Presentation Outline

1 Objectives

2 Modelling Framework

3 Model Validations

4 Model Applications

5 Summary

1 Objectives

1. A pavement aging model

- *It can obtain different pavement aging profiles based on the site-specific environment*
- *It can distinguish the binders with different aging sensitivity*
- *It can capture the effects of air voids on pavement aging*

2. A pavement performance model with aging considerations

- *It can obtain the pavement remaining life considering aging*
- *It can distinguish the pavement performance built with different binders*

3. Model developments and validations are based on experimental part

2 Modelling Framework-Multiphysics aging model

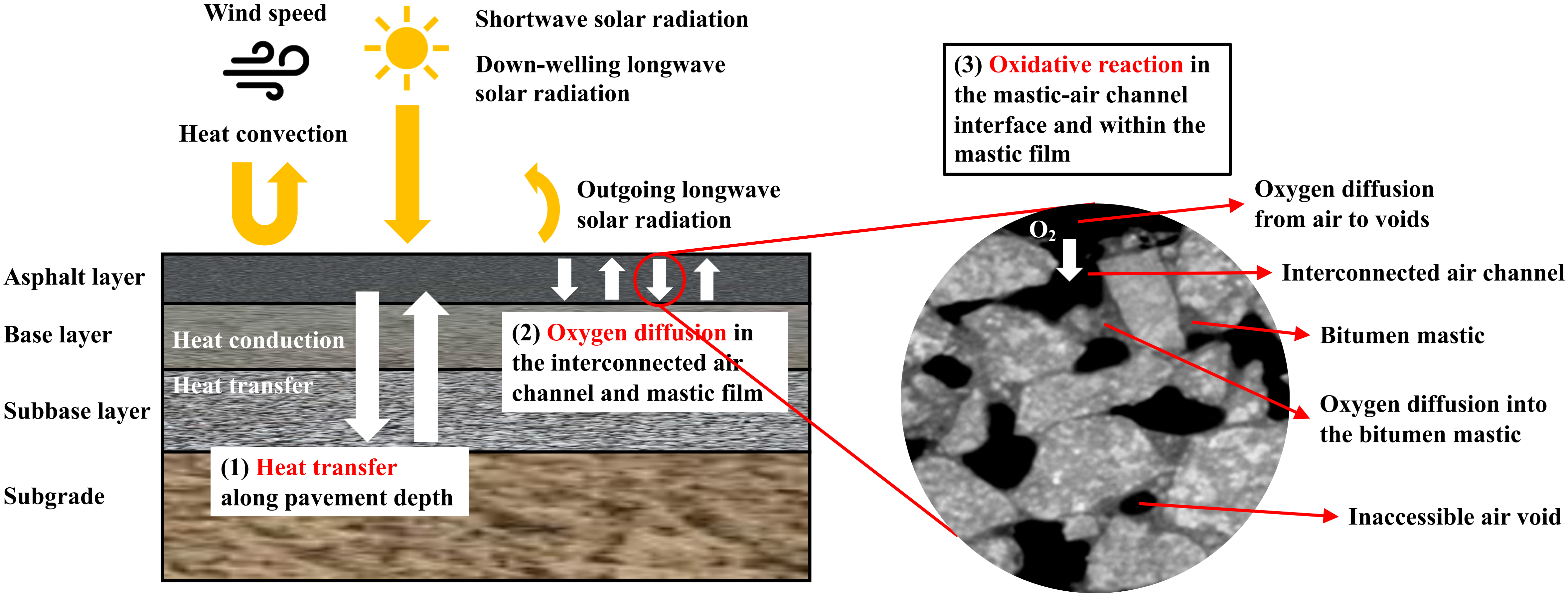


***Fig. 1** Three physics of pavement field aging*

***Hanyu Zhang**, et al. "Framework to predict asphalt pavement aging and its effect on pavement remaining fatigue life." **AAPT,** 2025*

2 Modelling Framework-Multiphysics aging model

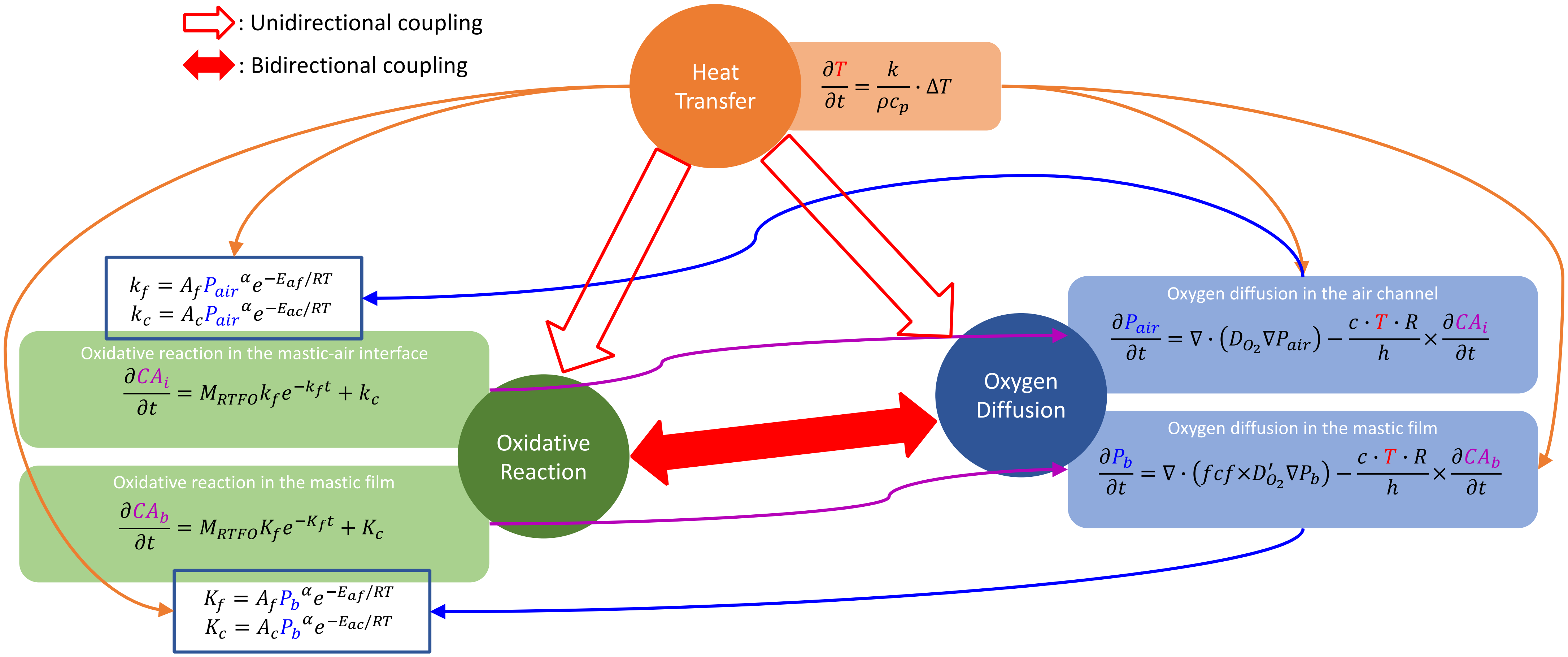


Fig. 2 *Governing equations and circular dependency of pavement field aging*

Charles Glover, *et al. "Evaluation of binder aging and its influence in aging of hot mix asphalt concrete: technical report."*
Texas A&M Transportation Institute, *2014.*

2 Modelling Framework-Coupling of aging and mechanical models

External factors (e.g., temperature, aging) change the molecular volume system and molecular motions, results in the change of material properties (e.g., viscosity, modulus)

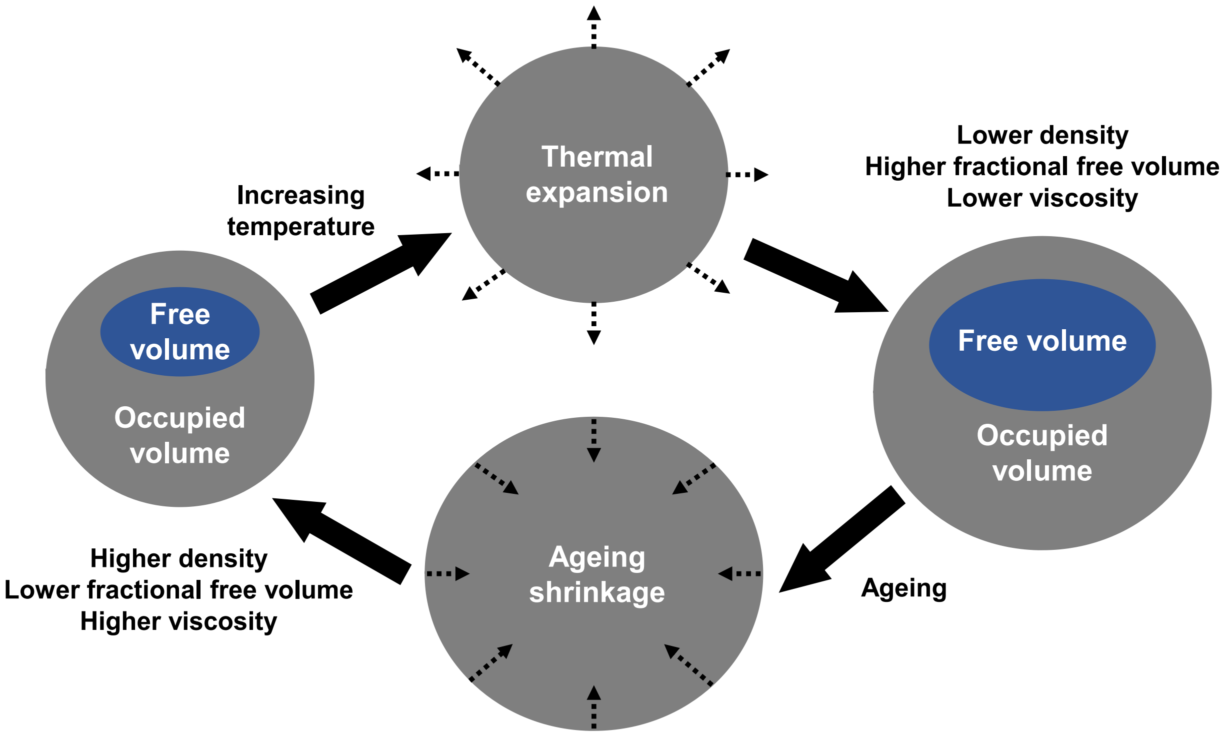


***Fig. 3** Fractional free volume changes of asphalt materials due to increased temperature and aging level*

Original free volume model

$$f = f_g + \alpha_f (T - T_g)$$

Extended model considering aging

$$f = f_R + \alpha_T (T - T_R) - \beta_{CA} (CA - CA_R)$$

Time-temperature-aging shift factor

$$\lg \phi_{T,CA} = -C_1 \left[\frac{C_3(T - T_R) - C_2(CA - CA_R)}{C_2 C_3 + C_3(T - T_R) - C_2(CA - CA_R)} \right]$$

***Hanyu Zhang**, et al. "A time-temperature-ageing shift model for bitumen and asphalt mixtures based on free volume theory." **International Journal of Pavement Engineering**, 2023.*

2 Modelling Framework-A new viscoelastic-continuum damage model for asphalt concrete

For pavement performance and fatigue life evaluations, we need to know the damage evolutions

Step 1: Damage density, apparent stress/strain, effective stress/strain based on continuum damage mechanics

$$D = \frac{A^c}{A^T} = \frac{l^2}{L^2} \qquad \sigma_{ij}^A = \sigma_{ij}(1-D) \qquad \varepsilon_{ij}^A = \frac{\varepsilon_{ij}}{1-D}$$

Step 2: VE-continuum damage constitutive model

$$\sigma_{ij}^A = (1-D)^2\left(K_\infty \varepsilon_{kk}^{ve,A}\delta_{ij} + 2G_\infty e_{ij}^{ve,A}\right) + (1-D)\sum_{m=1}^{M}\left\{K_m\left[\varepsilon_{kk}^{ve,A}(1-D) - \varepsilon_{kk}^{m\cdot vi}\right]\delta_{ij} + 2G_m\left[e_{ij}^{ve,A}(1-D) - e_{ij}^{m\cdot vi}\right]\right\}$$

$$\begin{cases}\phi_{T,CA}\tau_m \dot{\varepsilon}_{kk}^{m\cdot vi} + \varepsilon_{kk}^{m\cdot vi} - \varepsilon_{kk}^{ve,A}(1-D) = 0\\ \phi_{T,CA}\tau_m \dot{e}_{ij}^{m\cdot vi} + e_{ij}^{m\cdot vi} - e_{ij}^{ve,A}(1-D) = 0\end{cases}$$

Step 3: Use of pseudo strain to exclude the energy dissipation due to viscoelastic deformation

$$\varepsilon_{ij}^R(t) = \frac{1}{E_R}\int_{0^-}^{t} E_{ijkl}(t-s)\frac{d\varepsilon_{kl}(s)}{ds}\,ds$$

Step 4: Dissipated pseudo strain energy as the driving force for damage evolution

$$DPSE_d^A = \int_{N\times T}^{(N+1)\times T} \sigma_{ij}^A(t)\,d\varepsilon_{ij}^{R,A}(t) = \frac{|E_0^*|\pi sin(\delta_N - \delta_0)}{E_R|E_N^*|}\left[\left({\sigma_{11}^A}^2 + {\sigma_{22}^A}^2 + {\sigma_{33}^A}^2\right) - 2v_0^*(\sigma_{11}^A\sigma_{22}^A + \sigma_{11}^A\sigma_{33}^A + \sigma_{22}^A\sigma_{33}^A) + 2(1+v_0^*)\left({\sigma_{12}^A}^2 + {\sigma_{23}^A}^2 + {\sigma_{13}^A}^2\right)\right]$$

Step 5: Pseudo *J*-integral Paris' law for damage evolution

$$\frac{\partial D}{\partial N} = A(\Delta J_R)^n$$

$$\Delta J_R = \frac{DPSE_N^A}{CSA_N} = \frac{DPSE_d^A \cdot L^3}{\partial(6L^2\cdot D)/\partial N} = \frac{L}{6}DPSE_d^A\left(\frac{\partial D}{\partial N}\right)^{-1}$$

$$\frac{\partial D}{\partial N} = A^{\frac{1}{n+1}}\left(\frac{L}{6}DPSE_d^A\right)^{\frac{n}{n+1}}$$

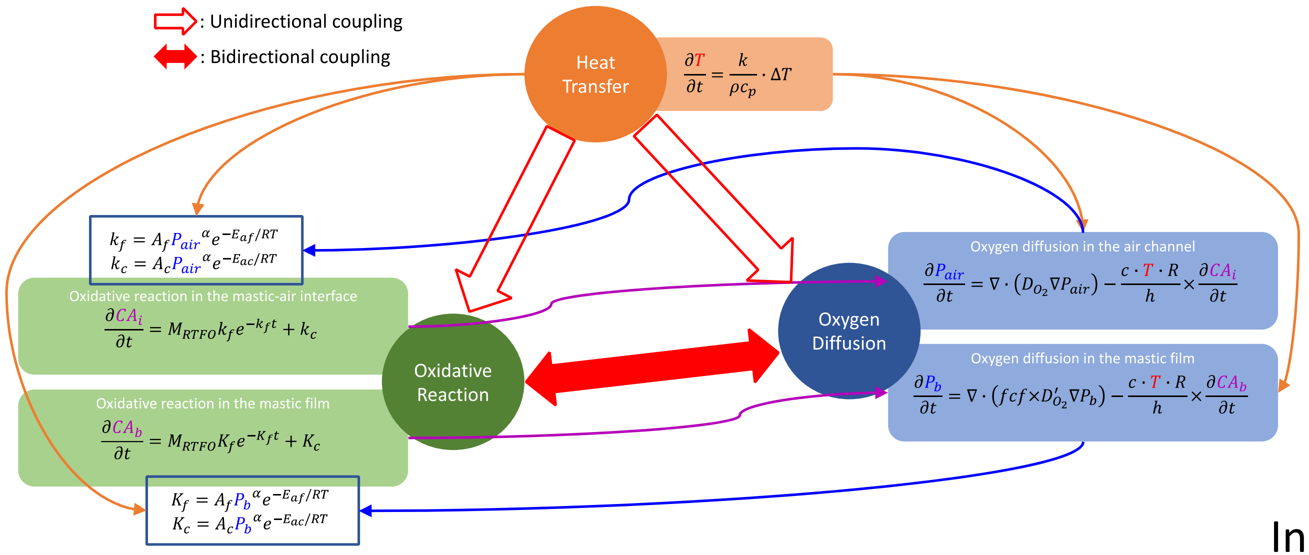
Remark: fatigue life can be obtained by integrating both sides based on a certain fatigue failure criterion (e.g., D=0.5)

__Hanyu Zhang__, et al. "A new viscoelastic-continuum damage model for asphalt concrete with applications to cyclic indirect tensile fatigue tests." __International Journal of Fatigue__, 2025.

2 Modelling Framework-Workflow of the model

Pavement aging model

Output T and CA functions



$$\lg \phi_{T,CA} = -C_1 \left[\frac{C_3(T - T_R) - C_2(CA - CA_R)}{C_2C_3 + C_3(T - T_R) - C_2(CA - CA_R)} \right]$$

Time-temperature-aging shift model

Input shift factor $\phi_{T,CA}$

Viscoelastic-continuum damage model

$$\sigma_{ij}^{A} = (1-D)^2\left(K_\infty \varepsilon_{kk}^{ve,A}\delta_{ij} + 2G_\infty e_{ij}^{ve,A}\right) + (1-D)\sum_{m=1}^{M}\left\{K_m\left[\varepsilon_{kk}^{ve,A}(1-D) - \varepsilon_{kk}^{m\cdot vi}\right]\delta_{ij} + 2G_m\left[e_{ij}^{ve,A}(1-D) - e_{ij}^{m\cdot vi}\right]\right\}$$

$$\begin{cases} \phi_{T,CA}\tau_m \dot{\varepsilon}_{kk}^{m\cdot vi} + \varepsilon_{kk}^{m\cdot vi} - \varepsilon_{kk}^{ve,A}(1-D) = 0 \\ \phi_{T,CA}\tau_m \dot{e}_{ij}^{m\cdot vi} + e_{ij}^{m\cdot vi} - e_{ij}^{ve,A}(1-D) = 0 \end{cases}$$

$$\frac{\partial D}{\partial N} = A^{\frac{1}{n+1}}\left(\frac{L}{6} DPSE_d^A\right)^{\frac{n}{n+1}}$$

3 Model Validations

The model inputs are based on the testing results of the original binders (at least from the same refinery with the same PG), mixture air voids, pavement structures, and site-specific environments.

Road section	Location	Measurements	Purposes
SE2 (E6)	Uddevalla, Sweden	Carbonyl index of recovered binder, pavement temperature, FWD	Validating temperature predictions Validating carbonyl predictions Validating pavement response model
SE1 (RV-17)	Marieholm, Sweden	Carbonyl index of recovered binder, IDT fatigue test	Validating carbonyl predictions Validating material constitutive model
BE2	Assenede, Belgium	Carbonyl index of recovered binder, IDT fatigue test	
CZ2	Podhradí, Czech Republic	Carbonyl index of recovered binder	Validating carbonyl predictions

3 Model Validations-Temperature prediction

The model successfully captures the daily temperature variations and seasonal temperature changes

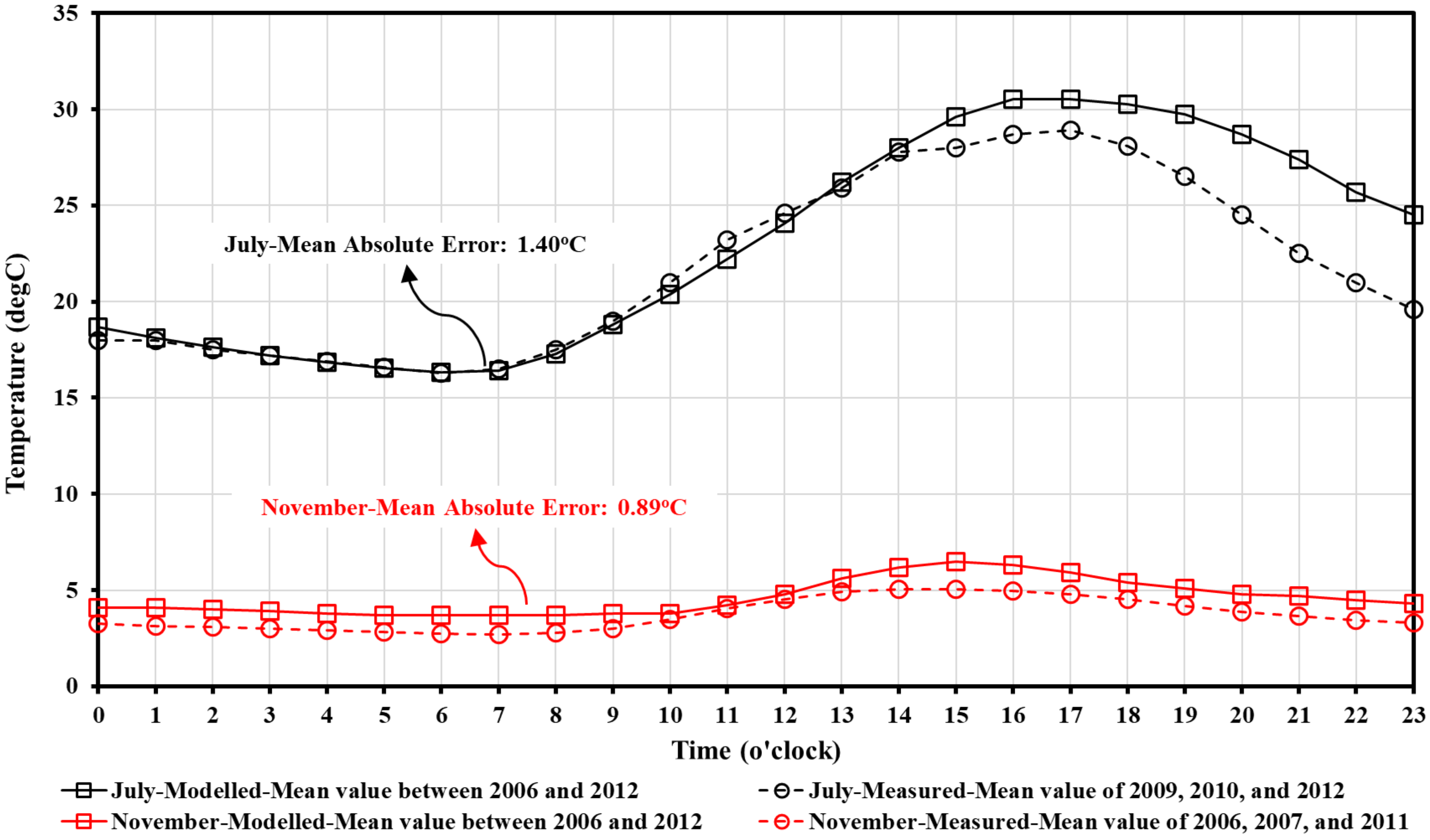


Fig. 4 *Comparison of modelled and measured temperatures at 2 cm below the road surface of SE2 road section*

Data Source: Temperature measurements were taken from **VTI** report

3 Model Validations-Carbonyl index prediction

- The model can describe the different aging gradients based on the on-site environment conditions
- The model can distinguish the aging evolutions of binders with different aging sensitivities
- The model can identify the effects of air voids on aging evolutions and aging gradients

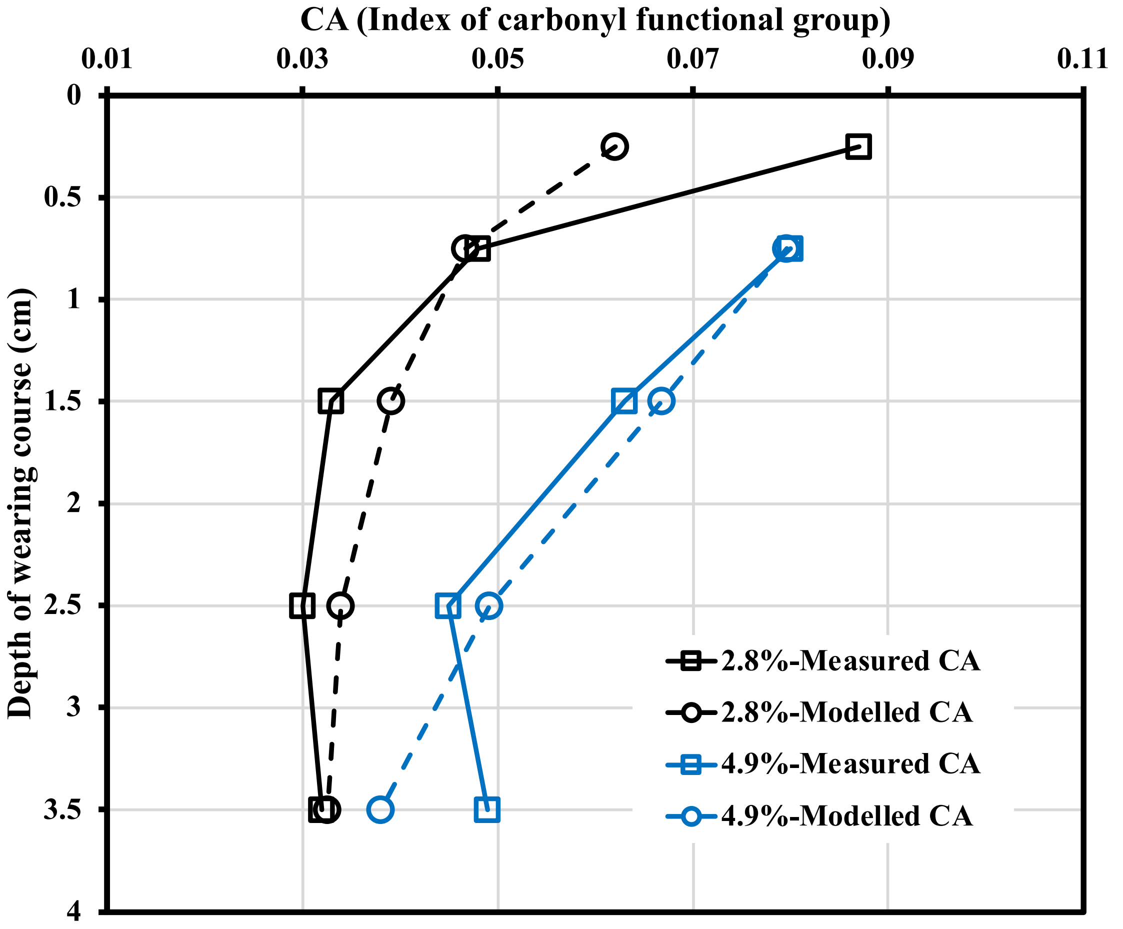


Fig. 5 *Comparison of modelled and measured CA for BE2 section (11 years aging)*

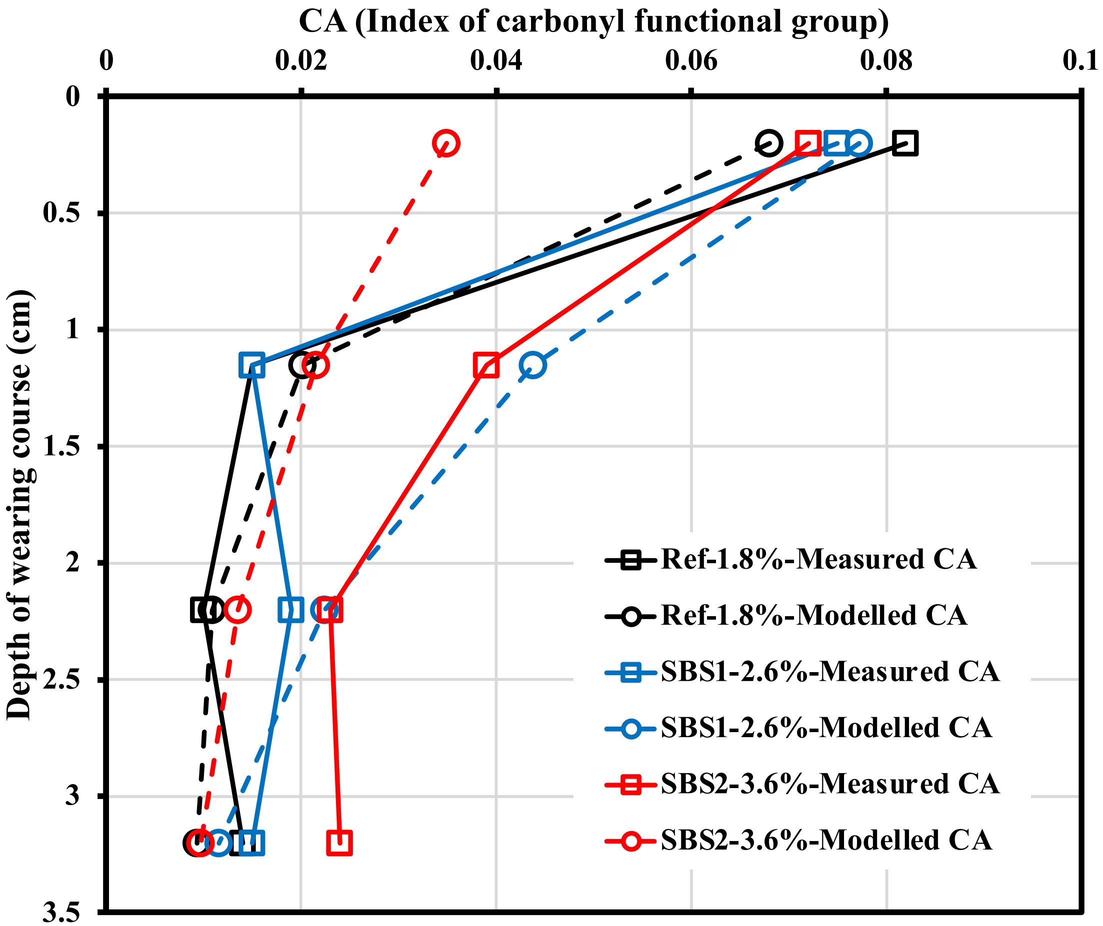


Fig. 6 *Comparison of modelled and measured CA for SE2 section (16 years aging)*

3 Model Validations-Carbonyl index prediction

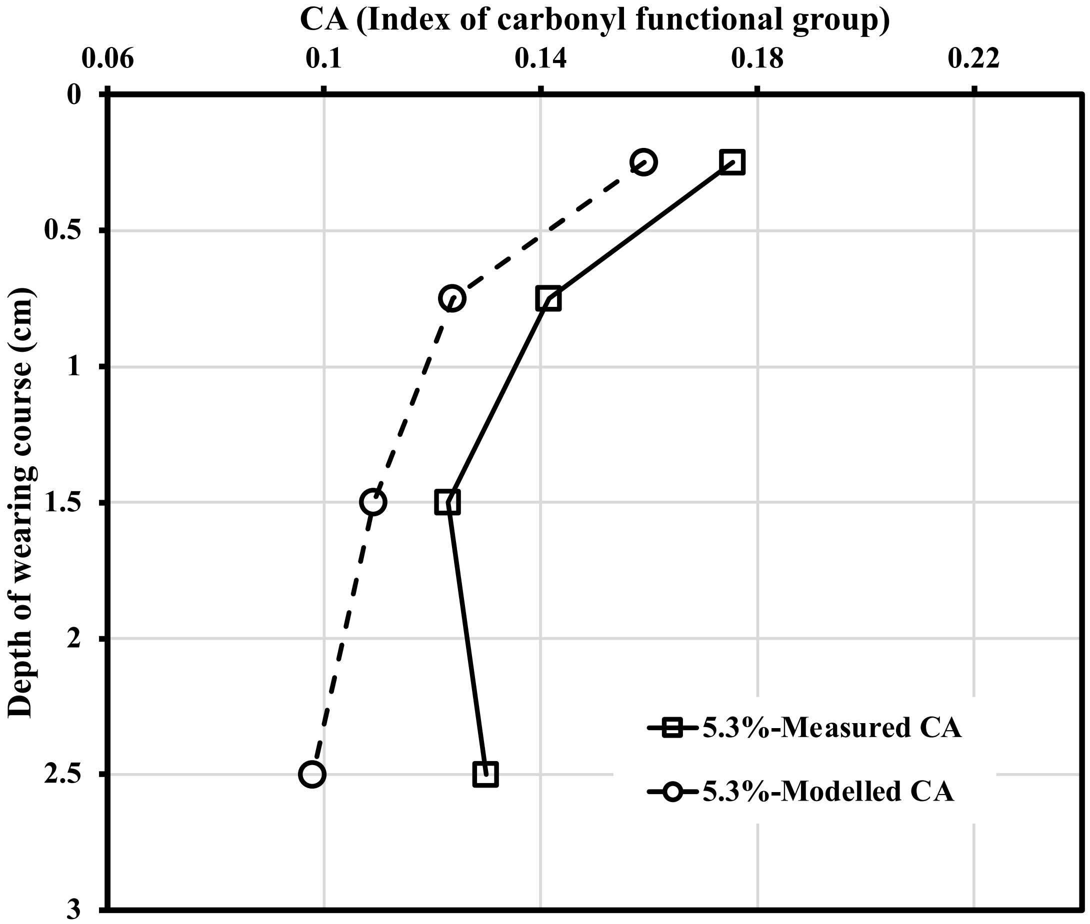


Fig. 7 *Comparison of modelled and measured CA for SE1 section (12 years aging)*

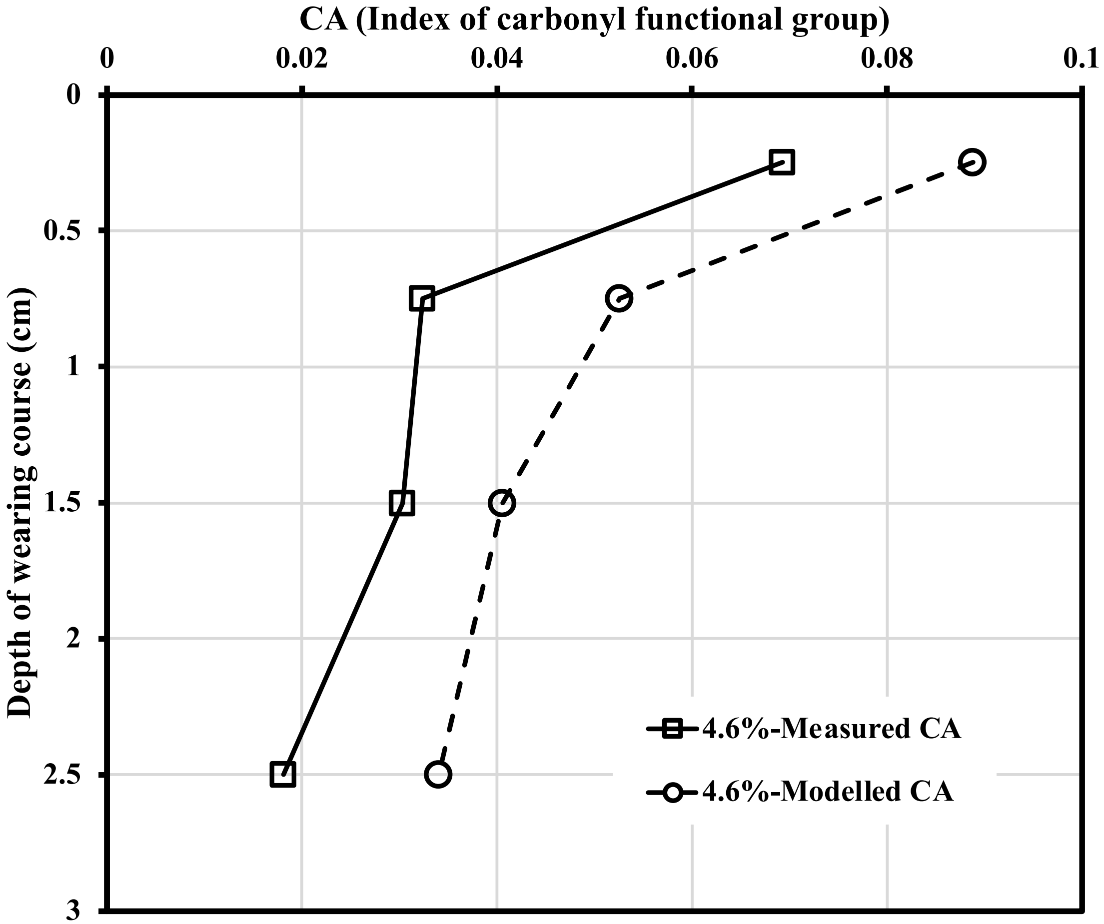


Fig. 8 *Comparison of modelled and measured CA for CZ2 section (6 years aging)*

3 Model Validations-Material constitutive model

The model successfully captures the strain evolutions under fatigue load and the transition load cycles before the final failure

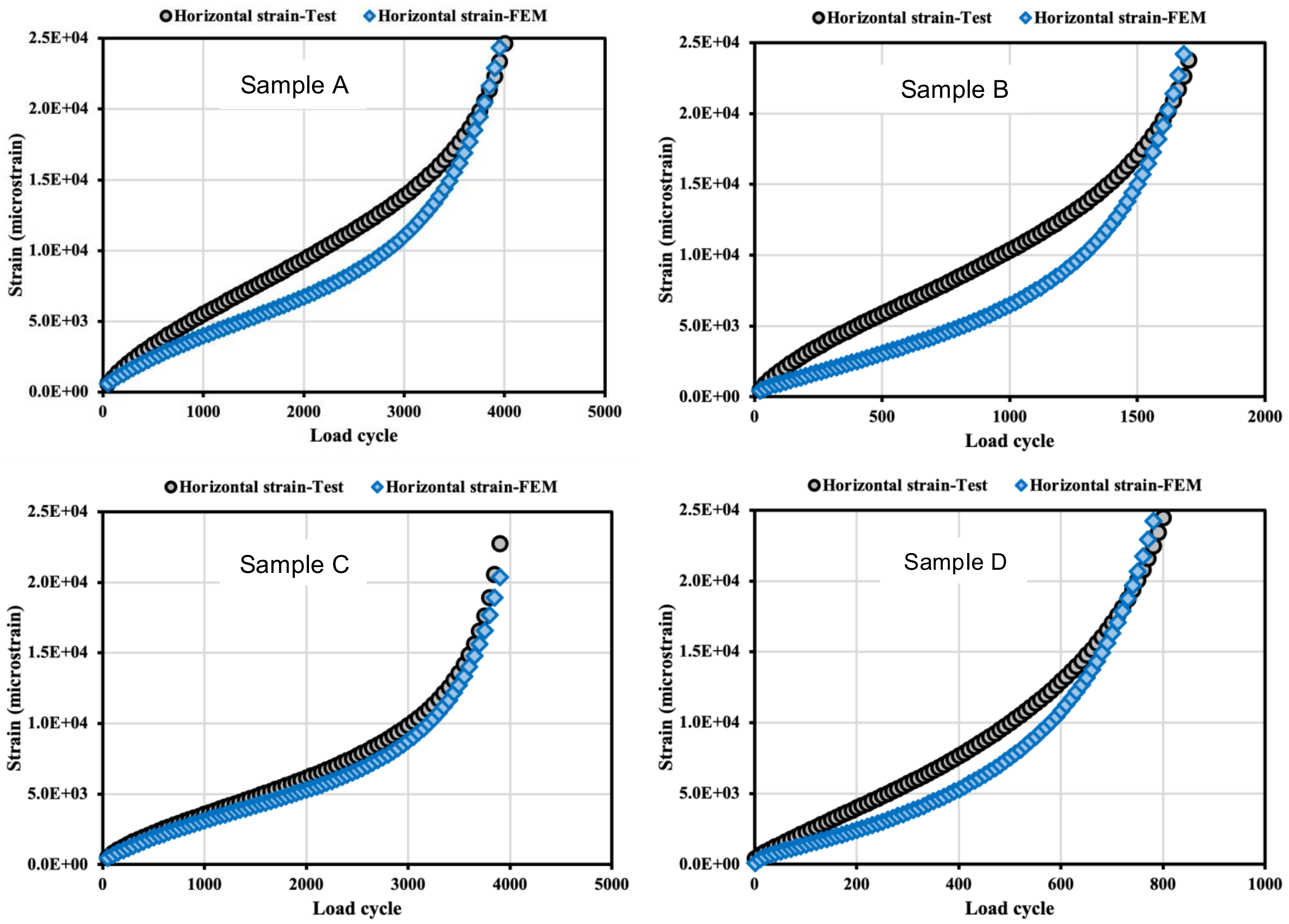


Fig. 9 *Comparison of modelled and measured strain response in the cyclic IDT fatigue tests (SE1 and BE2 sections)*

3 Model Validations-Pavement response model

The model successfully captures the pavement response under FWD load and its evolutions with aging

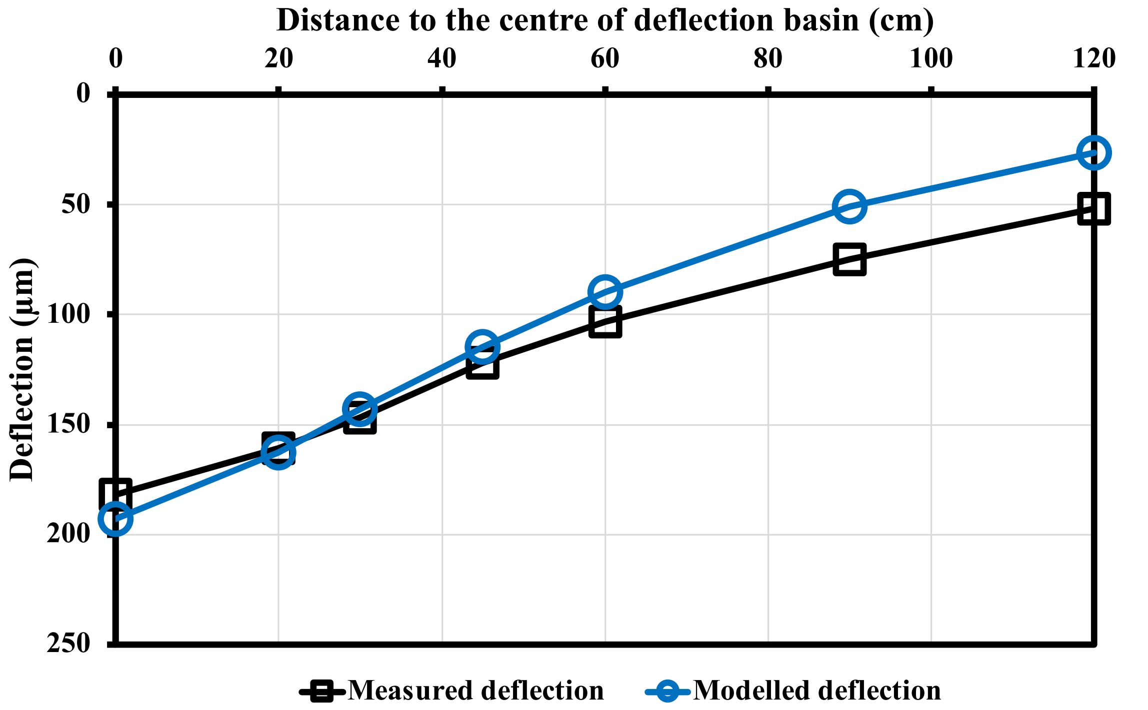


Fig. 10 Comparison of modelled and measured deflection basins (SE2 section)

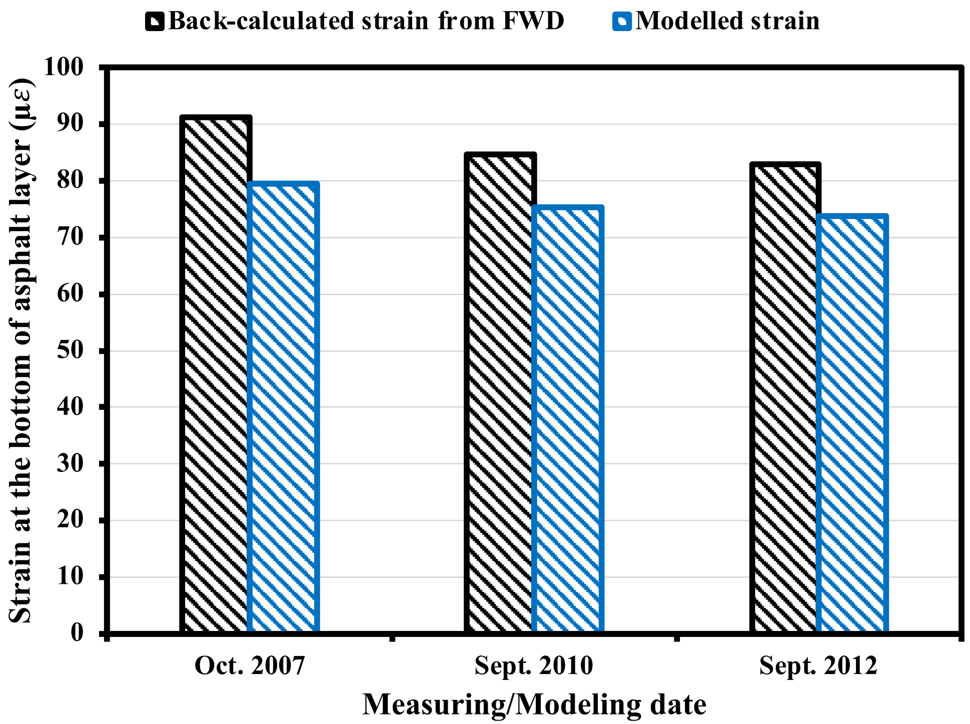


Fig. 11 Comparison of modelled and back-calculated transverse strain at the bottom of asphalt layer (SE2 section)

Data Source: FWD measurements and back-calculated strain were taken from **VTI** report

4 Model Application I-Fatigue life prediction considering field aging

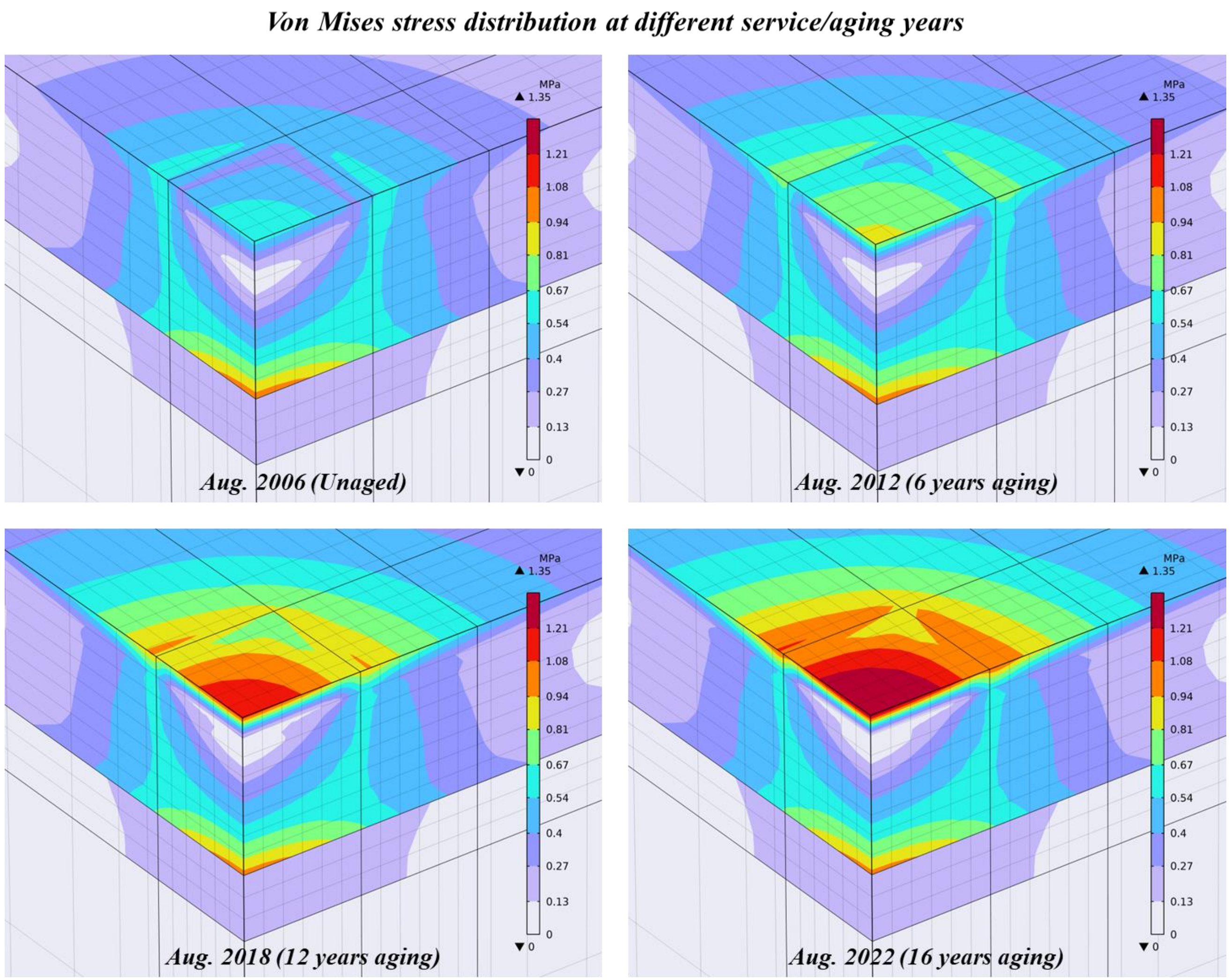


Fig. 12 *Von Mises stress distributions at different service years*

Main finding:

High stress moves from the bottom of asphalt layer to the road surface with pavement aging; thus, it potentially changes the cracking mode from bottom-up to top-down.

4 Model Application I-Fatigue life prediction considering field aging

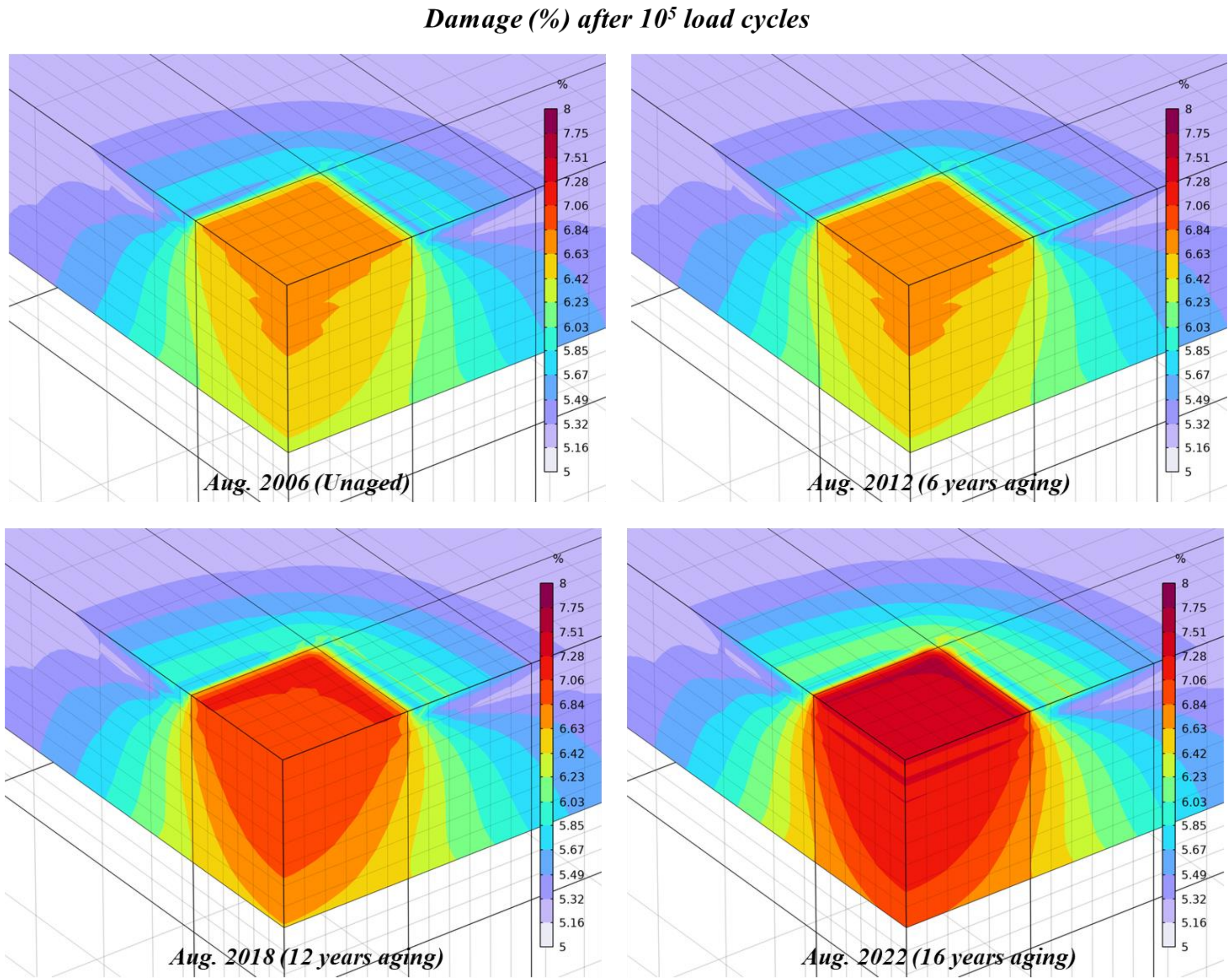


***Fig. 13** Pavement damage conditions after 10^5 load cycles at different service years*

Main finding:

16 years aging introduces more than 50% extra damage on the road surface (loading area and the edges), potentially contribute to the longitudinal cracking along the wheel path

***Hanyu Zhang**, et al. "Temporal homogenization modelling of viscoelastic asphalt concretes and pavement structures under large numbers of load cycles." **ASCE Journal of Engineering Mechanics**, 2024.*

***Hanyu Zhang**. "Coupled oxidative ageing and mechanical Multiphysics modelling of asphalt pavements." **PhD Thesis**, 2025.*

4 Model Application I-Fatigue life prediction considering field aging

In this case, 16 years aging would shorten the pavement minimum remaining fatigue life up to 1.6 years when only consider the effect of ageing on pavement modulus

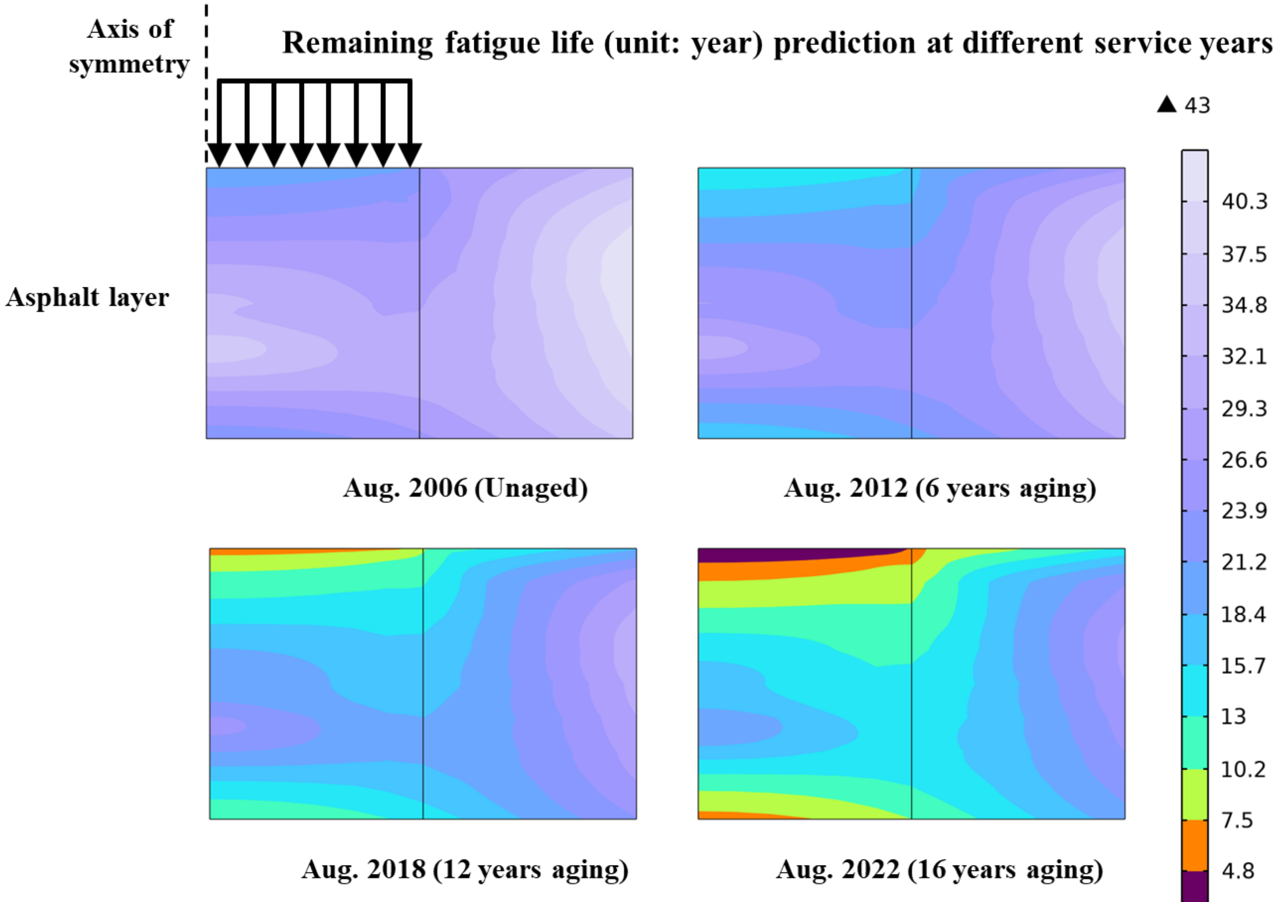


Fig. 14 Remaining fatigue life prediction at different service years

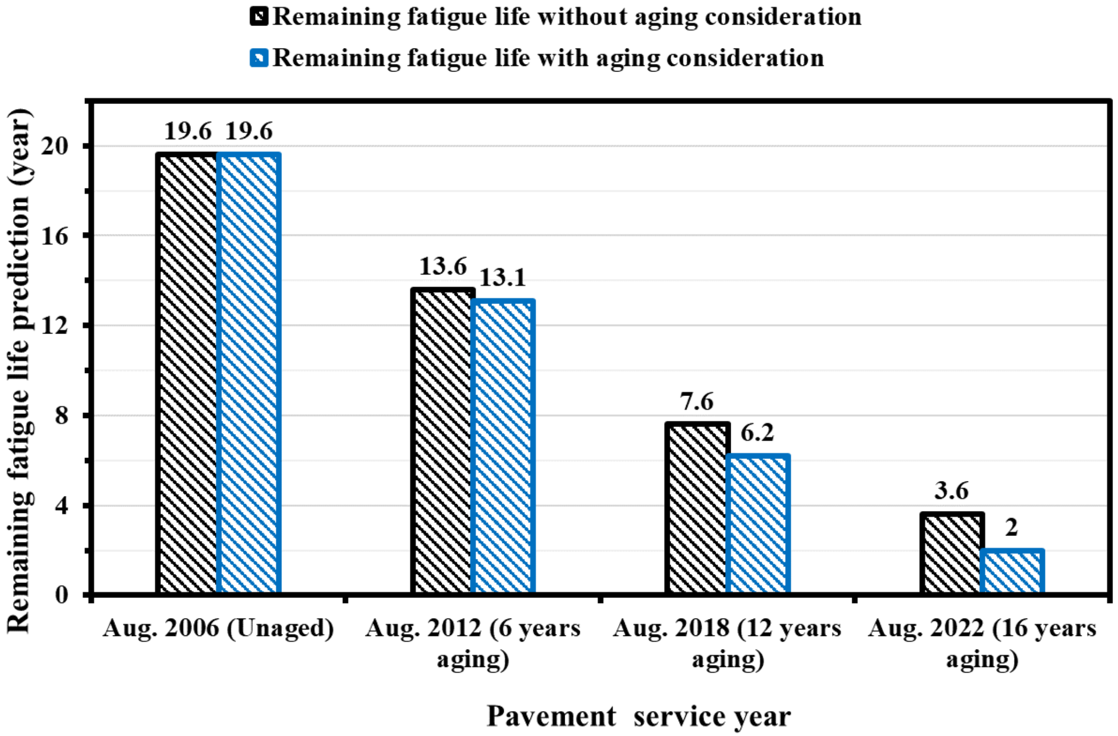


Fig. 15 Comparison of minimum pavement remaining fatigue life predictions with and without aging considerations

4 Model Application II-Performance comparison of roads built with different binders (Material selection)

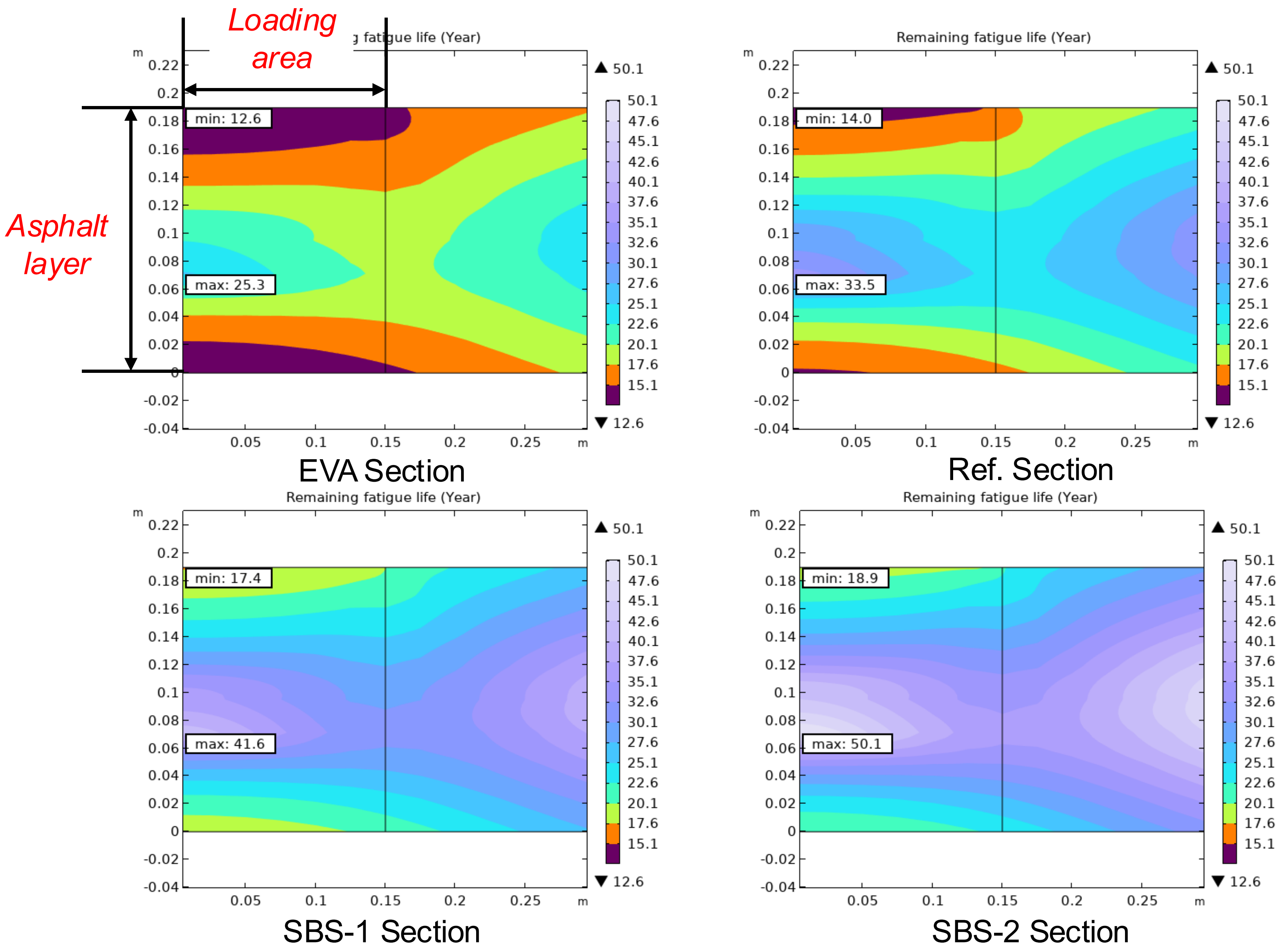


***Fig. 16** Comparison of pavement remaining fatigue life predictions of four different road sections of E6*

4 Model Application II-Performance comparison of roads built with different binders (Material selection)

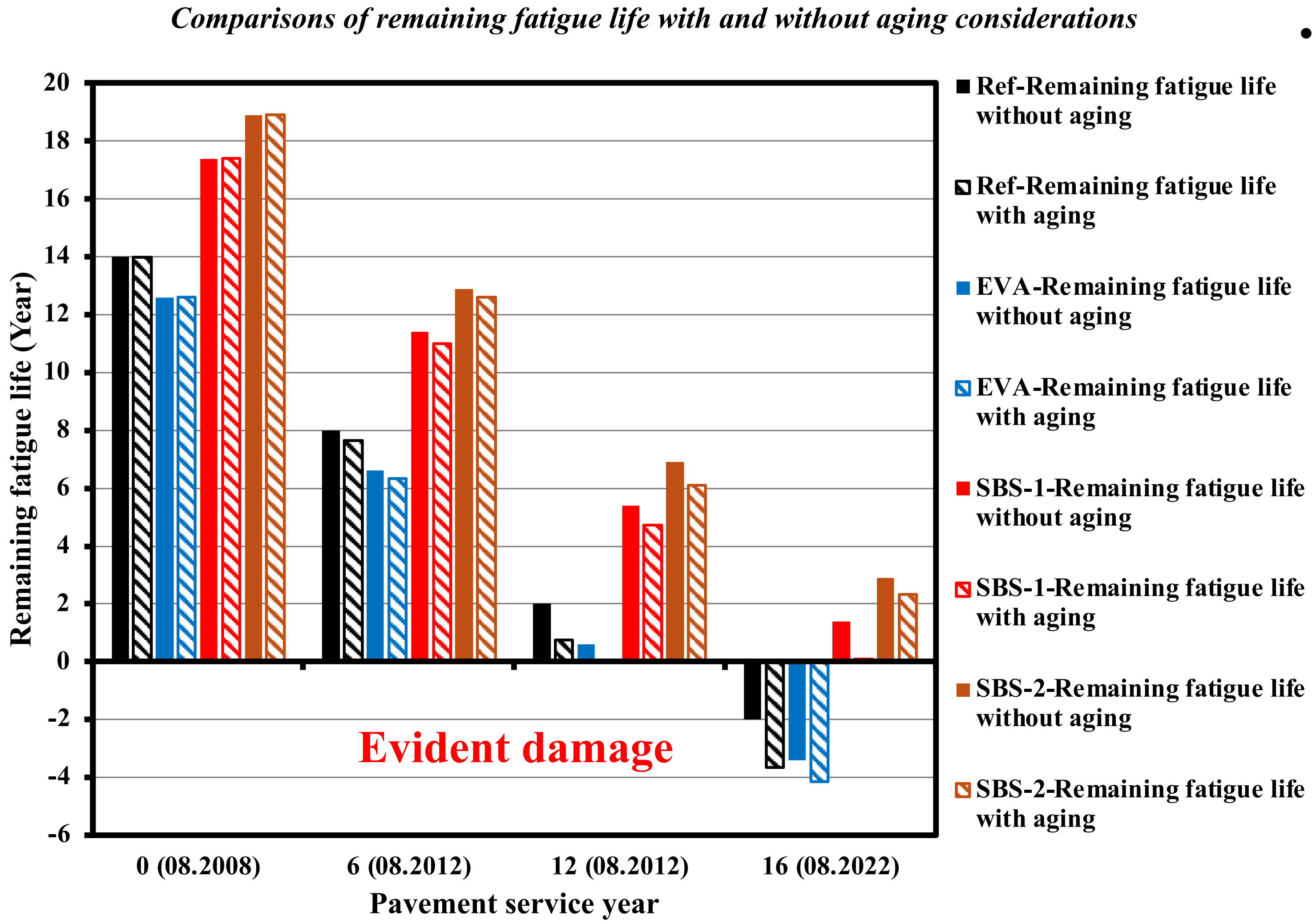


Fig. 17 *Comparison of pavement remaining fatigue life predictions of four different road sections with and without aging considerations*

- SBS 2 > SBS 1 > Ref. > EVA
- Modelling performance ranking is consistent with lab tests and field inspections

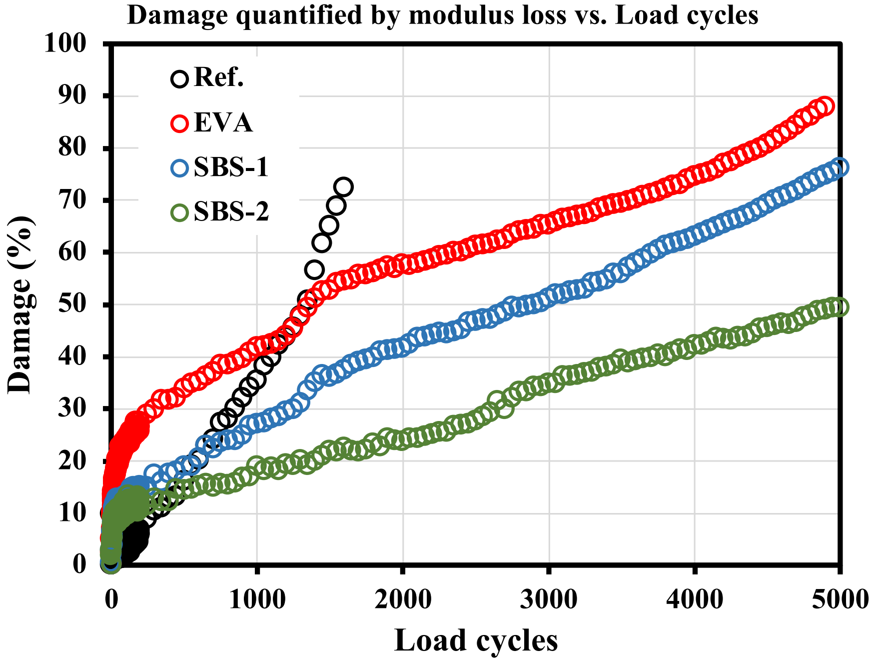


Fig. 18 *Comparison of lab tested fatigue performance of field cores drilled from four road sections of SE2*

5 Summary

- Aging gradient is as evident as temperature gradient, and should be considered in pavement mechanical analysis and performance predictions

- Carbonyl index (CA) is a fundamental parameter to quantify aging evolution and gradient in the pavement structure, replacing the empirical modulus-based aging characterizations

- The model has been validated at different scales (material scale and structure scale) and by different measurements (temperature, CA value, and FWD response)

- Field aging would change the positions of high stress region to the road surface and potentially contribute to top-down cracking

5 Summary

- 16 years field aging would introduce more than 50% extra damage on the road surface (edge of loading area), and it potentially leads to longitudinal cracking

- In this case study, field aging would shorten the pavement remaining fatigue life up to 1.6 years when only considering the effects of aging on modulus change and gradient

- The model have two major applications: (1) predicting pavement performance considering aging; and (2) compare the performance of roads built with different binders

- The model can consider the effects of maintenance and rehabilitation on extending the pavement remaining service life

- The model can be compiled into a program or a module of AASHTOWare Pavement ME Design for the user committee.

Publications

- Soenen, H., et al. (2021). Rheological and chemical properties of field aged binders and their variation within the wearing course. Road Materials and Pavement Design, 23(sup1), 36–54.
- Zhang, H., et al. (2022). Experimental and statistical analysis of bitumen's field ageing in asphalt pavements. Transportation Research Record, 2676(7), 495-511.
- Zhang, H., et al. (2023). A time-temperature-ageing shift model for bitumen and asphalt mixtures based on free volume theory. International Journal of Pavement Engineering, 24(1).
- Zhang, H., et al. (2024). Comparing laboratory ageing with long-term field ageing of bitumen in the hot-mix and warm-mix asphalt pavements. In: Proceedings of the 8th E&E Congress (pp. 618-629).
- Zhang, H., et al. (2024). Temporal homogenization modeling of viscoelastic asphalt concretes and pavement structures under large numbers of load cycles. ASCE Journal of Engineering Mechanics, 150(11).
- Zhang, H., et al. (2025). Prediction of asphalt pavement fatigue life considering field ageing: a case study of the E6 motorway in Sweden. In: Transportforum 2025 (pp. 358-359).
- Zhang, H., et al. (2025). A new viscoelastic-continuum damage model for asphalt concrete with applications to cyclic indirect tensile fatigue tests. International Journal of Fatigue, 201(109114).
- Zhang, H., et al. (2025). Framework to predict asphalt pavement aging and its effect on pavement remaining fatigue life. Transportation Research Record (AAPT Special Issue).
- Soenen, H., et al. (2025). Relationships between pavement performance and properties of recovered binders. (to be submitted to ISBM 2026)

Thank You and Questions!