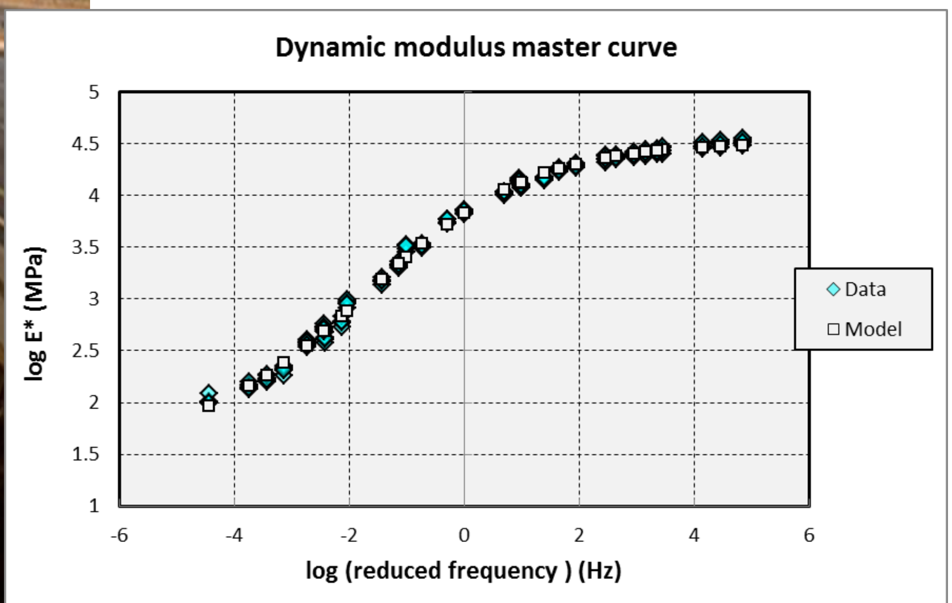
Asphalt resilient response model – Input levels

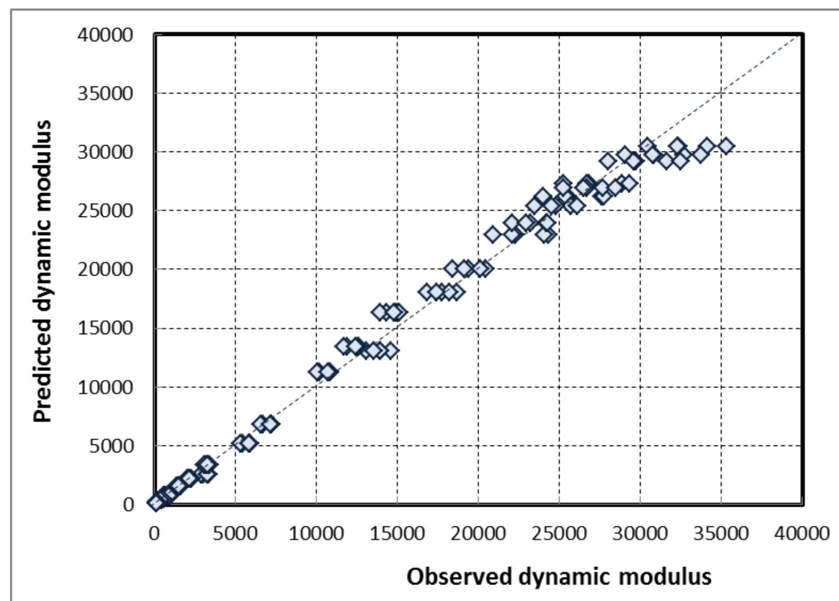


Asphalt resilient response model – Basic input level

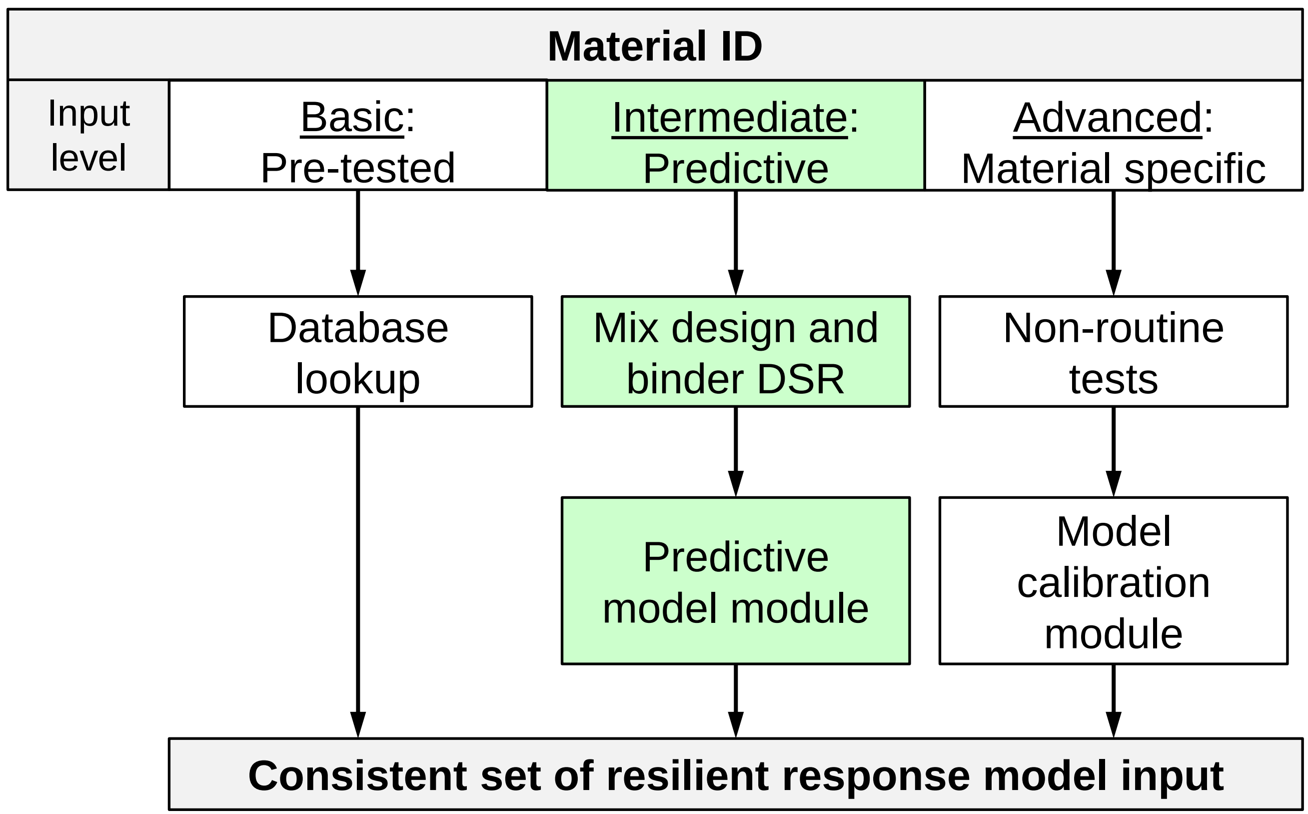
- Preloaded binder and dynamic modulus model coefficients
  - Pick-a-mix from a list

AC medium 60/70 pen binder





Asphalt resilient response model – Input levels



Asphalt resilient response model – Intermediate input level

- Predictive dynamic modulus model
  - Witczak predictive model

Symbol	Description	Depends on ….
δ'	Minimum parameter	Aggregate grading and mix volumetric composition
α	Range parameter	Aggregate grading
β	Location parameter	Binder viscosity at reference temperature
γ	Slope parameter	Constant = 0.313351
ψ	Shift parameter	Constant = 1.255882

Asphalt resilient response model – Intermediate input level

- Predictive dynamic modulus model
  - Witczak predictive model

$$\log\left(E^*\right) = \delta' + \frac{\alpha}{1 + e^{\beta + \gamma\left\{\log t - \psi\left(\log \eta_T - \log \eta_{Tr}\right)\right\}}}$$

$$\delta' = \delta_1' + \delta_2 pp_{200} + \delta_3 pp_{200}^2 + \delta_4 p_4 + \delta_5 \left(V_a\right) + \delta_6 \left(VFB\right)$$

$$\alpha = \alpha_1 + \alpha_2 p_4 + \alpha_3 p_{38} + \alpha_4 p_{38}^2 + \alpha_5 p_{34}$$

pp_{200} = percentage of aggregate passing the 0.075 mm sieve

p_4 = cumulative percentage of aggregate retained on the 4.75 mm sieve

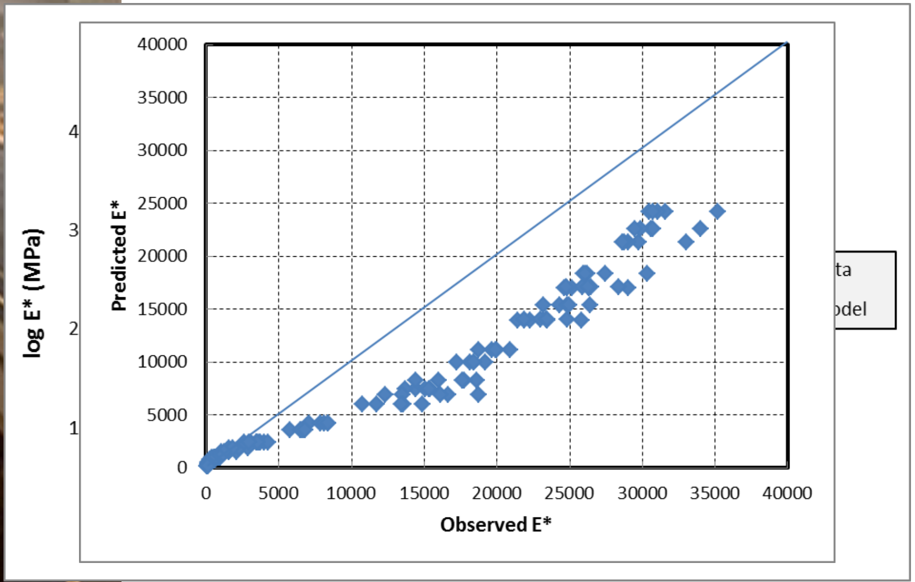
p_{38} = cumulative percentage of aggregate retained on the 9.5 mm sieve

p_{34} = cumulative percentage of aggregate retained on the 19.0 mm sieve

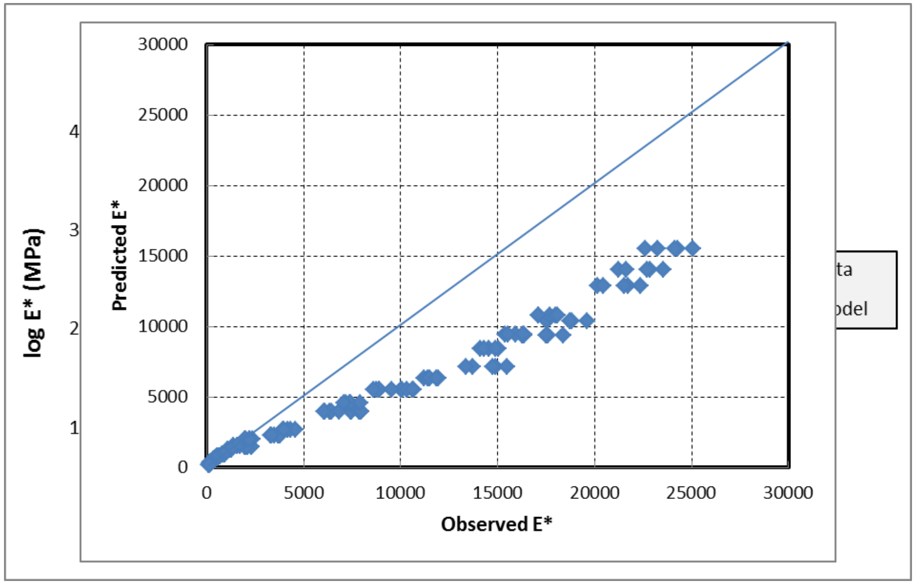
Asphalt resilient response model – Intermediate input level

- Predictive dynamic modulus model
  - Witczak predictive model not accurate enough

BTB 40/50 pen binder

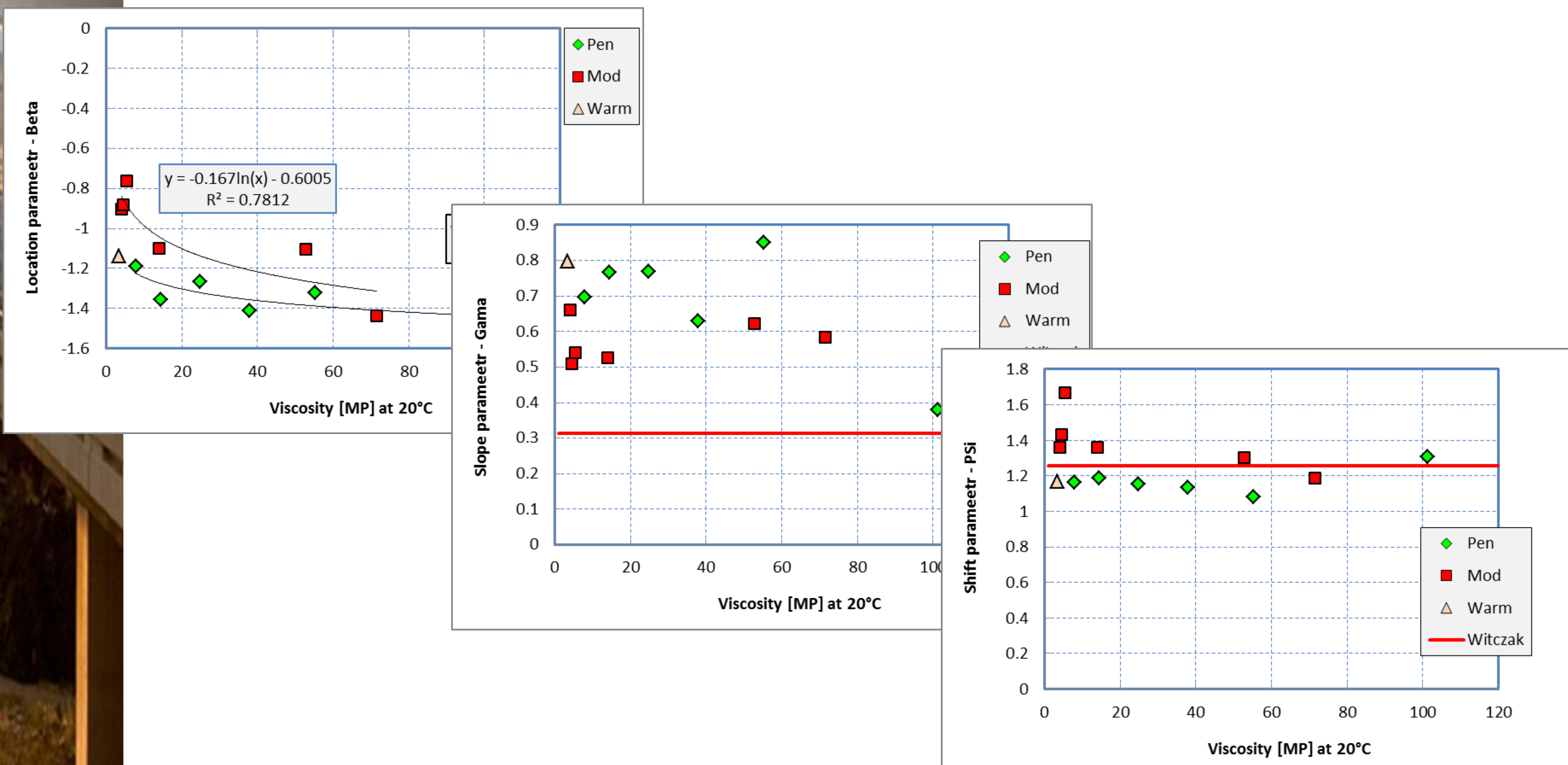


AC medium A-E2 binder



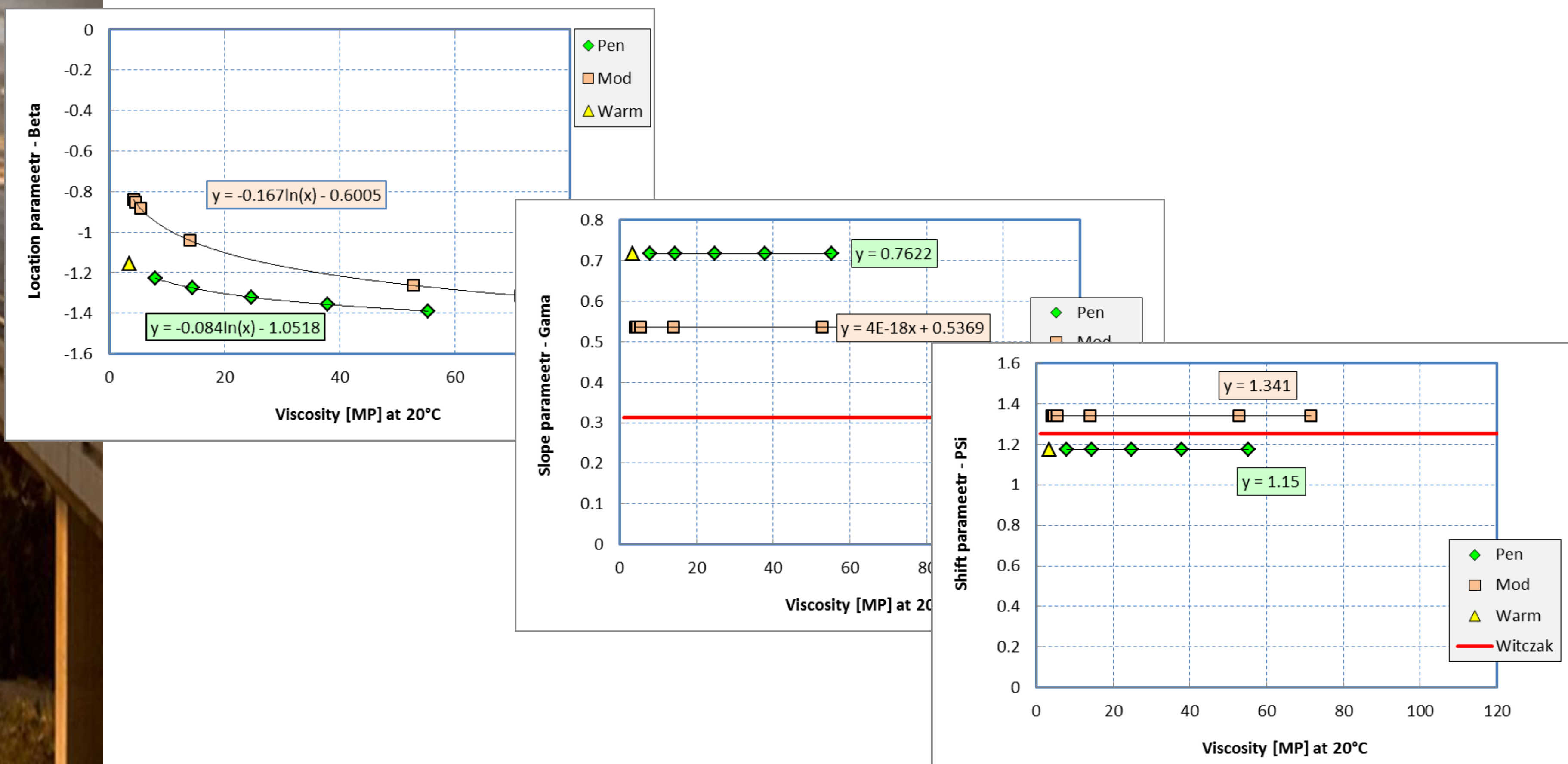
Asphalt resilient response model – Intermediate input level

- Predictive dynamic modulus model
  - SA mixes



Asphalt resilient response model – Intermediate input level

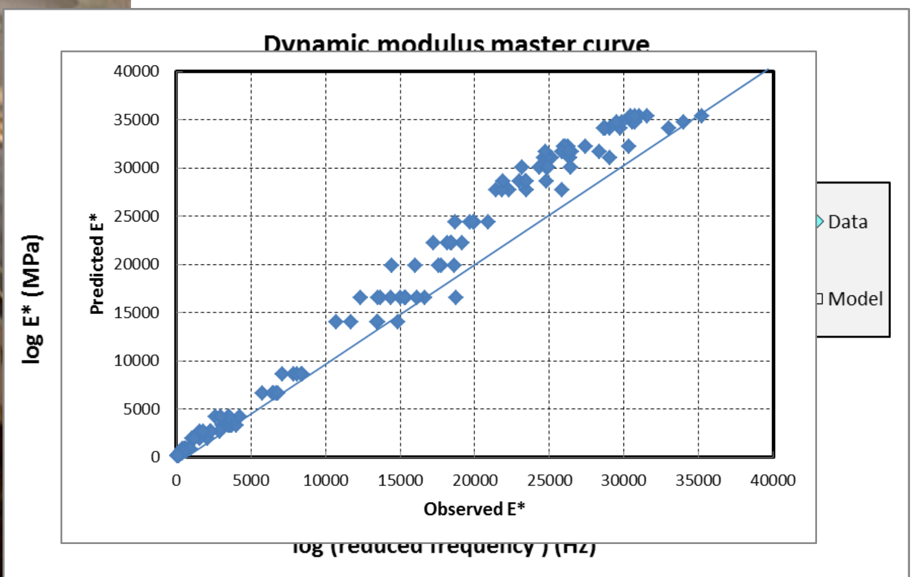
- Predictive dynamic modulus model
  - SA mixes excluding EME with 20/30 pen binder



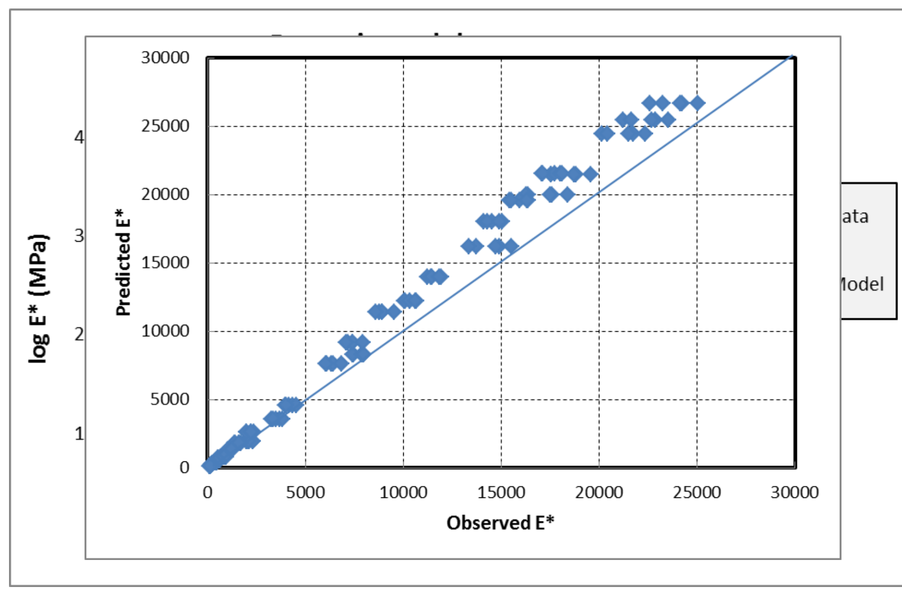
Asphalt resilient response model – Intermediate input level

- Predictive dynamic modulus model
  - SA recalibrated predictive model <u>excluding EME</u>

BTB 40/50 pen binder



AC medium A-E2 binder

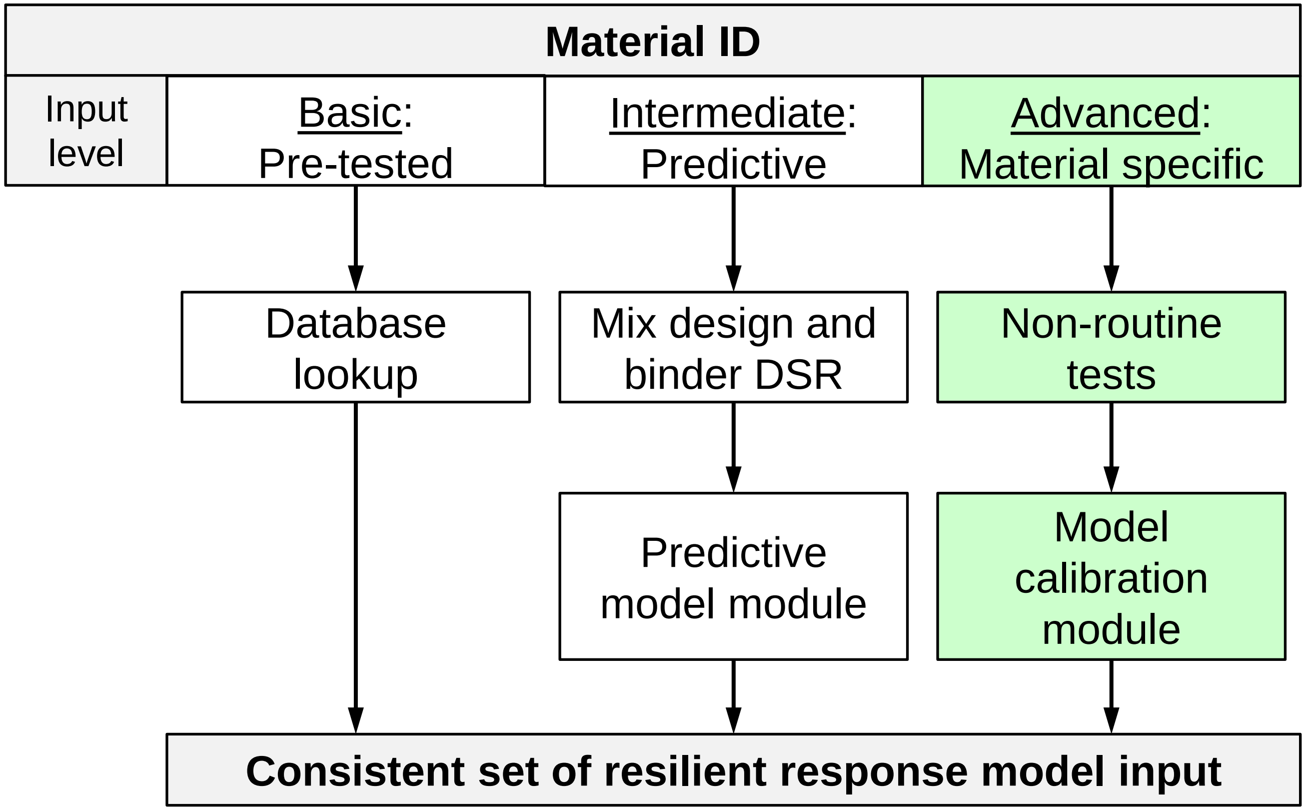


Asphalt resilient response model – Intermediate input level

- Predictive dynamic modulus model
  - South African predictive model <u>excluding EME with 20/30 pen binder</u>

Symbol	Description	Modification
δ'	Minimum parameter	Constant term δ_1' optimised and adjusted for metric units
α	Range parameter	Constant term α_1 optimised
β	Location parameter	Different models for penetration grade and modified binders
γ	Slope parameter	
ψ	Shift parameter	

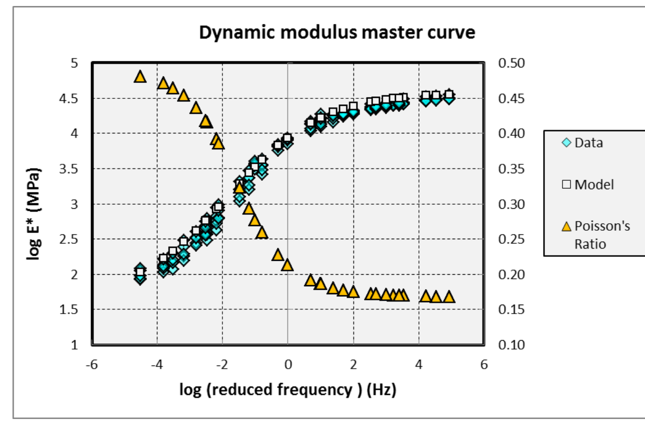
Asphalt resilient response model – Input levels



- Advanced level
  - Mix specific dynamic modulus testing
  - Model calibration module in software
  - Same prediction accuracy as basic level

Asphalt resilient response model – Recursive input

- Asphalt dynamic modulus (E*) determined from
  - Sub-layer temperature (*Thermal*-PADS models)
  - Sub-layer load-pulse duration (heavy vehicle speed)
- Cross-anisotropic layer input
  - $E_v = E^*$
    - Increases with time due to ageing
  - $E_h = (1 - \text{fatigue damage}) \times E_i^*$
    - Decreases with time due to fatigue
  - Poisson's ratio
    - Low temperature – high frequency ≅ 0.17
    - High temperature – low frequency ≅ 0.48
    - Average 0.27 – 0.31



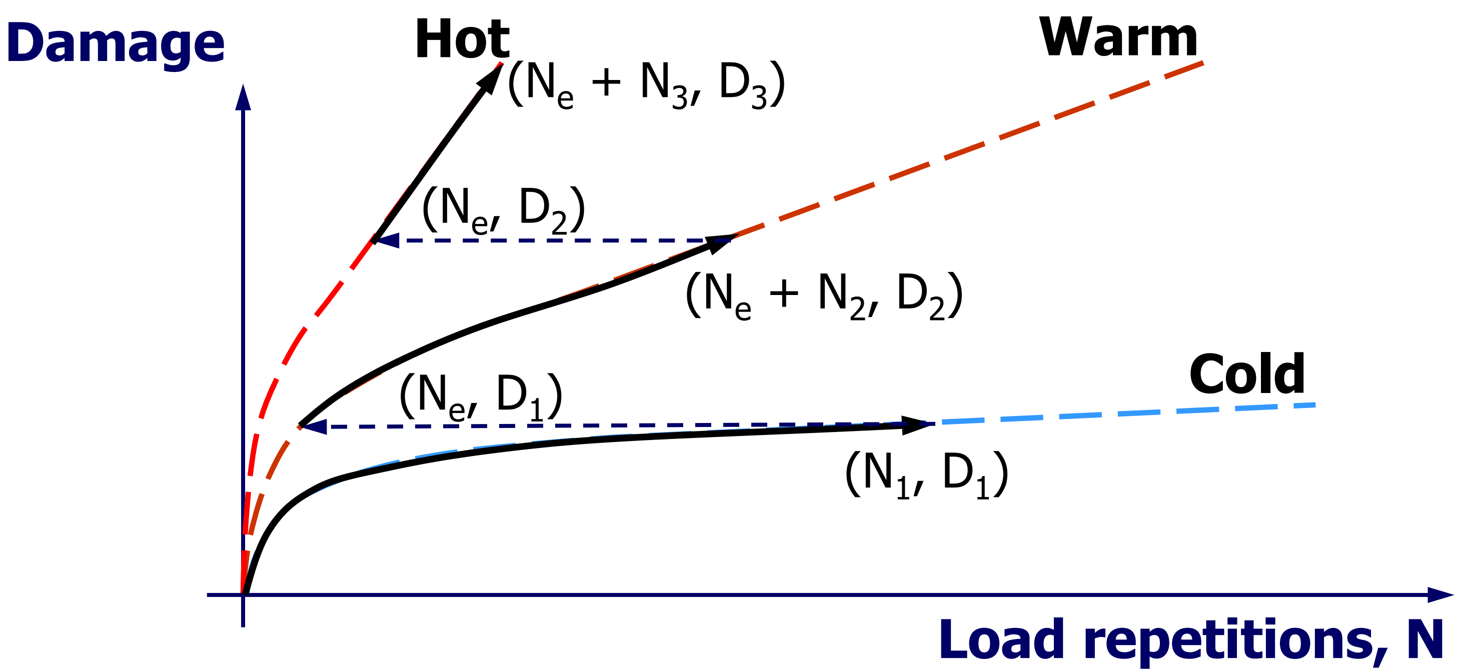
$$\nu_{ac} = 0.15 + \frac{0.35}{1 + e^{a + bE^*}}$$

Asphalt models

Damage Models

Damage model concepts

- Traditional approach for non-linear recursive simulation
  - Strain-hardening approach



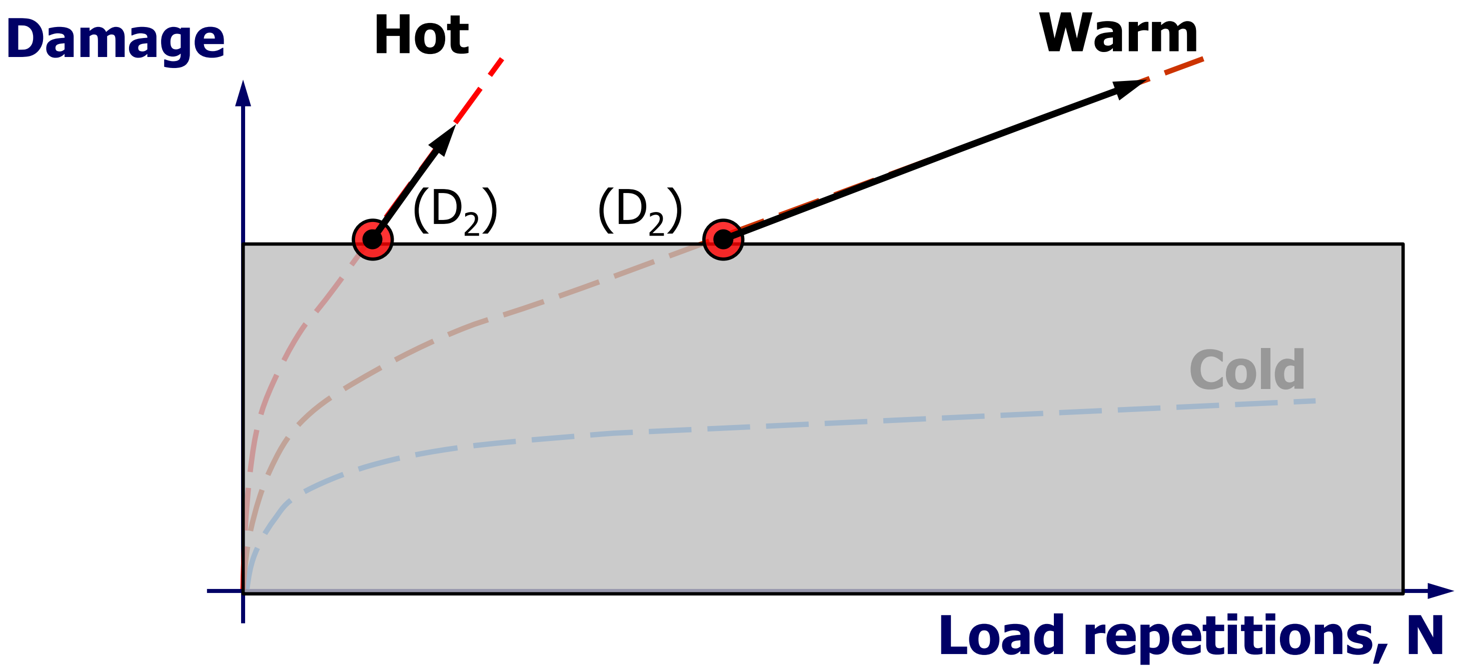
Damage model concepts

- Proposed SARDS approach
  - The recursive damage simulation relies on so-called "memory-less" damage models
  - "Memory-less system" originates from the Markov property that is a requirement for Markov chain simulation
    - A system for which the likelihood of a given future state, at any given moment, depends only on its present state, and not on any past states
  - Eliminates repetitive calculations required by the strain-hardening approach adopted in other recursive simulation packages

Damage model concepts

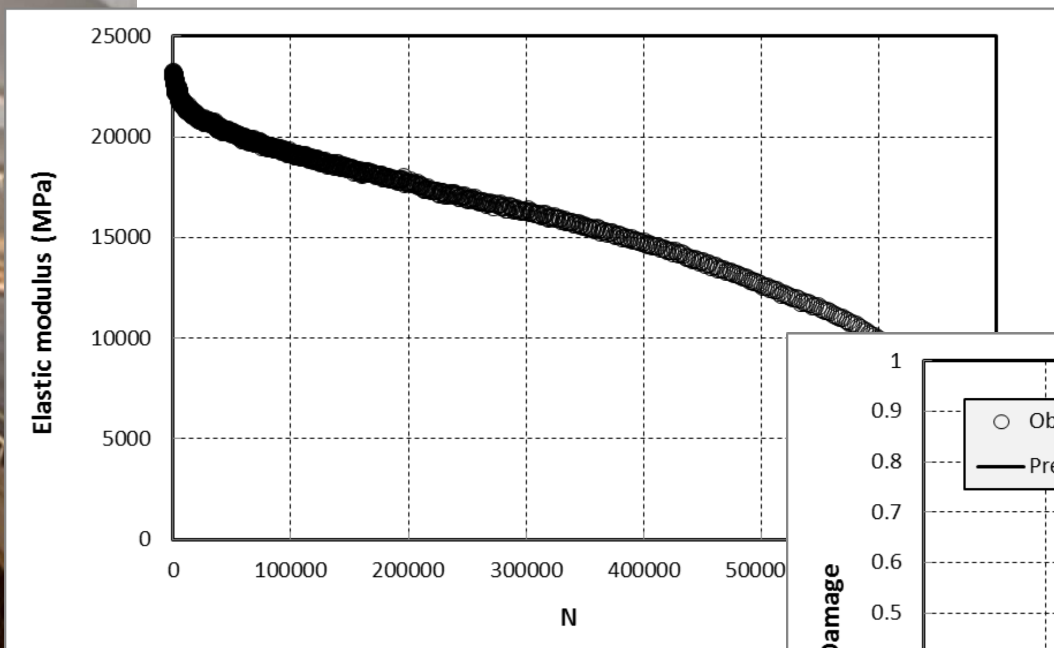
- SARDS approach
  - Memory-less model
  - Only look forward

$$\frac{\partial D}{\partial N} = f\left(D, \sigma/\varepsilon, T\right)$$

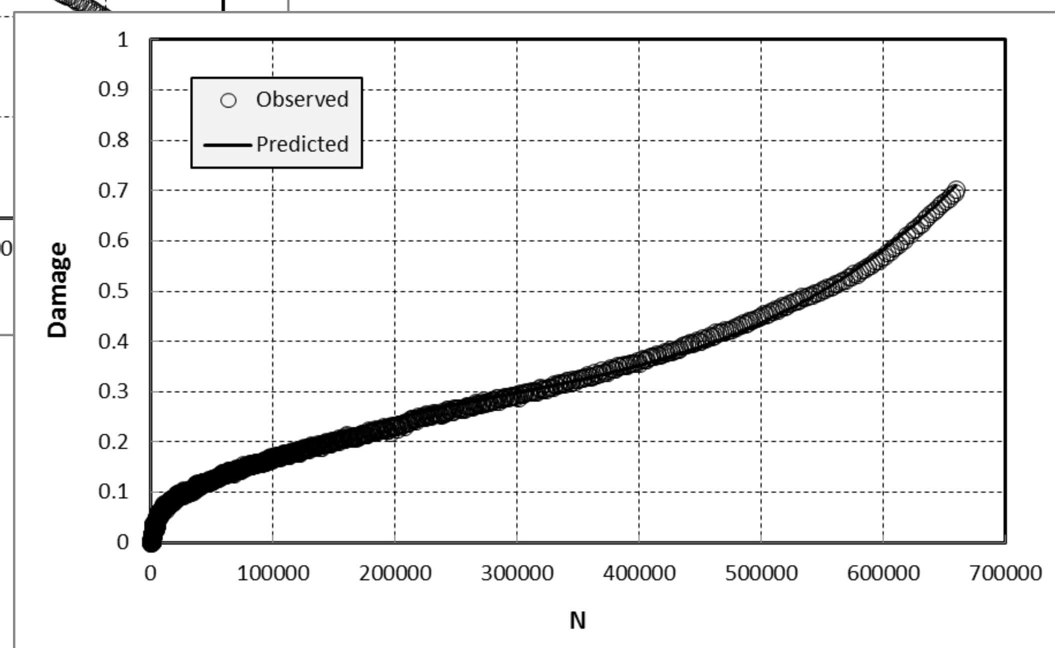


Asphalt damage model – Fatigue

- Continuous damage model



$$\text{Fatigue Damage} = \left(1 - \frac{E}{E_i}\right)$$



Memory-less fatigue damage model

- Initial strain based model
  - Conventional wisdom says fatigue is a strain phenomenon

$$\frac{\partial D}{\partial N} = \frac{b}{e^{D}}\left(k + \frac{(D+s)^2}{a^2}\right)^{\frac{1}{c}}$$

$$a = \alpha_1 \varepsilon^{\alpha_2}$$

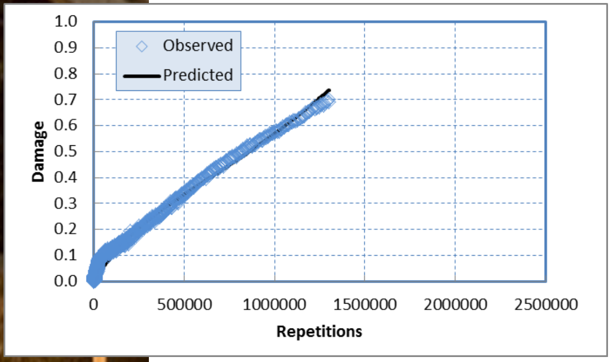
$$b = \beta_1 \varepsilon^{\beta_2}$$

$$c = \chi$$

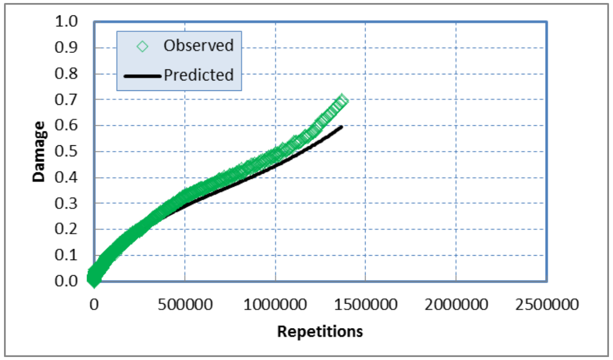
$$k = e^{\kappa_1} e^{\kappa_2 T} \varepsilon^{\kappa_3}$$

$$s = \gamma_1 - \gamma_2 \ln(\varepsilon)$$

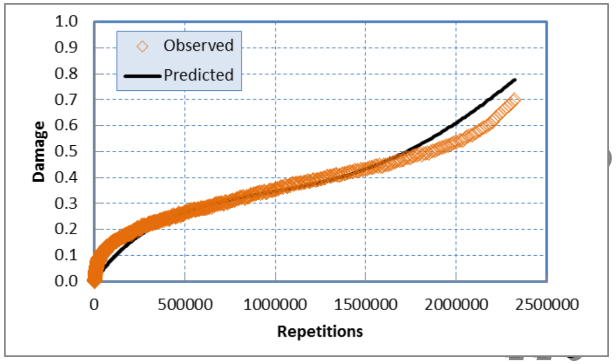
200 με at 5°C



200 με at 10°C



200 με at 20°C



Memory-less plastic strain damage model

- Shear strain based model

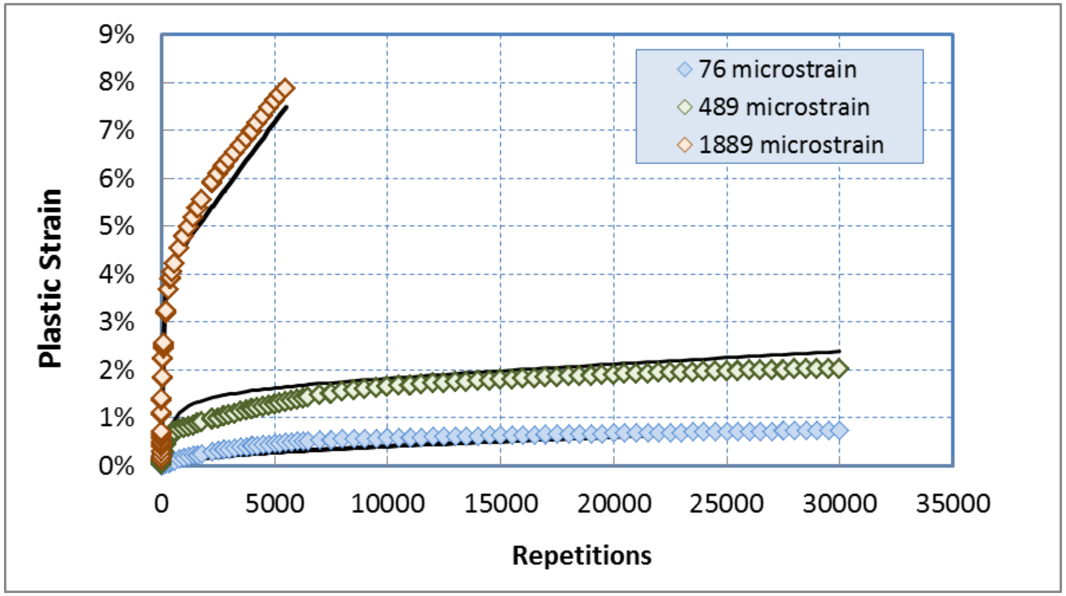
$$\frac{\partial D}{\partial N} = a - \frac{cPS}{\left[1+\left(\frac{cPS}{a}\right)^{b}\right]^{\frac{1}{b}}} + m$$

$$a = \alpha_1 \varepsilon^{\alpha_2}$$

$$m = \delta_1 e^{\delta_2 \varepsilon}$$

$$b = \beta_1 \varepsilon^{\beta_2}$$

$$c = \gamma_1 e^{\gamma_2 \varepsilon}$$



Development Cycles

- **Step 1**
  - **Laboratory calibrated models**
  - **Implement in recursive simulation**
  - **Is the correct behaviour simulated?**
- Step 2
  - Field calibration under controlled conditions
- Step 3
  - Field calibration under operational conditions

Asphalt models – Engineering input

- Basic level
  - Pick-a-mix
    - Binder and mix models pre-calibrated
    - Mix specific dynamic modulus model very accurate

Asphalt models – Engineering input

- Intermediate level
  - Mix design
    - Grading and volumetric composition for predictive E* model
    - Binder DSR testing of virgin, RTFOT and PAV aged binder
      - Binder model calibration by the system
- Binder model very accurate
- SA predictive model accurate enough
  - Excludes EME with 20/30 pen binder

Asphalt models – Engineering input

- Advanced level
  - Binder and mix non-routine tests
  - Model calibration by system
- Both binder and mix specific models very accurate

Asphalt models – Closing statements

- Comprehensive set of models available for inclusion in recursive simulation
- Resilient response model
  - Dynamic modulus and Poisson’s ratio models
  - Load-pulse duration and temperature effects accounted for
- Damage models
  - Memory-less fatigue damage model
  - Memory-less plastic strain damage model
- Ready to start with the recursive simulation …..