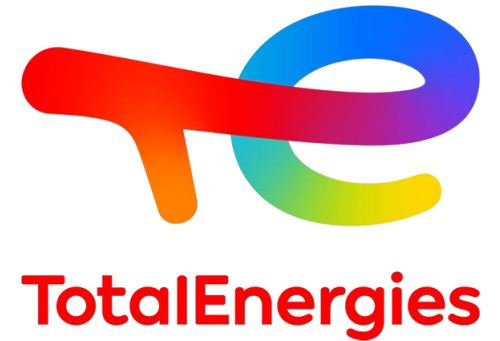




Asphalt Materials circularity with high RAP content: Rheometrics framework contribution to enable recycling binders

Yvong HUNG, Product Eng., Technology Lead
Bitumen Business Unit, Marketing Business Development

3rd International Conference on
Asphalt Recycling Technologies

21 / 22 SEPTEMBER 2026

Agenda

01

Background

04

Case study: AC evaluation by S-VECD

02

Method Framework

05

Conclusions & Take away!

03

Fields cases study: 2016-2026



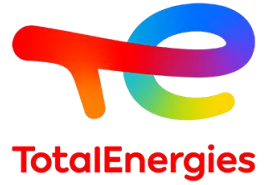
TotalEnergies

01

Background



Our motivations as materials technologist



- Contribute to scientific debate regarding materials circular economy and sustainable pavement infrastructures
- Share experimental investigations & field experiences with road industry and authorities stakeholders
- Paving technical doctrine dissemination to bridge RAP re-use & durable performances benefits
- Achieve together with our stakeholders present requirements & long term profitabilities

Promoting sustainable road industry



New standard requirements for road industry regarding society acceptance :

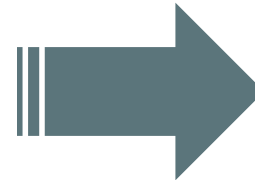
- Maintain high level of durable performance of materials and infrastructures
- Reinforce efforts about material circular economy
- Develop infrastructure with low environmental footprint



⊗ Challenges about recycled materials with high RAP content

- Damage tolerance
- Damage accumulation until failure

⊗ Risk of early aged damages and value loss of infrastructures



✓ Need advanced method framework to define the technical target for RAP re-use materials

✓ Reshape new class of recycling binders specifically oriented to balance the technical gap

Recycled asphalt mixture, What's the problem?

Virgin AC with SBS-Xlinked PmB

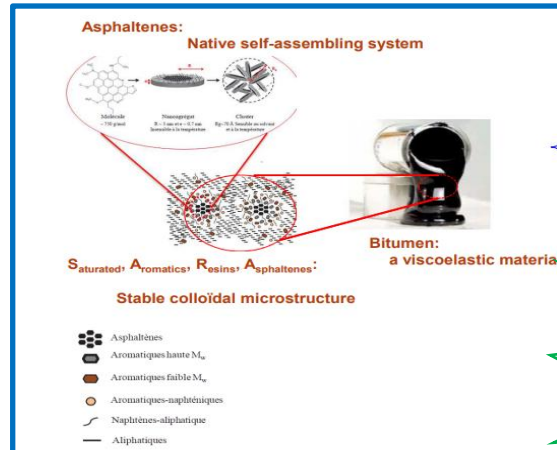


- Damage tolerance
- Cumulative damage acceptance until critical failure
- Under mechanical, thermal & chemical stress

Binder Level

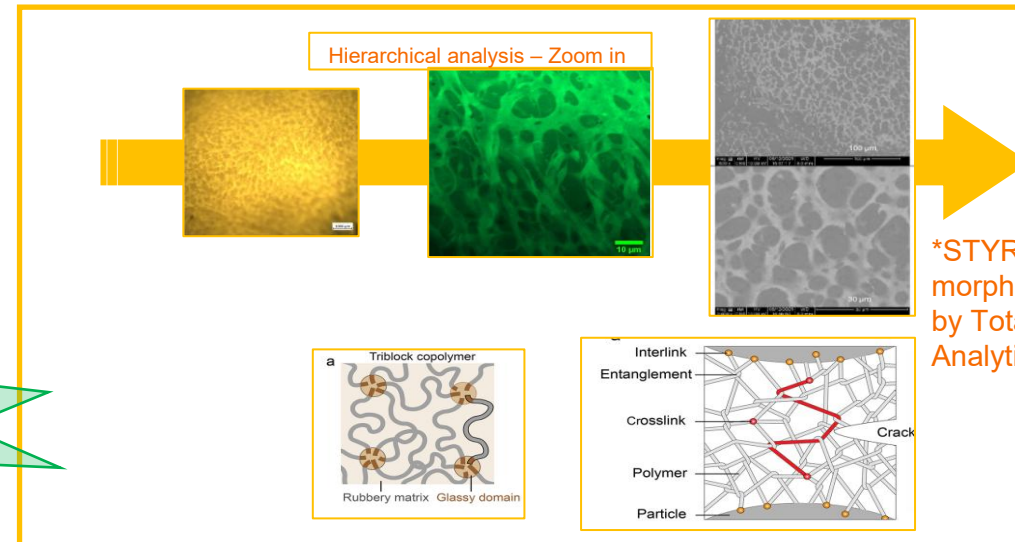
Multiscale & Associated Energy Dissipation Mechanism (MAEDM) « reservoir »

Colloidal motion, rearrangement, relaxation & local damage accommodation



Function of temperature, stress loading & rate, ageing

SBS network rearrangement, relaxation & local damage accommodation



*STYRELF morphologies captured by TotalEnergies R&D Analytical platform

D. Lesueur, *Adv. in Coll. and Int. Science*, vol. 145, 42-82, 2009

C.A. Lemarchand et al., *J. Chem. Phys.*, 149, 214901, 2018

M. Porto et al., *Materials*, 15, 905, 2022

G. Pipintakos et al., *Materials & Design*, 244, 113157, 2024

Z. Chen & Z. Suo, *Thermodynamic and Molecular Origins of Crack Resistance in Polymer Networks*, *Chem. Rev.* 126, 606-670, 2026

Recycled asphalt mixture, What's the problem?

Virgin AC with SBS-Xlinked PmB

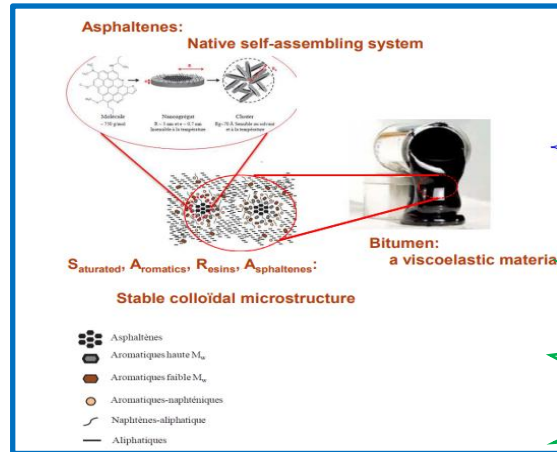


- Damage tolerance
- Cumulative damage acceptance until critical failure
- Under mechanical, thermal & chemical stress

Binder Level

Multiscale & Associated Energy Dissipation Mechanism (MAEDM) « reservoir »

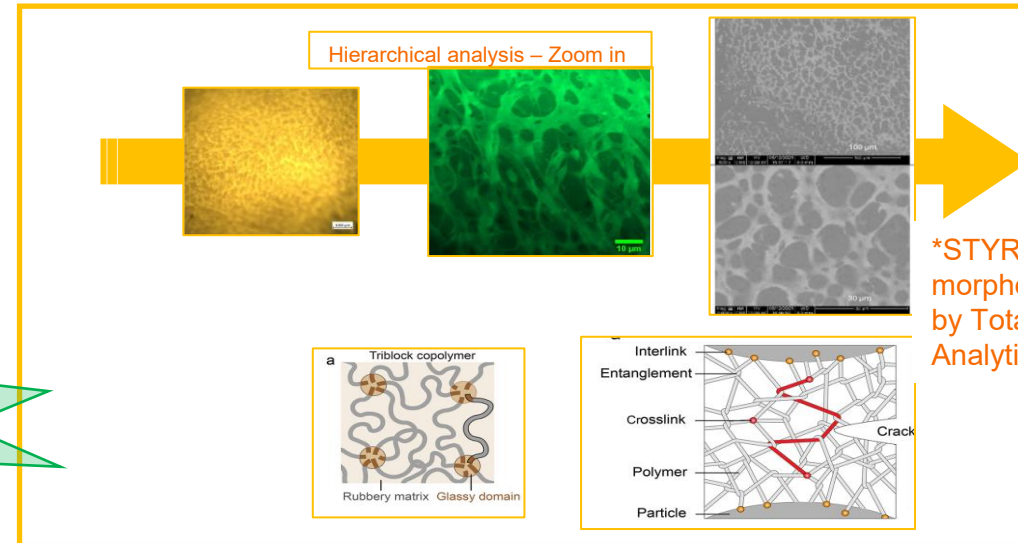
Colloidal motion, rearrangement, relaxation & local damage accommodation



Bitumen: a viscoelastic material

Function of temperature, stress loading & rate, ageing

SBS network rearrangement, relaxation & local damage accommodation



*STYRELF morphologies captured by TotalEnergies R&D Analytical platform

D. Lesueur, *Adv. in Coll. and Int. Science*, vol. 145, 42-82, 2009

C.A. Lemarchand et al., *J. Chem. Phys.*, 149, 214901, 2018

M. Porto et al., *Materials*, 15, 905, 2022

G. Pipintakos et al., *Materials & Design*, 244, 113157, 2024

Z. Chen & Z. Suo, *Thermodynamic and Molecular Origins of Crack Resistance in Polymer Networks*, *Chem. Rev.* 126, 606-670, 2026

Recycled asphalt mixture, What's the problem?

RAP materials



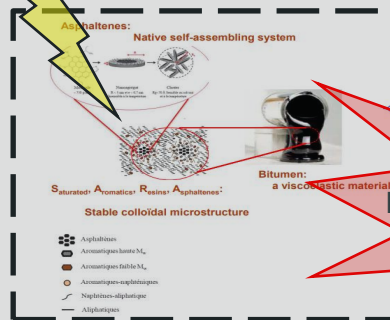
- Damage tolerance
- Cumulative damage acceptance until critical failure
- Under mechanical, thermal & chemical stress

Aged Binder Level

Multiscale & Associated Energy Dissipation Mechanism (MAEDM) « reservoir » depleted

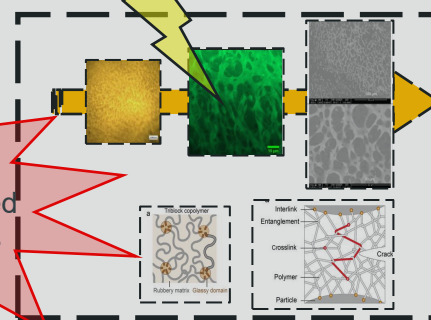
AGED BITUMEN

Detrimental colloidal MAEDM reservoir before failure



AGED SBS-Xlinked PmB

Detrimental network MAEDM reservoir before failure



Global material failure
MAEDM reservoir depleted
collapsed system occurs

RAP binder profile captured by DSR rheometrics

Recycled asphalt mixture, What's the problem?

RAP materials



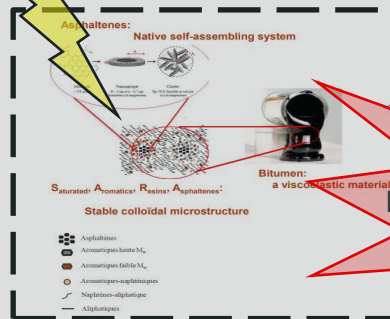
- Damage tolerance
- Cumulative damage acceptance until critical failure
- Under mechanical, thermal & chemical stress

Aged Binder Level

Multiscale & Associated Energy Dissipation Mechanism (MAEDM) « reservoir » depleted

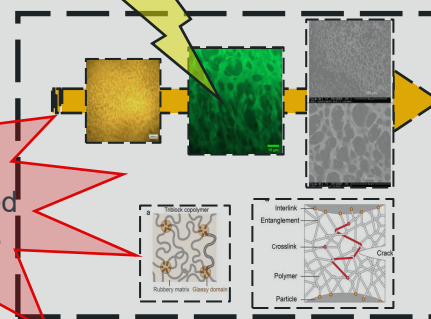
AGED BITUMEN

Detrimental colloidal MAEDM reservoir before failure



AGED SBS-Xlinked PmB

Detrimental network MAEDM reservoir before failure

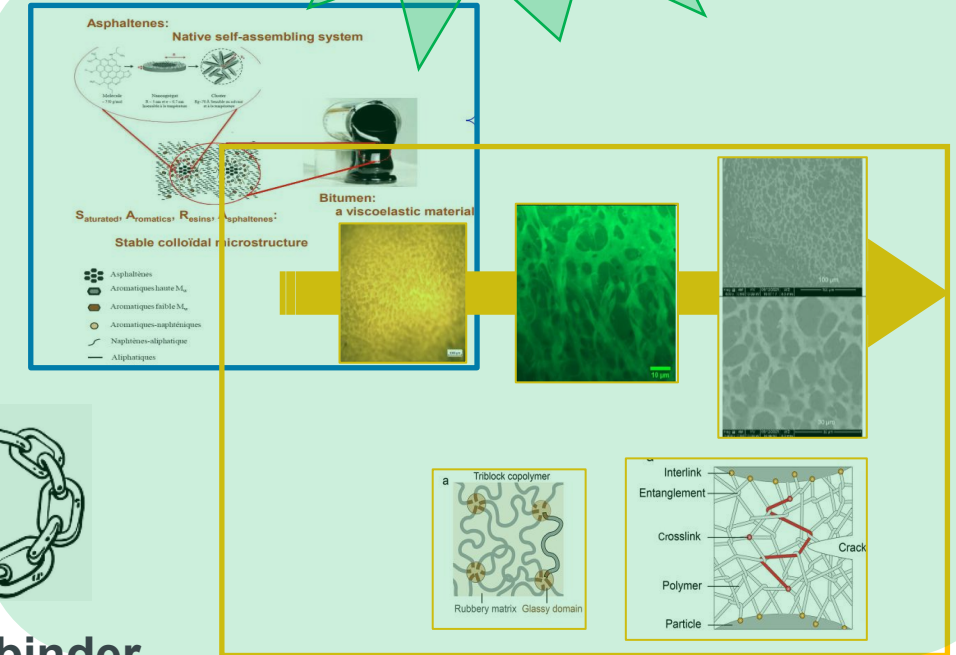


Global material failure
MAEDM reservoir depleted
collapsed system occurs



Blend binder

Fresh Binder level
Replenish the MAEDM reservoir



RAP binder profile captured by DSR rheometrics

Fresh binder profile designed by DSR rheometrics

The background of the slide is a composite image. On the left, there is a close-up photograph of a dark, granular surface, possibly sand or coal, with numerous small, glowing orange and yellow particles scattered across it. A white line drawing of a magnifying glass is overlaid on this image, with its handle extending towards the bottom left. On the right, the background transitions into a solid blue gradient.

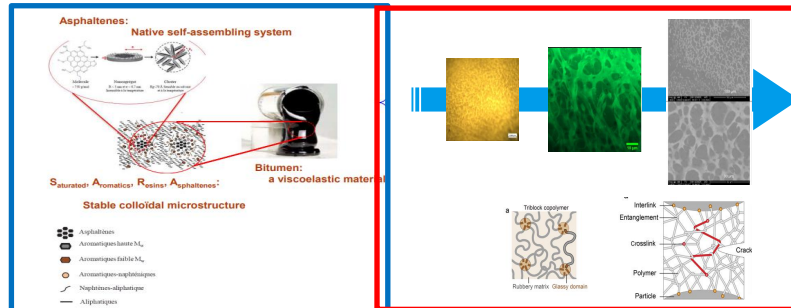
02

Method Framework

Bituminous binder, simply complex matter

Bituminous binders properties are intimately related to their microstructure:

➔ Deep-dive understanding their complex behavior of such microstructure enable to use different leverages to shape with efficiency polymer/additive contribution on materials targeted performances

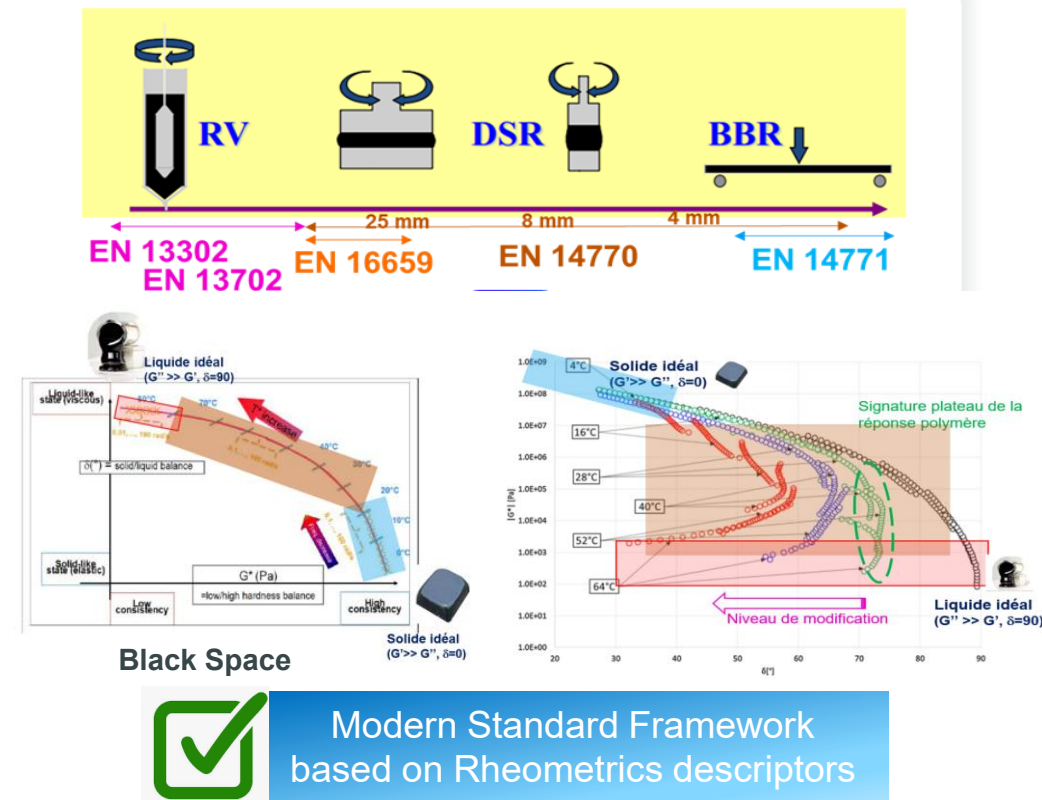
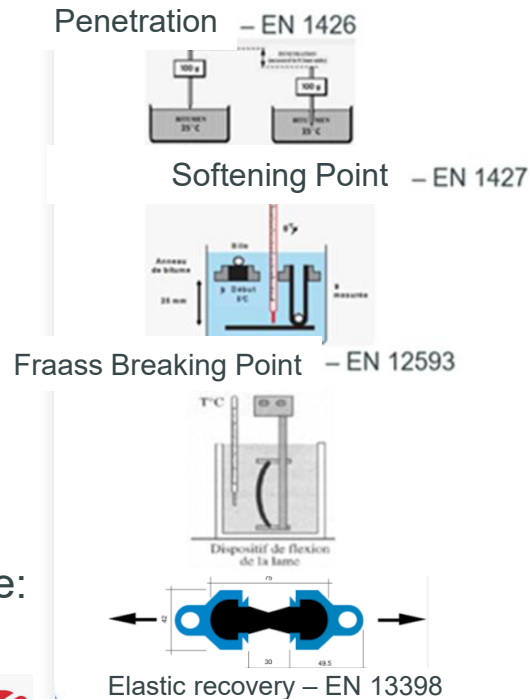


Probe the MAEDM reservoir gap between RAP binder profile ⇔ target virgin PmB profile:

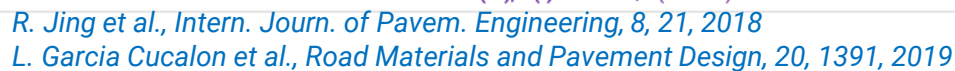
- Colloidal reservoir
- SBS network reservoir



Common Standard Framework



Modern Standard Framework based on Rheometrics descriptors



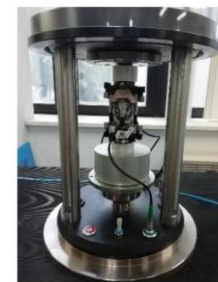
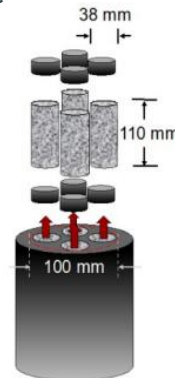
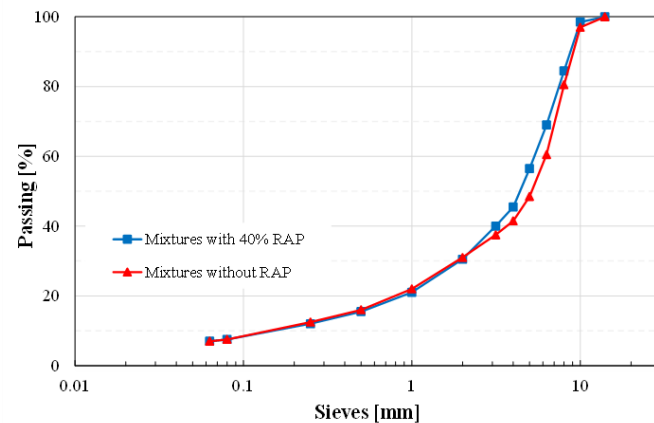
- T_{VET} (10 rad/s) → Probe mainly the colloidal reservoir metric
- $\delta @ G^* = 1 \text{ kPa}$ (1 rad/s) → Probe mainly SBS network reservoir metric

From AC Test methods toward S-VECD Characterization

Asphalt mixtures characterization plan using Asphalt Mixture Performances Tester (AMPT)

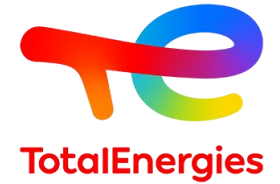
- preparation of specimens using Superpave Gyratory Compactor (SGC) according to AASHTO PP 99
- Dynamic modulus according to AASHTO TP 132 (2023)
- Cyclic Fatigue test according to AASHTO TP 133 (2021), AASHTO T 411 (2023),

BBSG 0/10 cl3 typical french design for wearing course



Geometry	Dynamic modulus test (D x H, mm)	Fatigue test (D x H, mm)
Small specimen	38 x 110	38 x 110

From AC Test methods toward S-VECD Characterization



Simplified ViscoElastic Continuum Damage framework (S-VECD)

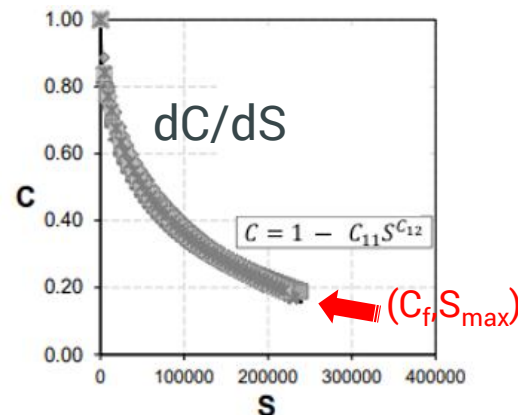
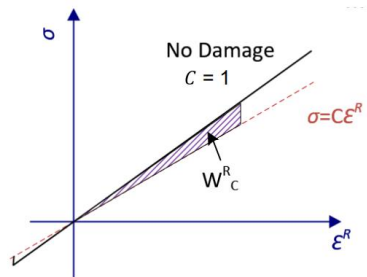
- Materials Integrity D represented by pseudo-modulus C (D). Damage Internal state variable S
- Damage characteristic curve C-S describes material integrity evolution alongside Internal damage accumulation
- D^R and S_{app} index display materials ranking according to damage tolerance and damage capacity

$$\frac{dS}{dt} = \left(-\frac{\partial W^R}{\partial S} \right)^\alpha$$

W^R : pseudo-strain energy
 α : the damage evolution rate (related to relaxation modulus of master curve)
 ε^R : pseudo-strain
 σ : applied stress
 C_{11} and C_{12} : fitting coefficients

$$C = \frac{\sigma}{\varepsilon^R}$$

$$C = 1 - C_{11} \cdot S^{C_{12}}$$



C-S curve describes only evolution of damage (dC/dS)
 C_f , S_{max} are related to critical failure stage (related to N_f)

D^R represents a measure of material Damage Tolerance ~ Toughness

$$D^R = \frac{\int_0^{N_f} (1-C) dN}{N_f} = \frac{\text{sum}(1-C)}{N_f}$$

S_{app} Index represents an apparent damage capacity of materials

$$S_{app} = 1000^{\left(\frac{\alpha}{2}-1\right)} \cdot \frac{a_{T(S_{app})}^{\frac{1}{\alpha+1}} \cdot \left(\frac{D^R}{C_{11}}\right)^{\frac{1}{C_{12}}}}{|E^*|^{\frac{\alpha}{4}}_{LVE,Sapp}}$$

N_f : number of cycles to failure

$a_{T(S_{app})}$: time-temperature shift factor between S_{app} temperature and reference temperature for dynamic modulus master curve

$|E^*|^{\alpha/4}_{LVE,SAPP}$: reference modulus calculated at the S_{app} reference temperature and for reduced frequency of $62,8 \times a_{T(S_{app})}$

Applied Ref temperature: 21 °C

- R. A. Schapery et al., *Intern. Journal of fracture*, 25 (3), 195, 1984
 Y. R. Kim et al., *Journal of the AAPT*, 66, 520, 1997
 G. R. Chehab et al., *Journal of the AAPT*, 72, 315, 2003
 B. S. Underwood et al., *Transportation Research Record*, 2296(1), 36, 2012
 Y. D. Wang et al., *Int. Journ. of Pav. Engineering*, 20(10), 1182, 2019
 Y.R. Kim et al., *FHWA-HRT-21-093 report*, 2022
 Y. D. Wang et al., *Int. Journ. of Pav. Engineering*, 23(2), 438, 2022

03

**France cases study:
Field worksites from 2016-2026**

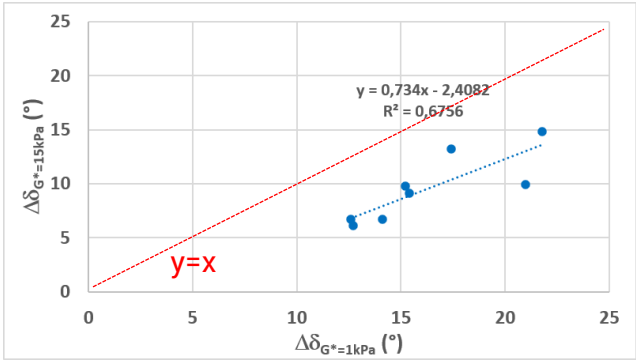
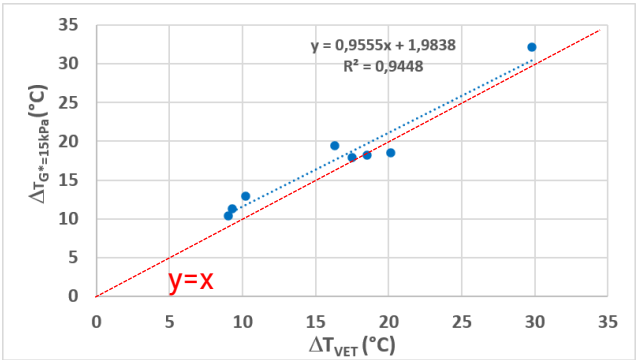
Rheometrics to discriminate RAP binder & PmB profiles



TotalEnergies

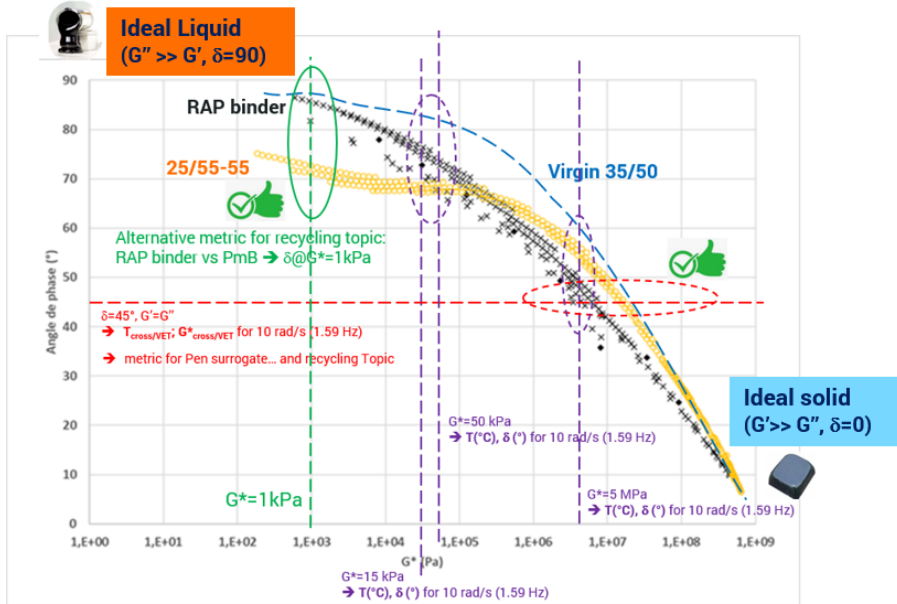
RAP stockpile	RAP1, AC	RAP2, AC	RAP3, porous AC	RAP4, thin layer AC	RAP5, RAP6, thin layer AC
Traffic class according to NF P98-086	T0 (++)	T1 (+)	TS (+++)	T0 (++)	T0 (++)
Climate characteristics	Mountain climate, severe weather in winter, moderate warm weather in summer		Mediterranean climate, hot weather in summer, smooth weather in winter, rainy periods in spring/fall	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period

$\Delta X = \text{Abs}(X_{\text{RAPbinder}} - X_i)$; i is target binder or blend binder
 X is T_{VET} , $T_{G^*=15\text{kPa}}$, $\delta_{G^*=1\text{kPa}}$ or $\delta_{G^*=15\text{kPa}}$



→ Variation ΔT_{VET} is equal to $\Delta T_{G^*=15\text{kPa}}$ but T_{VET} displays a fundamental viscoelastic criteria

→ Variation $\Delta \delta_{G^*=1\text{kPa}}$ capture more properly the magnitude of polymer phase signature than $\Delta \delta_{G^*=15\text{kPa}}$. Criteria are not equals

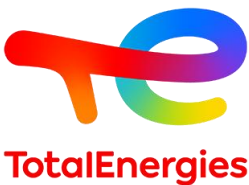


Using rheometrics proxies to define the MAEDM reservoir to fulfill:

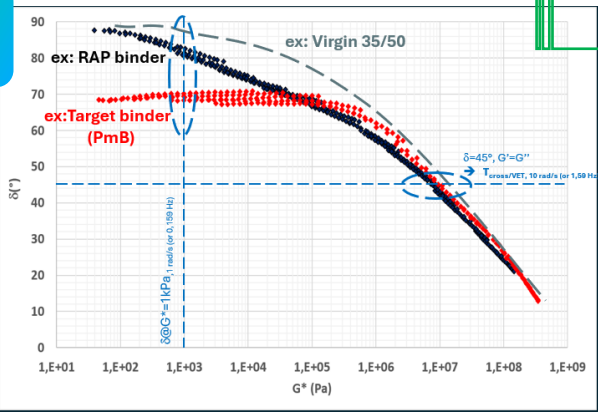
- T_{VET} (10 rad/s) → Probe mainly the colloidal reservoir metric
- $\delta@G^*=1\text{kPa}$ (1 rad/s) → Probe mainly SBS network reservoir metric



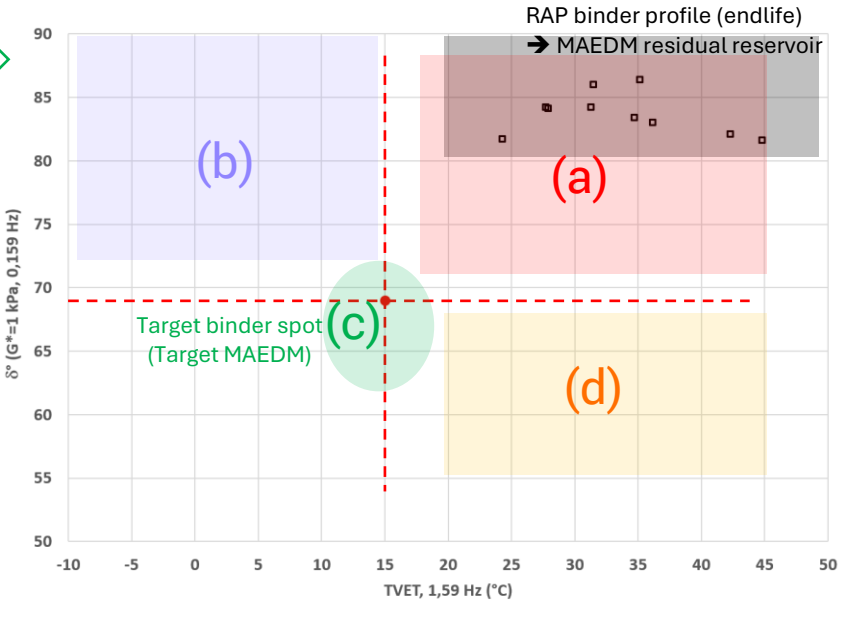
Method framework for RAP re-use and recycling binders



Black space G^* vs δ



Toward T_{VET} vs $\delta_{G^*=1\text{kPa}}$ 2D-visualization



RAP stockpile	RAP1, AC	RAP2, AC	RAP3, porous AC	RAP4, thin layer AC	RAP5, RAP6, thin layer AC
Traffic class according to NF P98-086	T0 (++)	T1 (+)	TS (+++)	T0 (++)	T0 (++)
Climate characteristics	Mountain climate, severe weather in winter, moderate warm weather in summer	Mediterranean climate, hot weather in summer, smooth weather in winter, rainy periods in spring/fall	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period

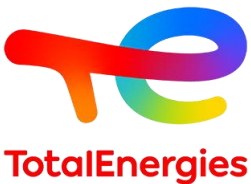
(a): Underbalanced global MAEDM reservoir of fresh binder
→ ex: hard bitumen, low polymer modification etc...

(b): Overbalanced colloidal & Underbalanced SBS network MAEDM reservoir of fresh binder
→ ex: very soft bitumen or recycling agent, etc...

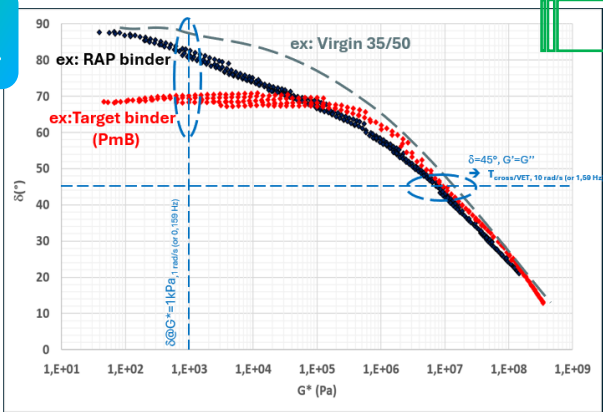
(d): Underbalanced colloidal & overbalanced SBS network MAEDM reservoir of fresh binder
→ ex: hard bitumen, high polymer modification, etc...

(c): Balanced colloidal & SBS network MAEDM reservoir of fresh binder
→ ex: balanced Recycling binder

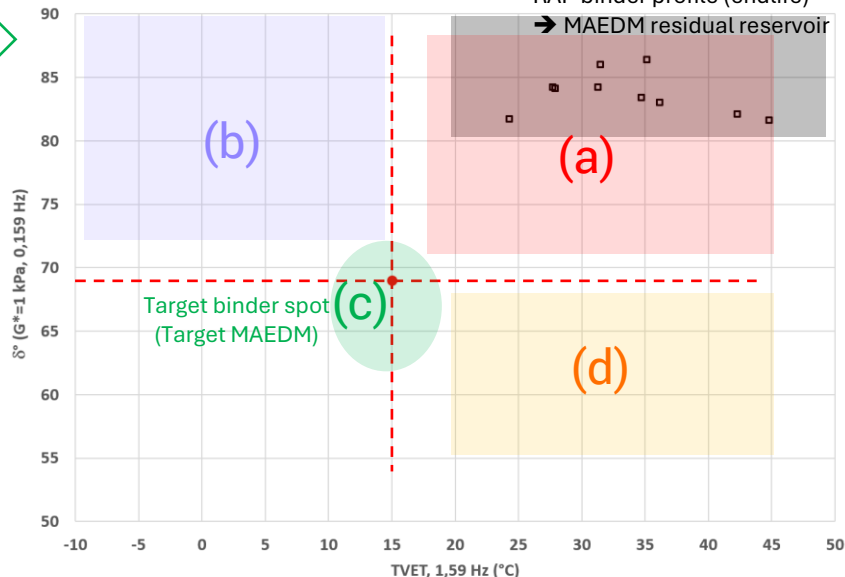
Method framework for RAP re-use and recycling binders



Black space G^* vs δ



Toward T_{VET} vs $\delta_{G^*=1kPa}$ 2D-visualization



RAP stockpile	RAP1, AC	RAP2, AC	RAP3, porous AC	RAP4, thin layer AC	RAP5, RAP6, thin layer AC
Traffic class according to NF P98-086	T0 (++)	T1 (+)	TS (+++)	T0 (++)	T0 (++)
Climate characteristics	Mountain climate, severe weather in winter, moderate warm weather in summer	Mediterranean climate, hot weather in summer, smooth weather in winter, rainy periods in spring/fall	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period

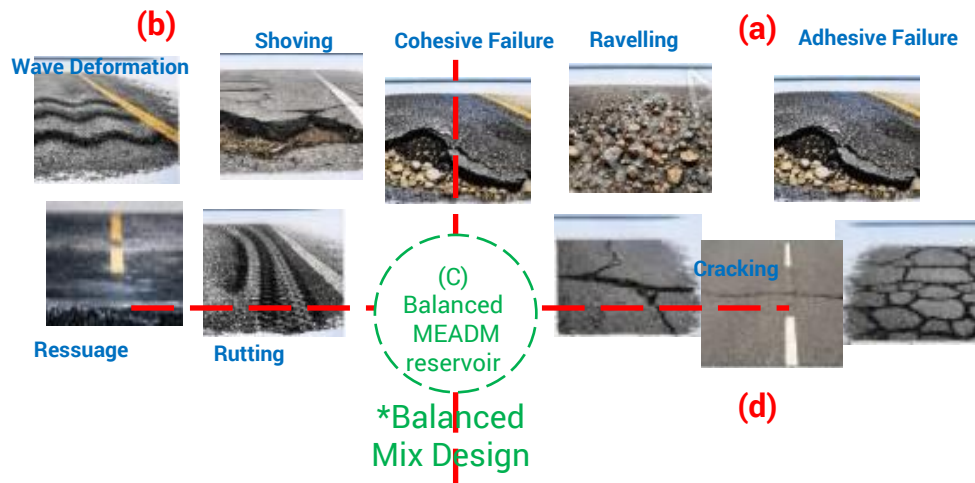
(a): Underbalanced global MAEDM reservoir of fresh binder
→ ex: hard bitumen, low polymer modification etc...

(b): Overbalanced colloidal & Underbalanced SBS network MAEDM reservoir of fresh binder
→ ex: very soft bitumen or recycling agent, etc...

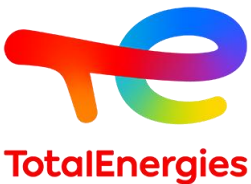
(d): Underbalanced colloidal & overbalanced SBS network MAEDM reservoir of fresh binder
→ ex: hard bitumen, high polymer modification, etc...

(c): Balanced colloidal & SBS network MAEDM reservoir of fresh binder
→ ex: balanced Recycling binder

Failure susceptibility related to undermanaged fresh binder

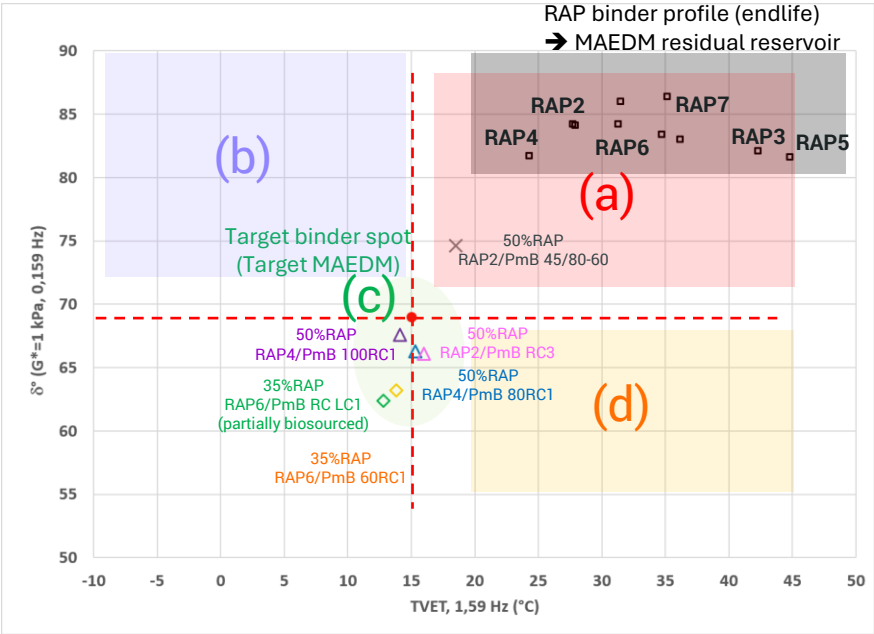
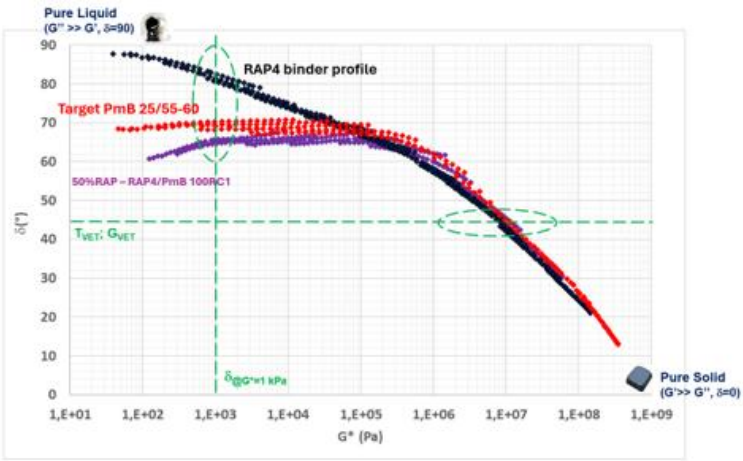


Method framework for RAP re-use and recycling binders



RAP stockpile	RAP1, AC	RAP2, AC	RAP3, porous AC	RAP4, thin layer AC	RAP5, RAP6, thin layer AC
Traffic class according to NF P98-086	T0 (++)	T1 (+)	TS (+++)	T0 (++)	T0 (++)
Climate characteristics	Mountain climate, severe weather in winter, moderate warm weather in summer	Mediterranean climate, hot weather in summer, smooth weather in winter, rainy periods in spring/fall	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period	

Target binder (virg_AC) PmB 25/55-60	Blend binder (rec AC) PmB 25/55-60			
	50%RAP (ratio)	RAP2/PmB 45/80-60 (45/55)	RAP2/PmB RC3 (45/55)	
	50%RAP (ratio)	RAP4/PmB 80RC1 (48/52)	RAP4/PmB 100RC1 (48/52)	
	35%RAP (ratio)	RAP6/PmB 60RC1 (33/67)	RAP6/PmB RC LC1 (33/67)	
	40%RAP (ratio)	RAP7/Bitumen 70/100 (40/60)	RAP7/PmB 25/55-60 (40/60)	
		RAP7/PmB100RC1 (40/60)	RAP7/PmB RC LC1 (40/60)	



Method framework for RAP re-use and recycling binders

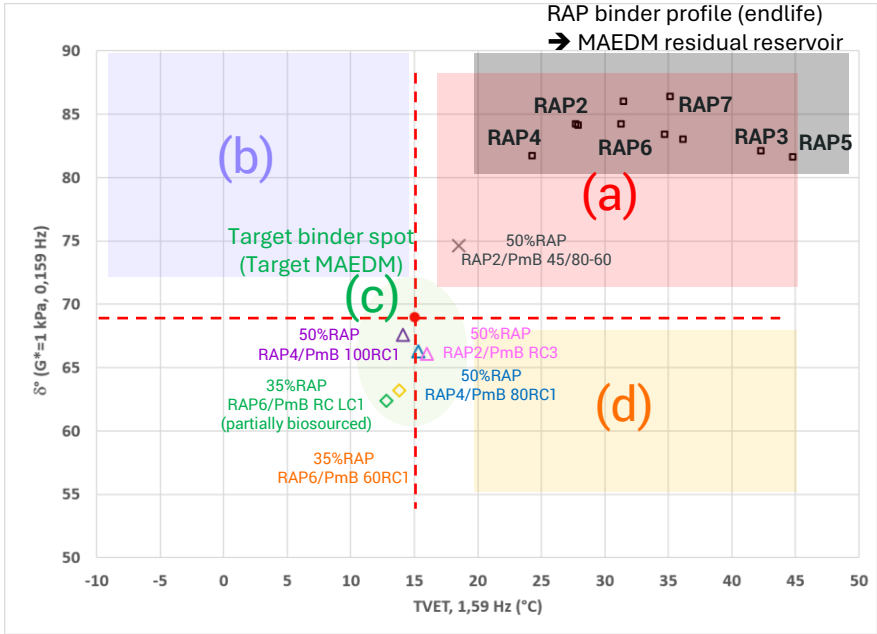
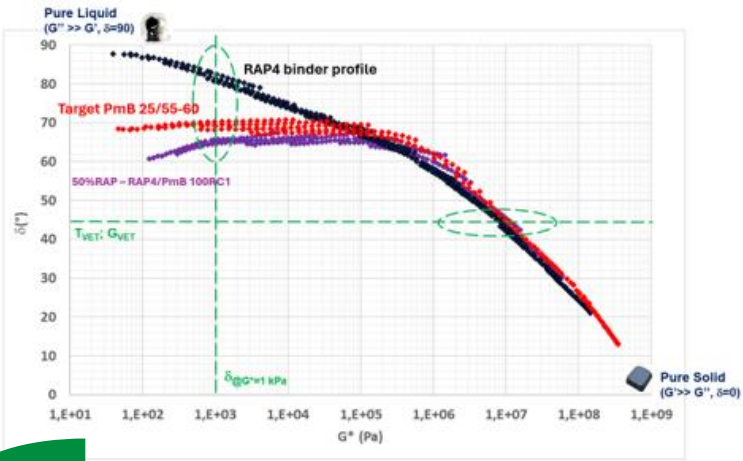


TotalEnergies

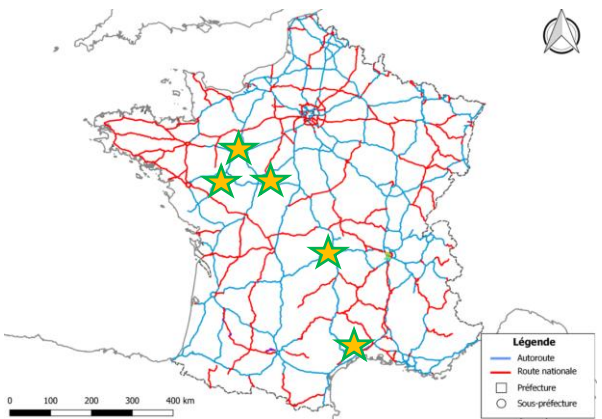
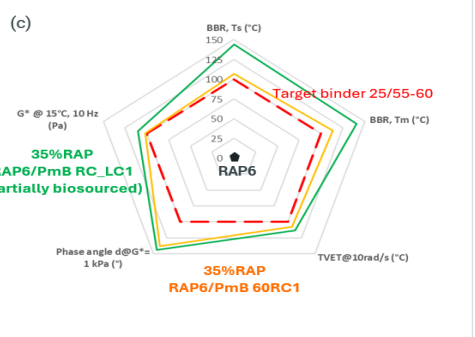
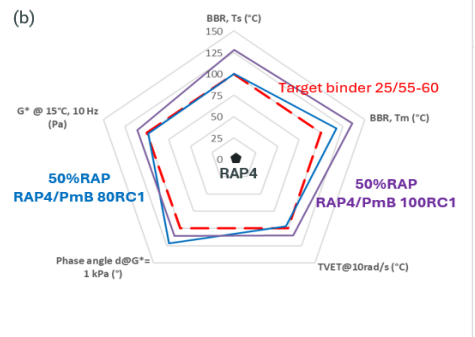
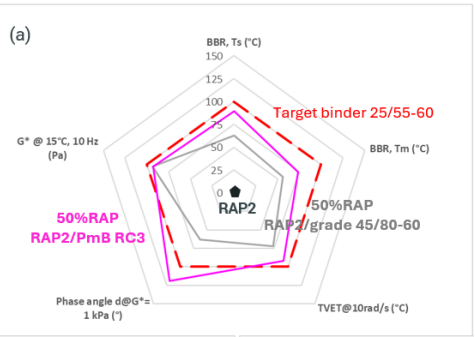


RAP stockpile	RAP1, AC	RAP2, AC	RAP3, porous AC	RAP4, thin layer AC	RAP5, RAP6, thin layer AC
Traffic class according to NF P98-086	T0 (++)	T1 (+)	TS (+++)	T0 (++)	T0 (++)
Climate characteristics	Mountain climate, severe weather in winter, moderate warm weather in summer	Mediterranean climate, hot weather in summer, smooth weather in winter, rainy periods in spring/fall	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period

Target binder (virg_AC) PmB 25/55-60	Blend binder (rec AC) PmB 25/55-60			
	50%RAP (ratio)	RAP2/PmB 45/80-60 (45/55)	RAP2/PmB RC3 (45/55)	
	50%RAP (ratio)	RAP4/PmB 80RC1 (48/52)	RAP4/PmB 100RC1 (48/52)	
	35%RAP (ratio)	RAP6/PmB 60RC1 (33/67)	RAP6/PmB RC LC1 (33/67)	
	40%RAP (ratio)	RAP7/Bitumen 70/100 (40/60)	RAP7/PmB 25/55-60 (40/60)	
		RAP7/PmB 100RC1 (40/60)	RAP7/PmB RC LC1 (40/60)	



Additional rheometrics with spider charts
(BBR-T_s, BBR-T_m, T_{VE}, 1,59Hz, $\delta_{G^*=1kPa, 0,159Hz}$, $G^*_{15^\circ C, 10 Hz}$)



Adjust the (recycling) fresh binder according to worksites characteristics:

- Binder target
- RAP content
- RAP binders characteristics

Method framework for RAP re-use and recycling binders

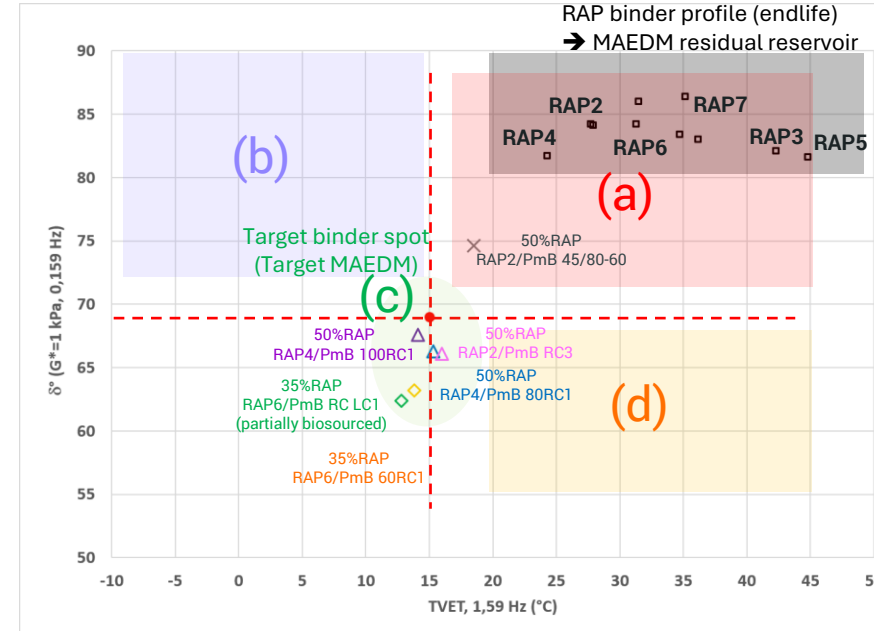


TotalEnergies

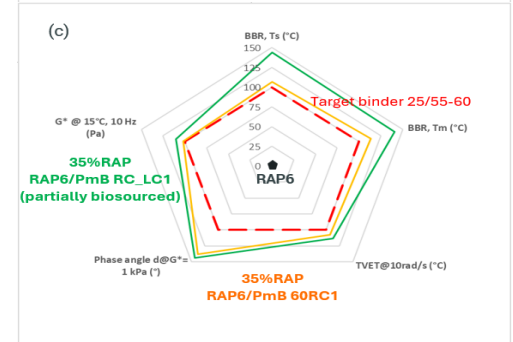
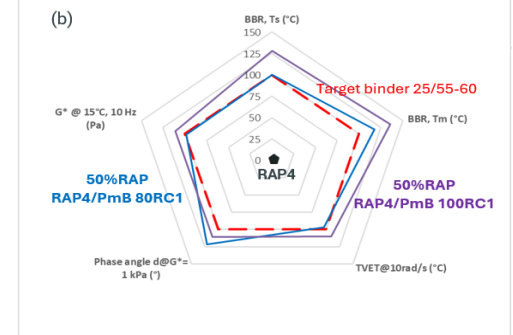
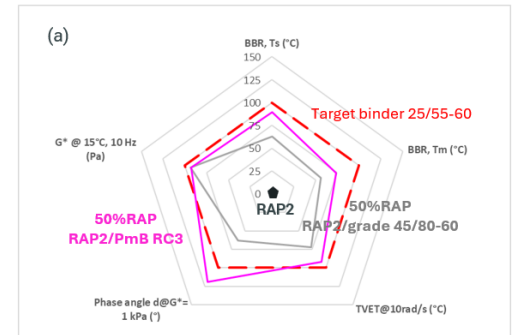


RAP stockpile	RAP1, AC	RAP2, AC	RAP3, porous AC	RAP4, thin layer AC	RAP5, RAP6, thin layer AC
Traffic class according to NF P98-086	T0 (++)	T1 (+)	TS (+++)	T0 (++)	T0 (++)
Climate characteristics	Mountain climate, severe weather in winter, moderate warm weather in summer	Mediterranean climate, hot weather in summer, smooth weather in winter, rainy periods in spring/fall	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period	Ocean climate, smooth weather, high rainy period

Target binder (virg_AC)	Blend binder (rec_AC) PmB 25/55-60
50%RAP (ratio)	RAP2/PmB 45/80-60 (45/55)
50%RAP (ratio)	RAP4/PmB 80RC1 (48/52)
35%RAP (ratio)	RAP6/PmB 60RC1 (33/67)
40%RAP (ratio)	RAP7/Bitumen 70/100 (40/60)
	RAP7/PmB100RC1 (40/60)

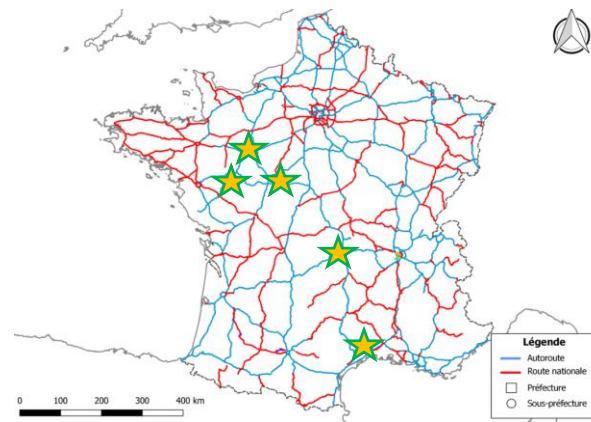


Additional rheometrics with spider charts (BBR-T_s, BBR-T_m, T_{VE}, 1,59Hz, δ_G=1kPa, 0,159Hz, G*15°C, 10 Hz)



High RAP Re-use and Recycling Binders

- ✓ Asphalt mixture with Balanced Mix-Design according French doctrine
 - ✓ Rutting
 - ✓ Water sensitivity
 - ✓ TSRST
- ✓ Recycling Binder Design with rheometrics proxies
- ✓ Replenish colloidal and SBS network MAEDM reservoir to mimic virgin target PmB
- ✓ Several worksites operated from 30 to 50%RAP since 2016



04

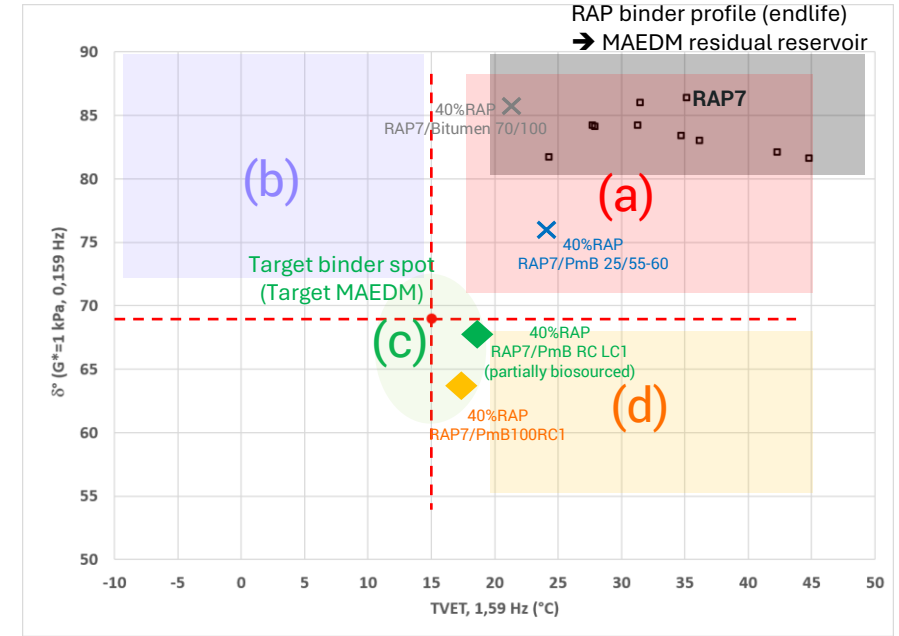
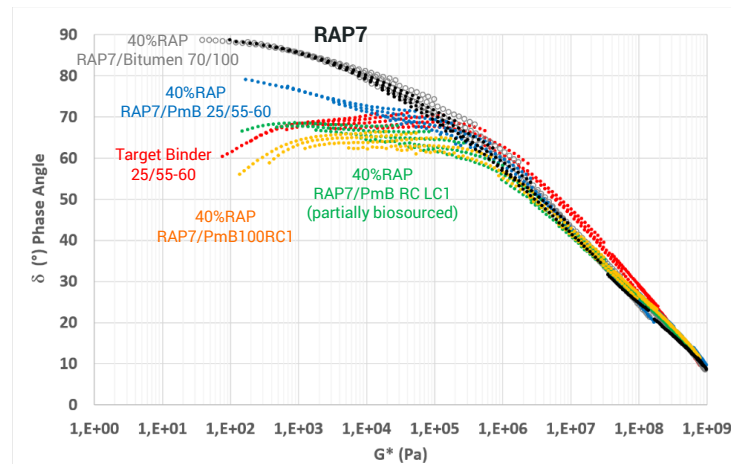
Case Study: Asphalt mixture evaluation by S-VECD

AC 40%RAP case study: Benchmark of candidates



Target binder (virg_AC) PmB 25/55-60	Blend binder (rec_AC) PmB 25/55-60		
	50%RAP (ratio)	RAP2/PmB 45/80-60 (45/55)	RAP2/PmB RC3 (45/55)
	50%RAP (ratio)	RAP4/PmB 80RC1 (48/52)	RAP4/PmB 100RC1 (48/52)
	35%RAP (ratio)	RAP6/PmB 60RC1 (33/67)	RAP6/PmB RC LC1 (33/67)
40%RAP (ratio)		RAP7/Bitumen 70/100 (40/60)	RAP7/PmB 25/55-60 (40/60)
		RAP7/PmB100RC1 (40/60)	RAP7/PmB RC LC1 (40/60)

Binders	RAP content (%)	MAEDM reservoir profile		
		Virgin Colloidal	Virgin SBS network	Aged Colloidal (Aged SBS network)
Target PmB 25/55-60	0	✓	✓	✗
70/100	40	✓	✓	✗
PmB 25/55-60	40	✓	✓	✗
PmB 100RC1	40	✓	✓	✗
PmB RC LC1	40	✓	✓	✗



For 40%RAP7,

➔ 70/100 and 25/55-60 candidates didn't match target binder spot.
Will not replenish the target MAEDM both colloidal and SBS network reservoir

➔ PmB100RC and PmB RC LC1 candidates match target binder spot.
Will replenish the target MAEDM, SBS network slightly balances colloidal reservoir

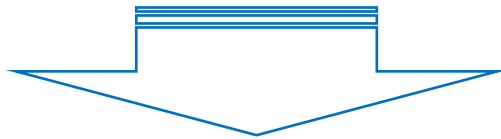
High RAP Re-use and Recycling Binders

In combinaison with 40%RAP, Candidates will no behave similarly related the MAEDM pathway

- 70/100
- PmB 25/55-60
- PmB 100RC1 and PmB RC LC1

AC 40%RAP case study: Dynamic modulus mapping

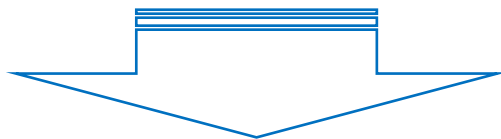
Binders	RAP content (%)	MAEDM reservoir profile		
		Virgin Colloidal	Virgin SBS network	Aged Colloidal (Aged SBS network)
Target PmB 25/55-60	0	✓	✓	✗
70/100	40	✓	✗	✓
PmB 25/55-60	40	✓	✓	✓
PmB 100RC1	40	✓	✓	✓
PmB RC LC1	40	✓	✓	✓



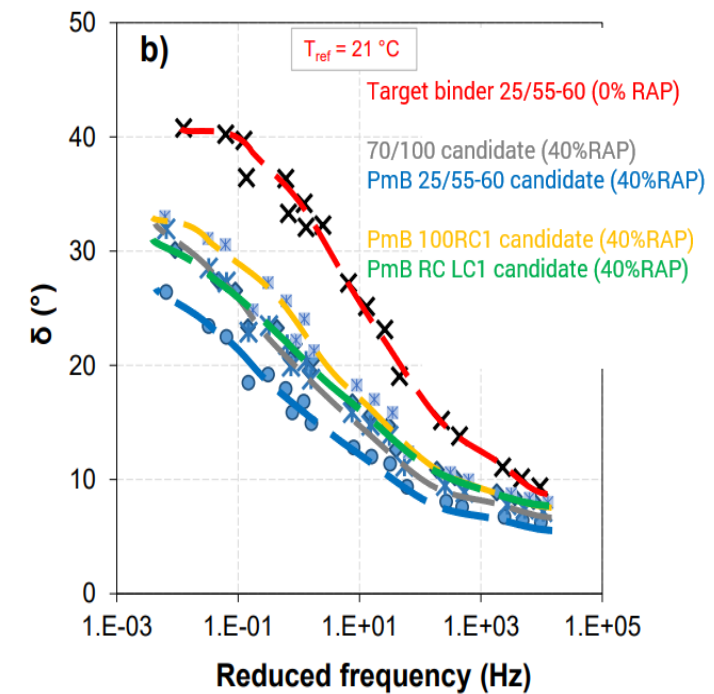
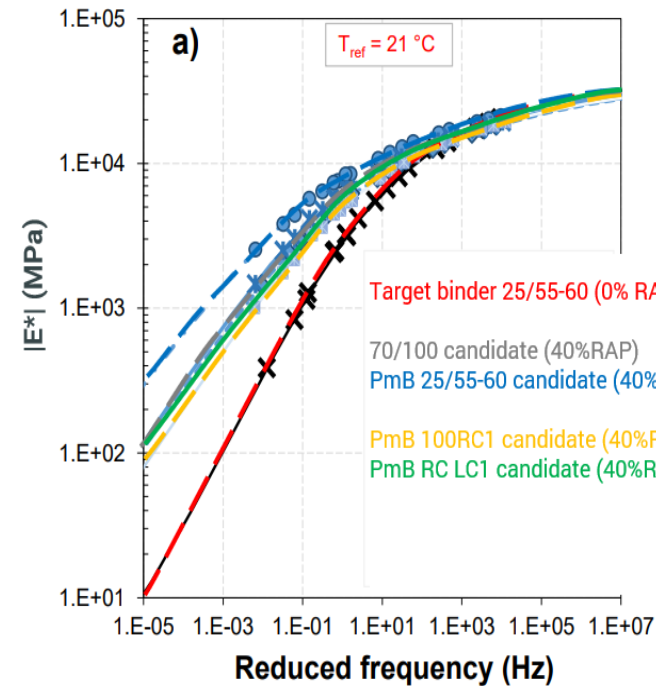
For 40%RAP,

- PmB 25/55-60 displays higher Modulus and higher elastic/viscous ratio behavior (lower δ)
- 70/100, PmB 100RC1 and PmB RC LC1 display similar modulus and intermediate elastic/viscous ratio

Target Binder (%0 RAP) displays the lower Modulus and the lower elastic/viscous ratio (higher δ)



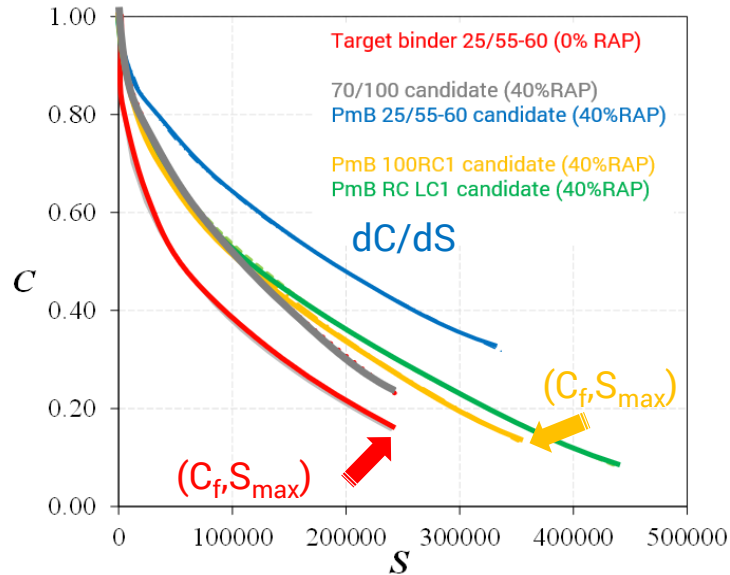
AC Dynamic Modulus test (Linear ViscoElastic Domain)



Expectation of 3 MAEDM reservoirs scenarii & pathways till failure

AC 40%RAP case study: S-VECD Mapping

Cyclic Fatigue test (Non Linear ViscoElastic Domain) + S-VECD Framework



Binders	RAP content (%)	MAEDM reservoir profile		
		Virgin Colloidal	Virgin SBS network	Aged Colloidal (Aged SBS network)
Target PmB 25/55-60	0	✓	✓	✗
70/100	40	✓ ✓	✗	✓
PmB 25/55-60	40	✓	✓	✓
PmB 100RC1	40	✓ ✓	✓ ✓	✓
PmB RC LC1	40	✓ ✓	✓ ✓	✓

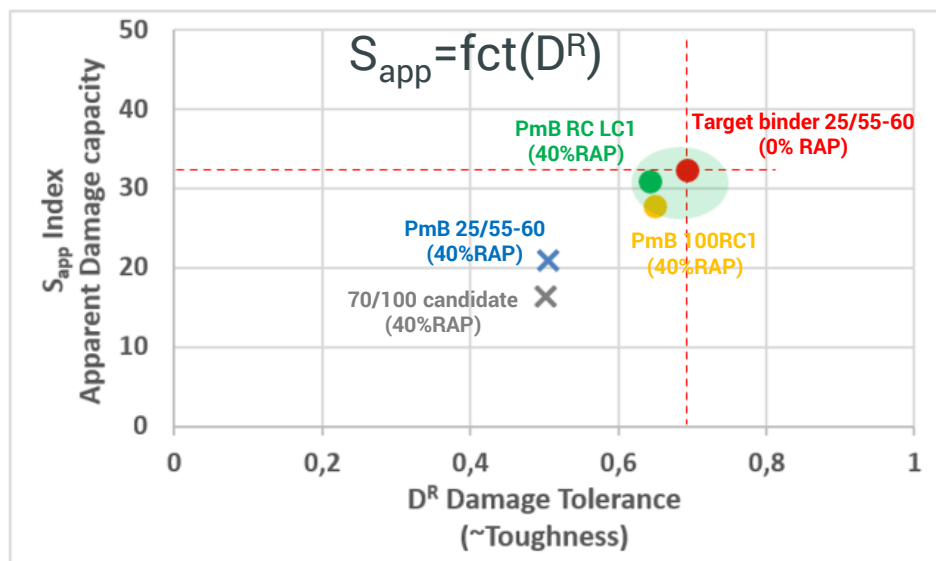
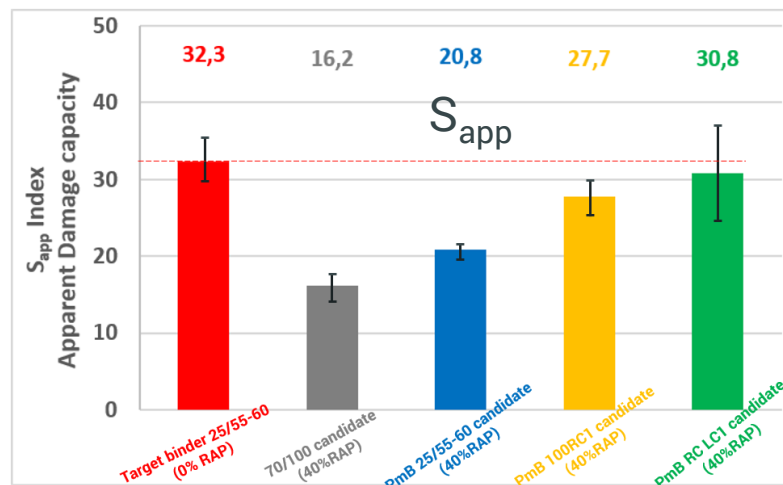
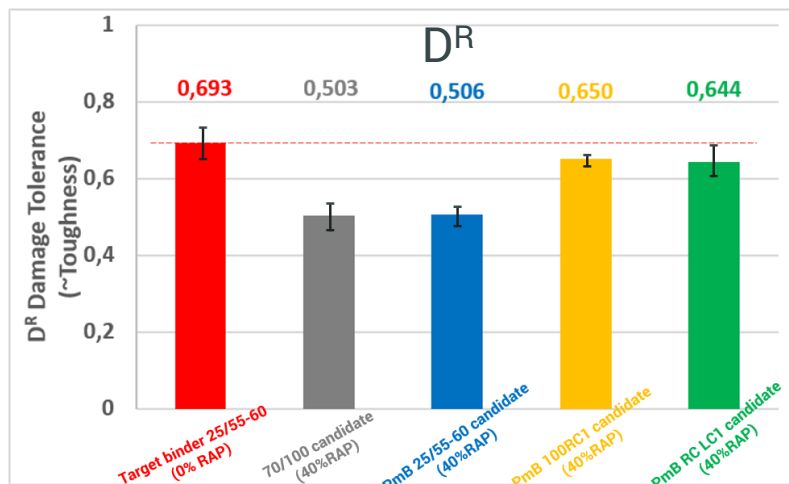
3 class of C-S curve for candidates according to viscoelastic behaviors of AC:

- Similar dC/dS (candidates **70/100**, **PmB100RC1** and **PmB RC LC1** with 40%RAP)
 - Lower C_f /Higher S_{max} → Higher Damage Tolerance & cumulated damage acceptance until failure
- Different dC/dS (target binder **PmB 25/55-60 w/o RAP** vs **PmB 25/55-60 with 40%RAP**)
 - 40%RAP induces alternative MAEDM pathway & Damage Tolerance profile
 - Materials integrity evolution VS Damage Tolerance/cumulated damage acceptance until failure?

AC 40%RAP case study: S-VECD Mapping



Cyclic Fatigue test (Non Linear ViscoElastic Domain) + S-VECD Framework



2 class of candidates according D^R and S_{app} criteria, for 40%RAP:

- Candidates **70/100**, PmB 25/55-60 didn't achieve same Damage Tolerance and Damage Capacity magnitude as anticipated to unbalanced MAEDM reservoir
- Candidates **PmB100RC1** and **PmB RC LC1** succeed to achieve same Damage Tolerance and Damage Capacity magnitude as anticipated by well balanced MAEDM reservoir



TotalEnergies

05

Conclusions & Take away!

Fields Feedback and Experimental Findings

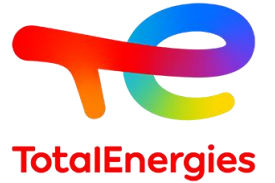


- ✓ French fields experiences succeed with high RAP reuse wearing courses cases study
 - ✓ Adapt scientific method framework to unlock the technical gap
 - ✓ Design recycling binders to enable
 - ✓ Similar viscoelastic profile
 - ✓ Similar damage tolerance
 - ✓ Similar damage accumulation acceptance until critical failure

Mechanisms Insight Hypothesis

- In the S-VECD framework, asphalt mixtures damage tolerance and damage accumulation acceptance until critical failure can be anticipated by binder MAEDM:
 - Colloidal reservoir consumption
 - SBS network reservoir consumption
- Based on colloidal and polymer network scientific background, MAEDM reservoir consumption can be split into:
 - Linear ViscoElastic domain (reversible process)
 - Non Linear ViscoElastic domain/Progressive damage evolution (partially reversible/irreversible process)
 - Critical failure behavior (irreversible process)

Acknowledgements



TotalEnergies: Viviane JULIEN, Stefan OEST, Zain KALEEM, Tobias HAGNER, Vincent GAULLIARD, Romain COLLIAT, Fan ZHANG, Ségolène LAAGE, Iliass TAHIRI, Audrey PLEYNET

UnivPM: Lorenzo PIGLIAPOCO, Lorenzo Paolo INGRASSIA, Francesco CANESTRARI

References:

- R.A. Schapery et al., *Correspondence principles and a generalized integral for large deformation and fracture analysis of viscoelastic media*, *Journal of fracture*, 25(3), 195, 1984
- Y. R. Kim et al., *Fatigue characterization of asphalt concrete using viscoelasticity and continuum damage theory*, *Journal of the AAPT*, 66, 520, 1997
- G. R. Chebab et al., *Characterization of asphalt concrete in uniaxial tension using a viscoelastoplastic continuum damage model*, *Journal of the AAPT*, 72, 315, 2003
- D. Lesueur, *The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification*, *Adv. in Coll. and Int. Science*, vol. 145, 42-82, 2009
- B.S. Underwood, *Simplified viscoelastic continuum damage model as platform for asphalt concrete fatigue analysis*, *Transportation Research Record*, 2296(1), 36, 2012
- C.A. Lemarchand et al., *ROSE bitumen: Mesoscopic model of bitumen and bituminous mixture*, *J. Chem. Phys.*, 149, 214901, 2018
- L. Garcia Cucalon et al., *The crossover temperature: significance and application towards engineering balanced recycled binder blends*, *Road Materials and Pavement Design*, 20, 1391, 2019.
- Y. D. Wang et al., *Development of a pseudo strain energy-based fatigue failure criterion for asphalt mixtures*, *Int. Journ. of Pav. Engineering*, 20(10), 1182, 2019
- G. Cuciniello et al., *Applicability of time-temperature superposition for laboratory-aged neat and SBS-modified bitumens*, *Constr. and Build. Mat.*, 263, 120964, 2020
- G. Cuciniello et al., *Effect of ageing on the damage tolerance of polymer modified bitumens investigated through the LAS test and fluorescence microscopy*, *Int. J. of Pav. Eng.*, 1083, 2020
- R. Jing, et al., *Rheological, fatigue and relaxation properties of aged bitumen*, *International Journal of Pavement Engineering*, 8, 21, 2020
- Y. R. Kim et al., *Hot-mix asphalt performances related specification based on viscoelastoplastic continuum damage (VEPCD) models*, *FHWA-HRT-21-093*, 2022
- Y. D. Wang et al., *Development of a fatigue index parameter, Sapp, for asphalt mixes using viscoelastic continuum damage theory*, *Int. Journ. of Pav. Engineering*, 23(2), 438, 2022
- M. Porto et al., *The Structure of Bitumen: Conceptual Models and Experimental Evidences*, *Materials*, 15, 905, 2022
- W. Wu et al., *Differing perspectives on the use of high-content SBS polymer-modified bitumen*, *Construction and Building Materials*, 411, 134433, 2024
- G. Pipintakos et al., *Engineering bitumen for future asphalt pavements: A review of chemistry, structure and rheology*, *Materials & Design*, 244, 113157, 2024
- M. Zauamanis et al., *Towards the development of classification criteria for highly polymer-modified binders*, *Road Mat. and Pav. Design*, 27, 125, 2026
- Z. Chen & Z. Suo, *Thermodynamic and Molecular Origins of Crack Resistance in Polymer Networks*, *Chem. Rev.* 126, 606-670, 2026
- Y. Hung et al., *Enrobés à fort taux d'AE: La rhéologie au service du choix du liant d'apport*, *RGRA*, 1015, 2026



TotalEnergies

Thanks!
Q&A