3.5 Routes to durability and sustainability: Recycling of PmB containing RAP

Dr. Xueyan Liu, Associate professor

Delft University of Technology, The Netherlands

Abstract

Recycling of base asphalt pavement with rejuvenators or soft binders has been applied for many decades and a lot of experience has been gained. However, the high-quality recycling technique of polymer modified asphalt (PMA) has still not been sufficiently studied. The aging mechanism of PMA is complex, including the combined effects of the oxidation of bitumen and the degradation of the polymer. The current commercially available rejuvenators are designed mostly for base bitumen and not suitable for the recycling of PMA. For this reason, this research aims at designing an innovative rejuvenator specifically for the recycling of PMA. Firstly, a series of performance-based test methods, including viscoelastic properties, rutting resistance, fatigue resistance, cracking resistance, relaxation ability and aging ability, has been performed to select the appropriate source materials and to determine the optimum ratio between different components. After that, a specific SBS-based rejuvenator was found to be most effective in PMA rejuvenation. To reveal the rejuvenation mechanism, an environment scanning electron microscope (E-SEM) was utilized in investigating the microstructure of the rejuvenated binder. The results illustrated that E-SEM method can distinguish the influence of rejuvenator dosage, rejuvenator types, and addition of fresh bitumen on the morphology of aged PMB, which can help us to have a better understanding of the rejuvenation mechanism.

About the speaker

Dr. Xueyan Liu is currently an associate Professor in the Section of Pavement Engineering of the Faculty of Civil Engineering & Geosciences of TU Delft. He works in the areas of constitutive modelling, numerical modelling and material experimental characterization. Within the research program of the Section Pavement Engineering, his research topics mostly relate to the development and implementation of constitutive models for the simulation of the static and dynamic response of various pavement engineering materials like soils, asphalt concrete, liner and reinforcing systems etc. and sustainable development technologies, i.e., multiscale modelling of asphaltic materials, warm/cold asphalt concrete technology, durability of asphalt surfacings on orthotropic steel deck bridge, accelerated pavement test, pavement continuous monitoring and sustainable development technologies. Dr. Liu was granted his doctoral thesis in 2003. During the same period, Dr. Liu participated also in the team that developed the ACRe model for Asphalt Concrete Response currently implemented in 3D Computer Aided Pavement Analysis system (CAPA-3D).

Dr. Liu has published more than 100 technical and journal papers on the mechanics and the finite element modelling of granular, concrete and asphaltic materials. Dr. Liu is a member of RILEM Technical Committee 272-PIM Phase and Interphase behaviour of Bituminous Materials and a member of Delft Centre for Materials (DCMat). He is also a member of ISAP, AAPT, APSE and IACMAG. Dr. Liu is an Editorial Board Member of Geomaterials (GM). Dr. Liu was appointed as Board member of the International Association of Chinese Infrastructure Professionals (IACIP) and member of the Academic Committee of the Key Laboratory of Road Structure and Materials Transportation Industry of the China Ministry of Transport. He is also actively involved in organizing inter/national workshops and conferences and was invited as Scientific/Technical committee member of several international conferences.

iFRAE DELFT 2021 5th International Symposium on Frontiers of Road and Airport Engineering

Workshop: Changes in binder properties and the role of additives

Routes to durability and sustainability: Recycling of PmB containing RAP

Xueyan Liu, Peng Lin, Sandra Erkens
Delft University of Technology, the Netherlands

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1. Introduction- Recycling

- In Europe, 49.44 mt RA available (figures 201
  - 68% reused into new Asphalt mixture,
  - 19% recycled as granular materials in unbound layers
- In China, 117 mt RA available
- In the US, 91.7 mt RA available
- In Janpan, 37 mt RA available

1. Introduction- Recycling

- Sustainability,
  - Reduction of CO_2 emission, 80% by 2050 (1990 baseline)
- Circular economy*,
  - Dec 2015 action plan → implemented in March 2019
  - Avoid, Reduce, Reuse, Recycle, Treat, Disposealong the whole life cycle of products
- Green Product Procurement**,
  - Integrating circular economy requirements
  - 2016, criteria for road design, construction and maintenance

*http://ec.europa.eu/environment/circular-economy/index_en.htm
** http://ec.europa.eu/environment/gpp/pdf/report_gpp_office_buildings.pdf

European Vision

1. Introduction- Recycling

Asphalt Recycling in the Netherlands

- 71% of the RAP is used in HMA and WMA recycling
- 11% of the RAP is used in Cold recycling
- 18% RAP is used in other applications.

New goals In the Netherlands

- 50% CO_2 and raw material reduction in 2030
- Be circular (no waste, no use of raw materials) in 2050

1. Introduction- Marketing

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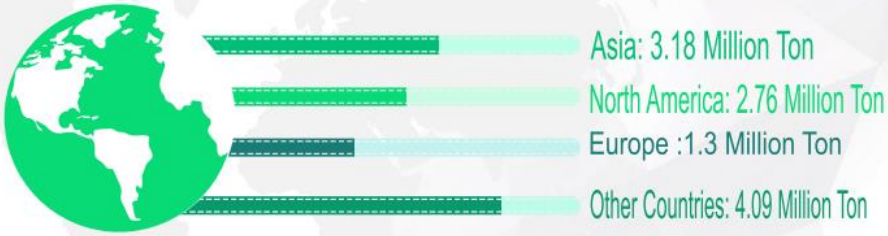
PMB Market Distribution

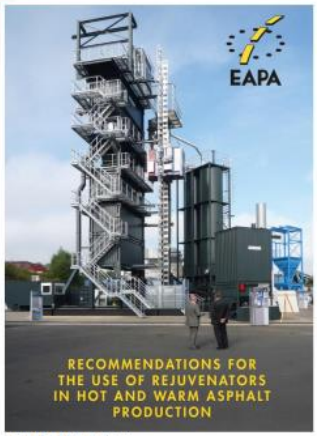


PMB in Global Market

More than 80% of PMB was used in pavement construction.

Global Polymer Modified Bitumen Market Professional Survey Report 2018

1. Introduction- Challenge



EAPA Workshop
Use of rejuvenators in asphalt mixtures
Padova (Italy), 10th - 11th September 2019

1. INTRODUCTION

Now

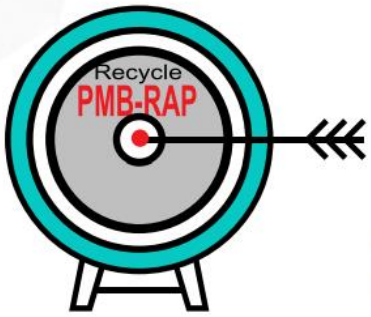
The reuse of RAP with standard bituminous binders up to 50 % addition rates is
successfully achieved.

Challenges

Over recent years more PMB has been used in asphalt production. However, 'standard technology ' may not be adequate for recycling such kind of RAP.

additives restore the rheological behaviour of the aged binder from reclaimed asphalt when blent with the (pre-heated) reclaimed asphalt. Rejuvenators also can avoid the need of using a soft paving grade bitumen to meet the require-ments.

1. Introduction- Goal



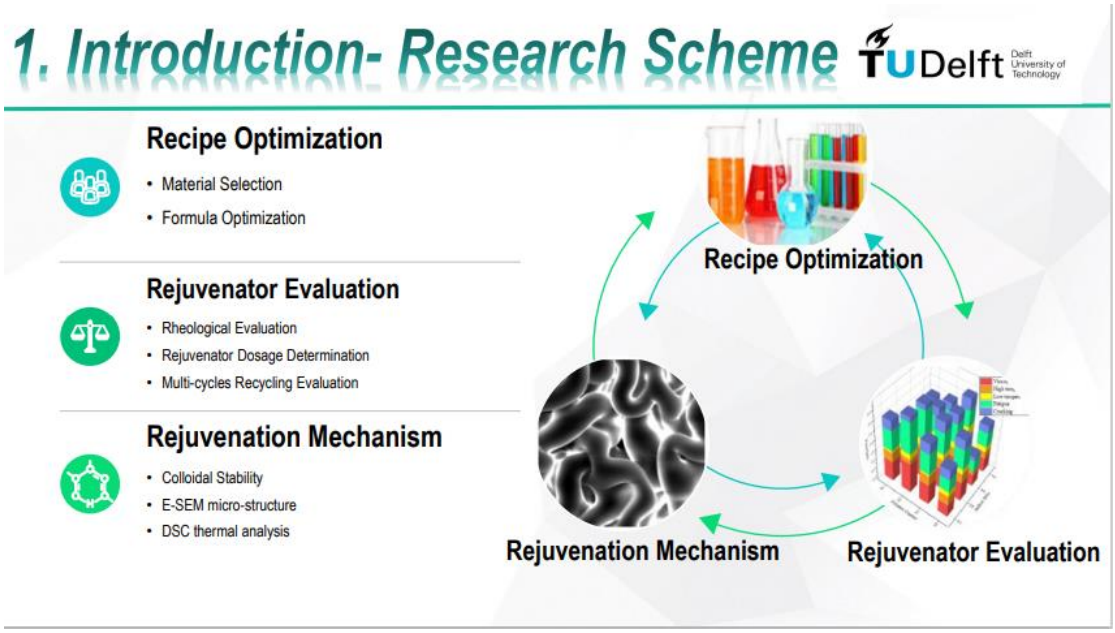
High –quality Recycling of PMB-RAP

Improve Quality

- **Activate** the **aged PMB in** the RAP
- **Fully use** the remaining polymer
- **Longer service life** of pavement

Increase Profit

- **Increase** the **PMB-RAP content**
- **Societal benefits**
- **Decrease the release of CO_2**


1. Introduction- Research Scheme
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Recipe Optimization
• Material Selection
• Formula Optimization
Rejuvenator Evaluation
• Rheological Evaluation
• Rejuvenator Dosage Determination
• Multi-cycles Recycling Evaluation
Rejuvenation Mechanism
• Colloidal Stability
• E-SEM micro-structure
• DSC thermal analysis
Recipe Optimization
Rejuvenation Mechanism
Rejuvenator Evaluation


02
Recipe Optimization

2.1 Recipe Optimization

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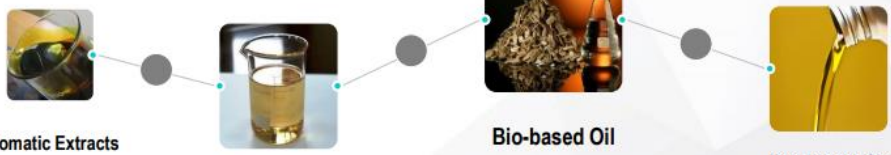
History of Rejuvenator Development



Aromatic Extracts

Advantage:
- Increase the RAP content.
- Standardization

Disadvantage:
- High viscosity
- Environmental and Health Problem

Aromatic + Paraffinic Oil

Advantage:
- Low viscosity

Disadvantage:
- Environmental Problem

Bio-based Oil

Advantage:
- Low viscosity
- Lower dosage
- Environmentally friendly

Disadvantage:
- Viscoelasticity

Rejuvenator for PMB

?

2.1 Recipe Optimization

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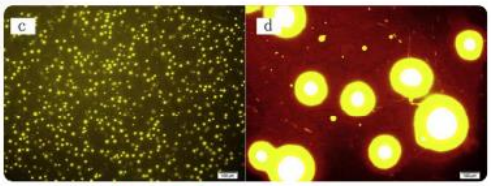
Complexity of aging mechanism in PMB



Degradation of polymer

Oxidation of Bitumen

SBS absorbs aromatics

Polymer will degrade into small molecular

Decrease of aromatics

Increase of asphaltenes

2.1 Recipe Optimization

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Challenges in rejuvenation of PMB

1. Hardening due to the oxidation of base bitumen
2. Property loss due to the degradation of polymer
3. Colloidal stability loss in the recycled PMB

2.1 Recipe Optimization

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Procedure of recipe optimization

Materials Selection

Determination of component ratio in rejuvenator

Mechanical property characterization


Material Selection
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EBA-based Rejuvenator
A
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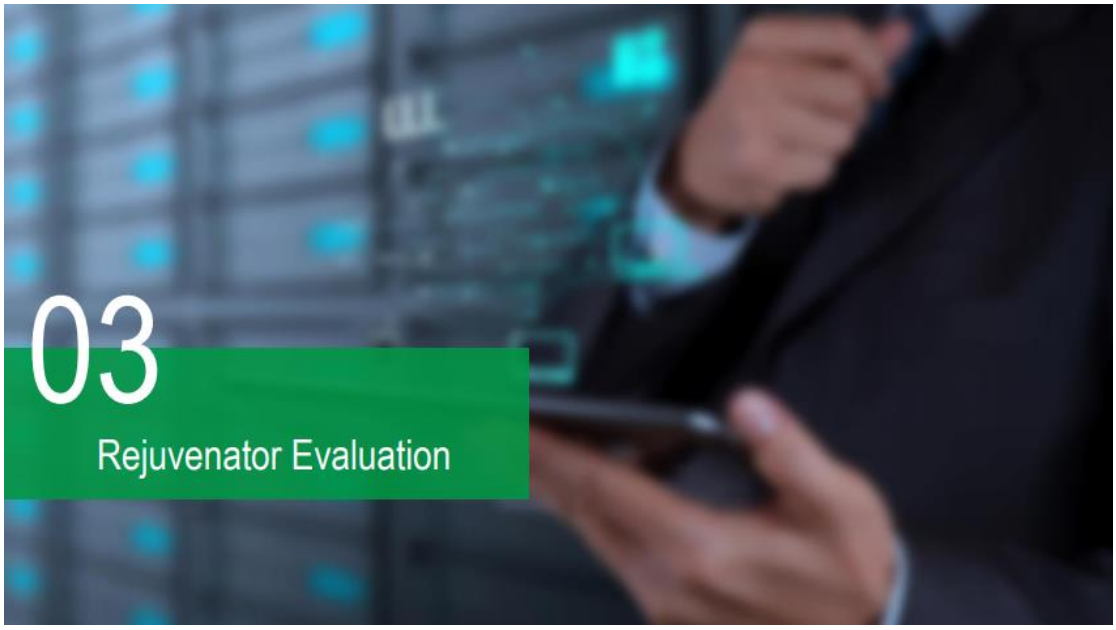
SBS-based Rejuvenator
B
TU Delft
Terminal blend (TB)-based Rejuvenator
C
TU Delft
TB/SBS-based Rejuvenator
D
Bio-based Rejuvenator
Rich in Saturates
E
Aromatic-based Rejuvenator
Rich in Aromatics
F


03
Rejuvenator Evaluation

Research Scheme

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Recipe Optimization

- Material Selection
- Formula Optimization

Rejuvenator Evaluation

- Rheological Evaluation
- Rejuvenator Dosage Determination
- Multi-cycles Recycling Evaluation

Rejuvenation Mechanism

- Colloidal Stability
- E-SEM micro-structure
- DSC thermal analysis

3. Rejuvenator Evaluation- Rheological Property

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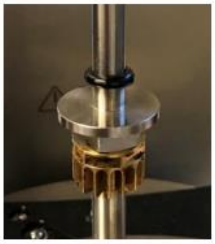

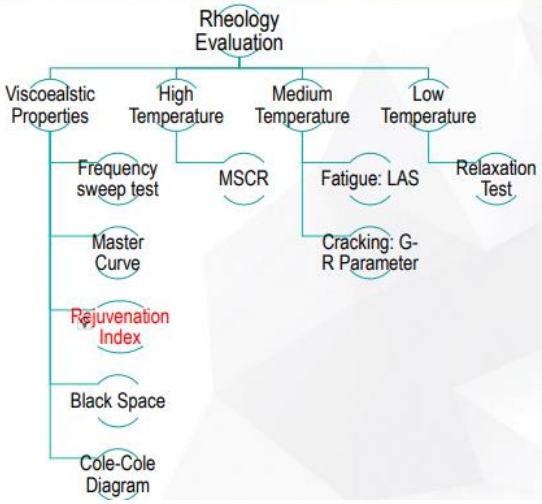

3. Rejuvenator Evaluation- Rheological Property

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Rejuvenation Indexes

$$A_{MH} = \int_{0}^{4} \log G^*(\xi) d\xi$$

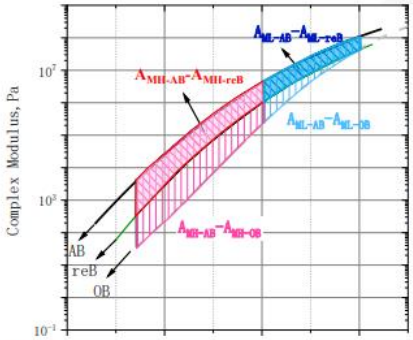
$$A_{ML} = \int_{-5}^{0} \log G^*(\xi) d\xi$$

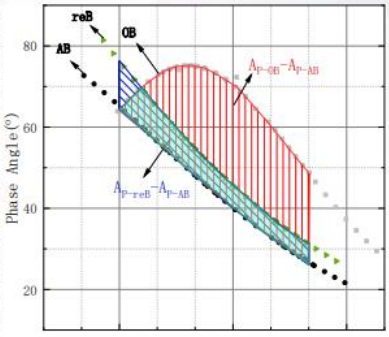
$$A_P = \int_{-5}^{4} \delta(\xi) d\xi$$

$$I_{MH} = \frac{A_{MH-AB} - A_{MH-reB}}{A_{MH-AB} - A_{MH-OB}} \times 100\%$$

$$I_{ML} = \frac{A_{ML-AB} - A_{ML-reB}}{A_{ML-AB} - A_{ML-OB}} \times 100\%$$

$$I_P = \frac{A_{P-reB} - A_{P-AB}}{A_{P-OB} - A_{P-AB}} \times 100\%$$





Indexes were defined as the ratio of the integral area difference of G* & δ between aged and rejuvenated bitumen in the selected frequency ra

3. Rejuvenator Evaluation- Rheological Property

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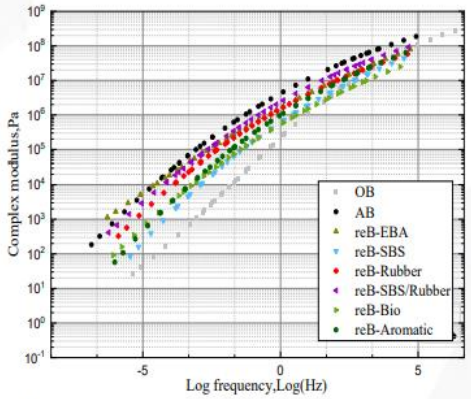
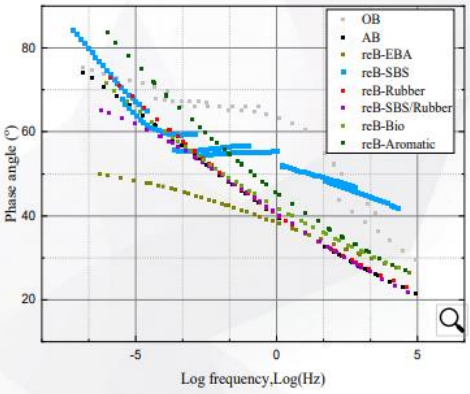
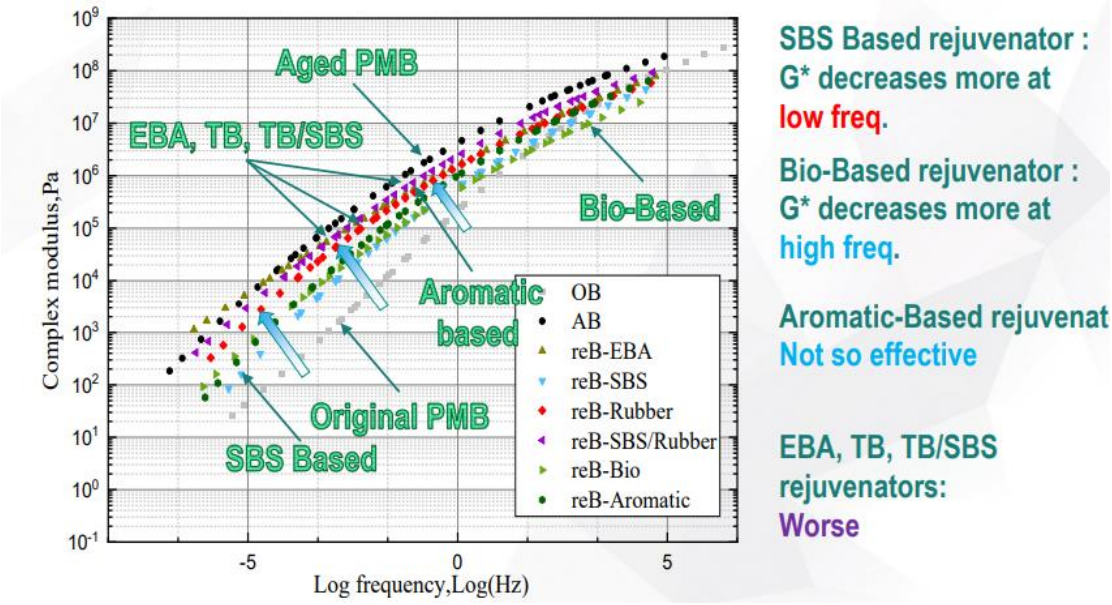
Viscoelastic-Master Curves





DSR frequency sweep tests between 0.01 and 10 Hz were performed at 0, 20, 30, 40, 60 and 80ºC
the reference temperature is 30 ºC.

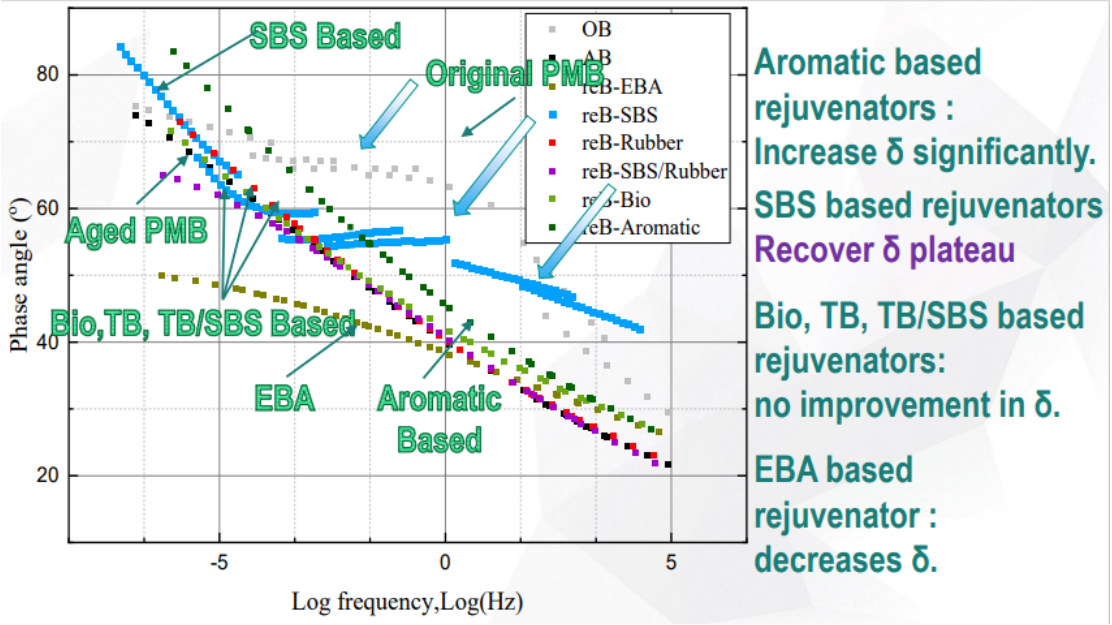


SBS Based rejuvenator : G* decreases more at low freq.

Bio-Based rejuvenator : G* decreases more at high freq.

Aromatic-Based rejuvenat Not so effective

EBA, TB, TB/SBS rejuvenators: Worse



Aromatic based rejuvenators : Increase δ significantly.

SBS based rejuvenators Recover δ plateau

Bio, TB, TB/SBS based rejuvenators: no improvement in δ.

EBA based rejuvenator : decreases δ.

3. Rejuvenator Evaluation- Rheological Property

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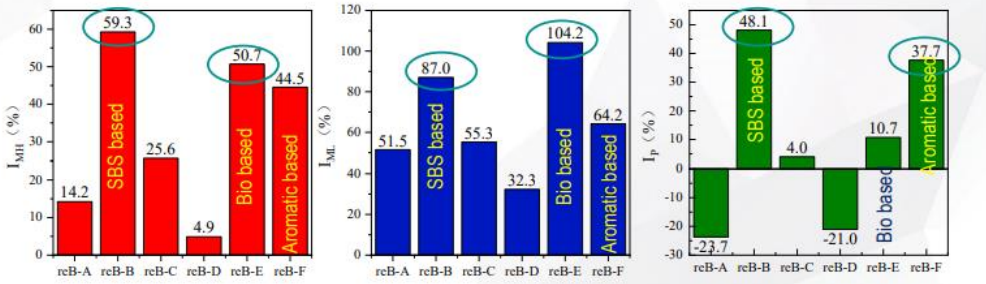
Rejuvenation Index



$$I_{MH} = \frac{A_{MH-AB} - A_{MH-reB}}{A_{MH-AB} - A_{MH-OB}} \times 100\% \qquad I_{ML} = \frac{A_{ML-AB} - A_{ML-reB}}{A_{ML-AB} - A_{ML-OB}} \times 100\% \qquad I_P = \frac{A_{P-reB} - A_{P-AB}}{A_{P-OB} - A_{P-AB}} \times 100\%$$

3. Rejuvenator Evaluation- Rheological Property

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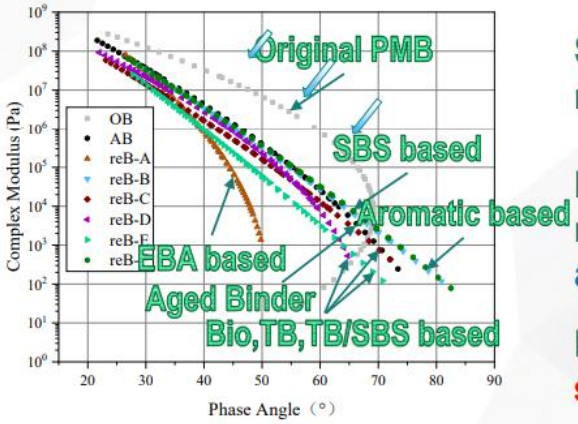
Viscoelastic-Black Space



Influence on viscoelastic property:

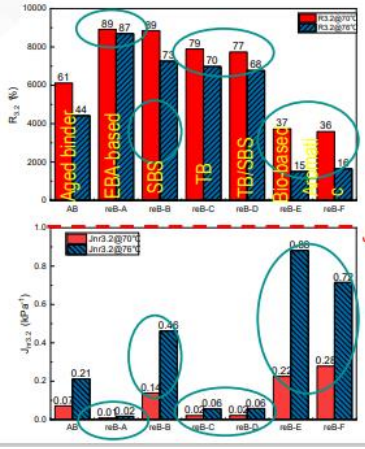
SBS and Aromatic based rejuvenators have positive effect

Bio, TB and TB/SBS based rejuvenators have a certain adverse effect

EBA based rejuvenator has significant adverse effect

3. Rejuvenator Evaluation- Rheological Property

igh Temperature Properties

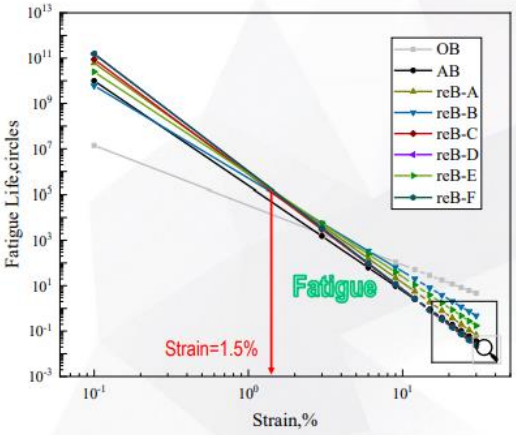


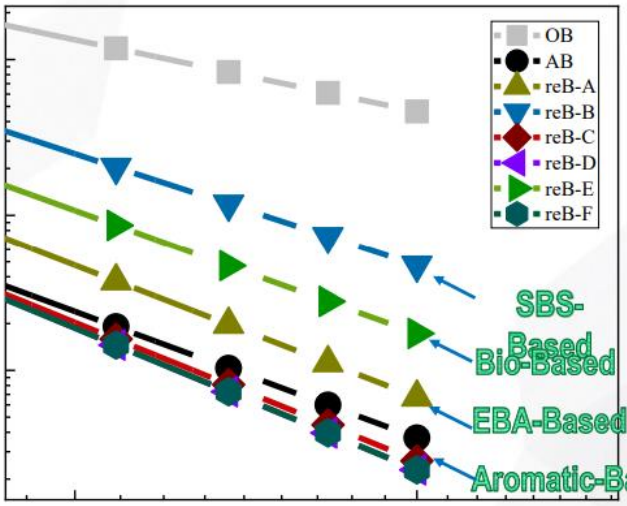
- EBA, TB, TB/SBS based rejuvenators have advantages in MSCR results.
- SBS based rejuvenator shows better strain recovery capacity compared with the reference rejuvenators.
- $J_{nr3.2}$ values of all binders at 76℃ are much lower than the maximum allowable value (2 kPa^{-1}) for the 'H' traffic level.

3. Rejuvenator Evaluation- Rheological Property

edium Temperature-Fatigue

LAS Test @ 10Hz & 20 ℃





Fatigue resistance :

- SBS based > Bio-based > EBA base
- Aromatic, TB, TB/SBS have adverse effect

3. Rejuvenator Evaluation- Rheological Property

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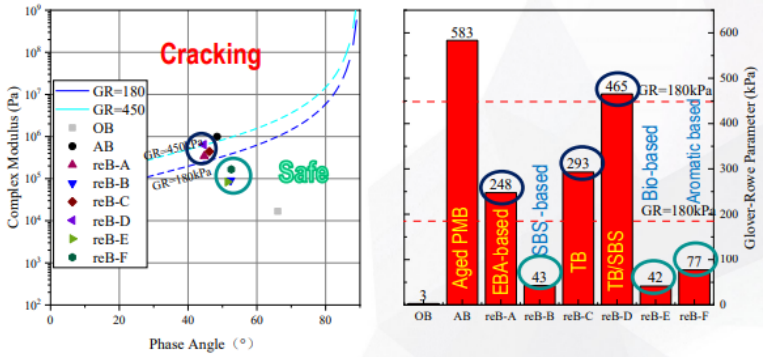
Medium Temperature-Cracking evaluation with G-R parameter



SBS, Bio, Aromatic based rejuvenators significantly improve cracking resistance

3. Rejuvenator Evaluation- Rheological Property

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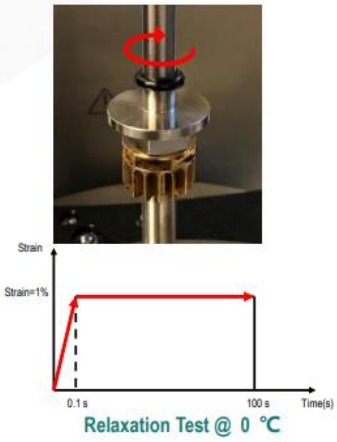
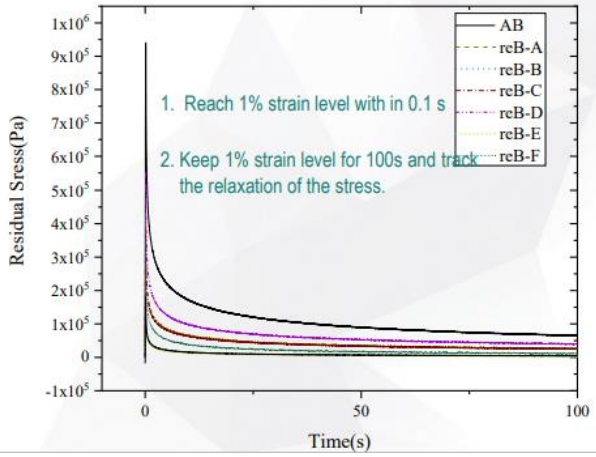
ow Temperature-Relaxation Test





3. Rejuvenator Evaluation- Rheological Property

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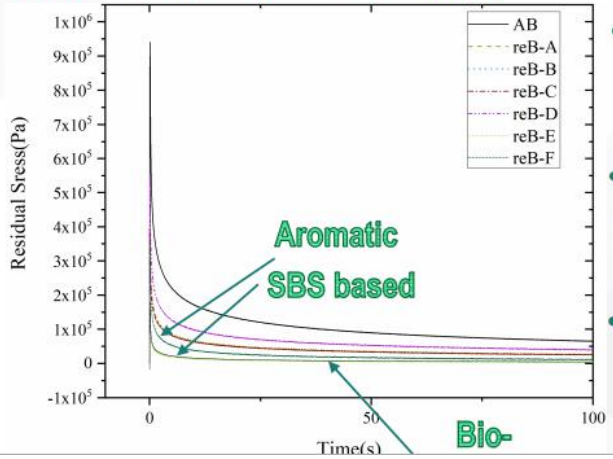
Low Temperature-Cracking



- SBS and Bio-based rejuvenator significantly improve relaxatio
- Aromatic rejuvenator improves stress relaxation to a certain e
- EBA, TB/SBS, TB based rejuven improve it not much

3. Rejuvenator Evaluation- Rheological Property

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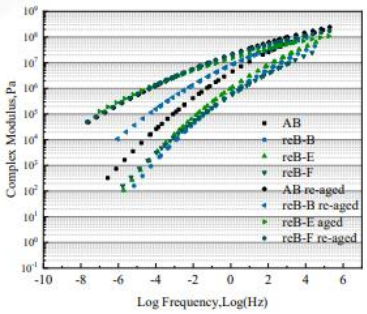
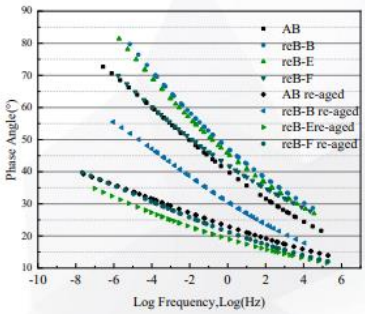
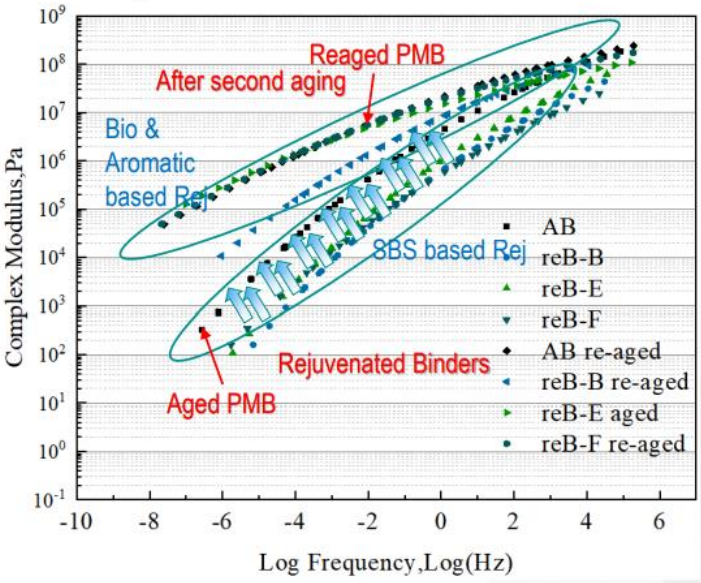
Anti-aging Properties





Xueyan Liu, Peng Lin et.al. "Effect of Rejuvenators on Performance-based Properties of Aged Polymer Modified Bitumen" .*99 th Transportation Research Board*.

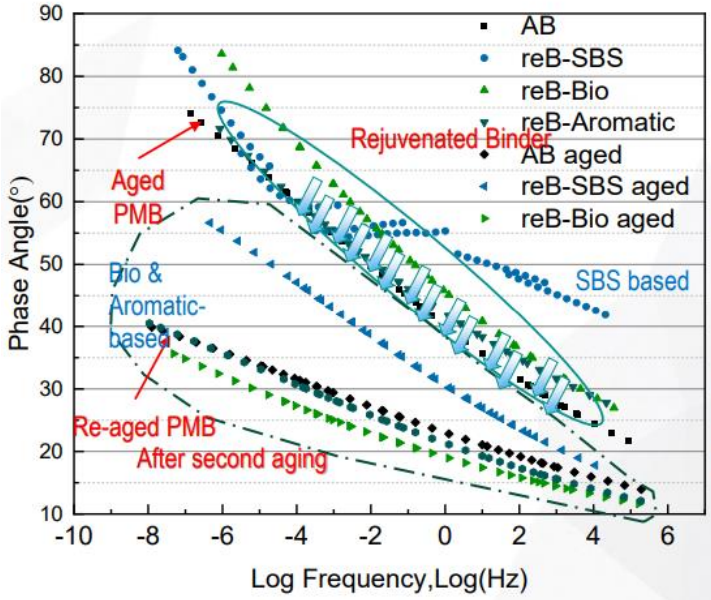


Bio & Aromatic based rejuvenators after second aging:

- **G* values are almost same**
- **Rejuvenation effect disappears**

SBS-based rejuvenator after second aging:

- **Remains rejuvenation effect**



Bio & Aromatic based Rejs after second aging:

- Result in lower δ values
- Rejuvenation effect disappears

SBS-based Rej after second aging:

- Remains rejuvenation eff

3. Rejuvenator Evaluation- Rheological Property

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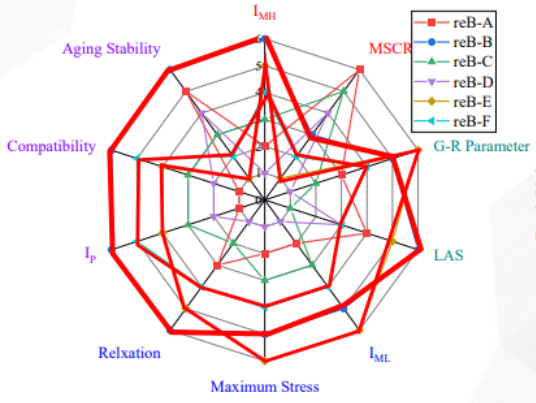
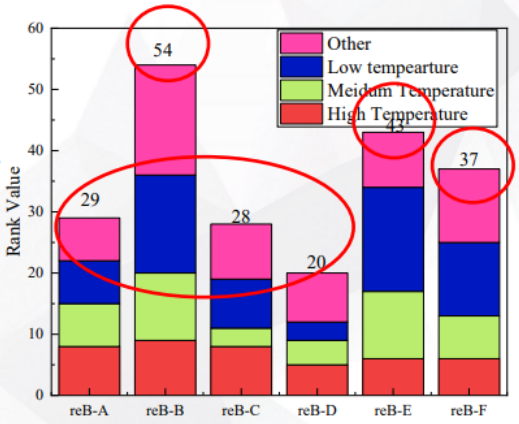
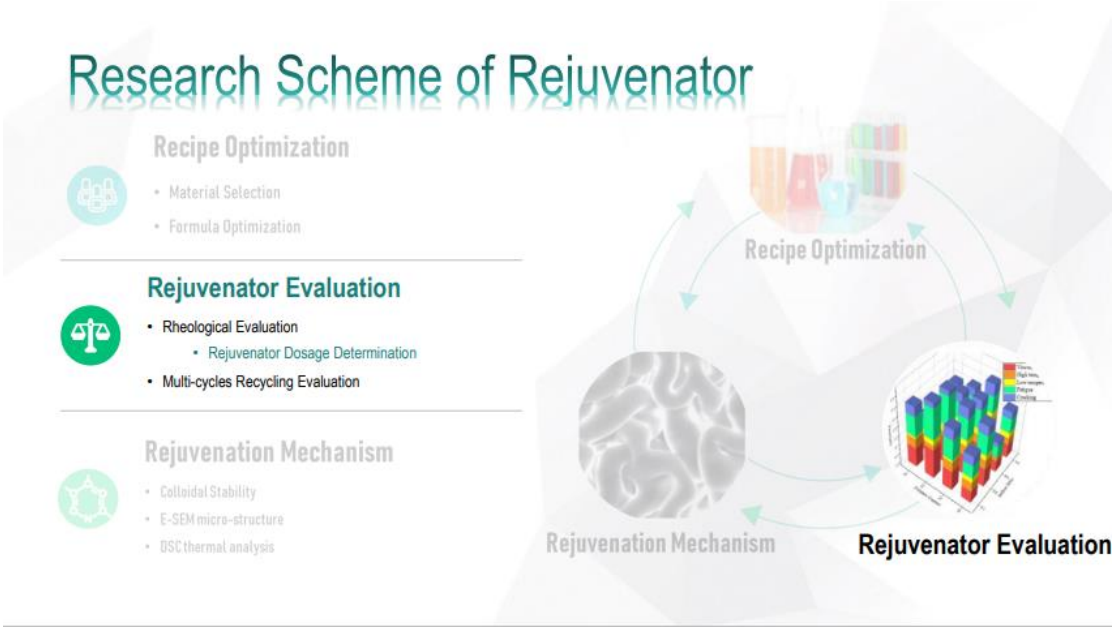
Radar Chart Analysis






Research Scheme of Rejuvenator
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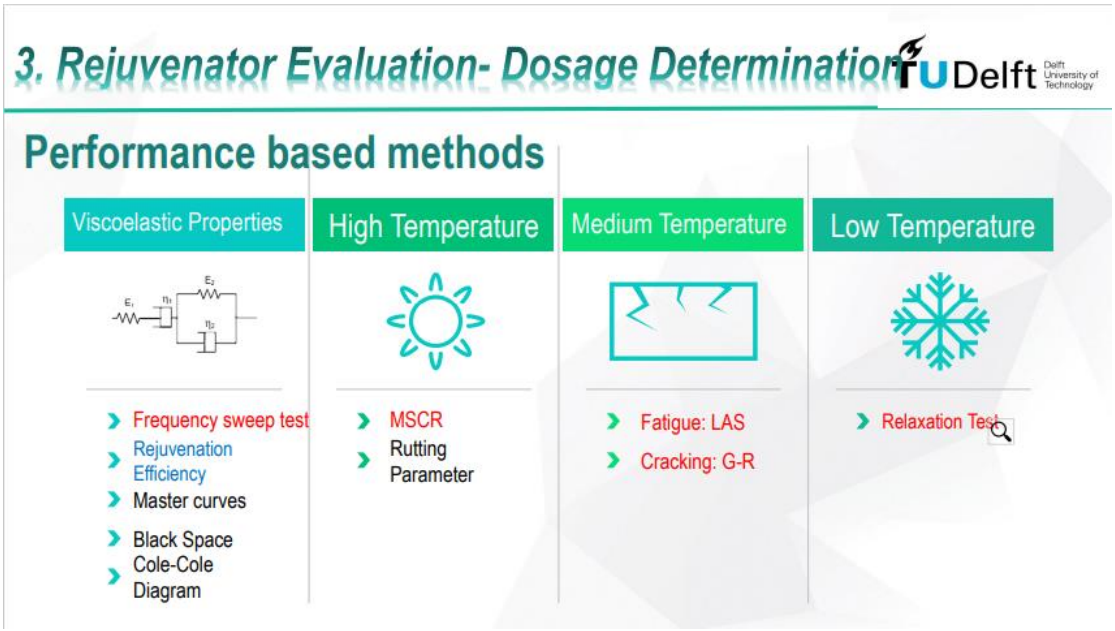
3. Rejuvenator Evaluation- Dosage Determination
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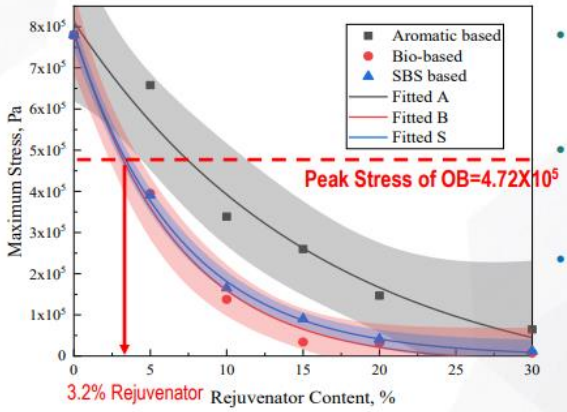
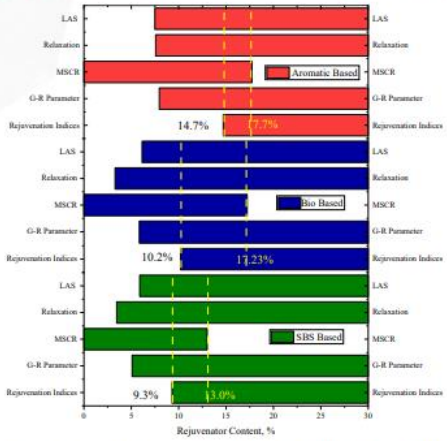
Performance based methods
Viscoelastic Properties
High Temperature
Medium Temperature
Low Temperature
Frequency sweep test
Rejuvenation Efficiency
Master curves
Black Space
Cole-Cole Diagram
MSCR
Rutting Parameter
Fatigue: LAS
Cracking: G-R
Relaxation Test

Low Temperature- Relaxation



- The maximum stress change shows an exponential relationship with rejuvenator dosage,
- SBS and Bio-based rejuvenators are more efficient than Aromatic-based rejuvenator in decreasing maximum stress
- Calculate the minimum rejuvenator dosage based on the peak stress equals to the one occurred in the original fresh binder

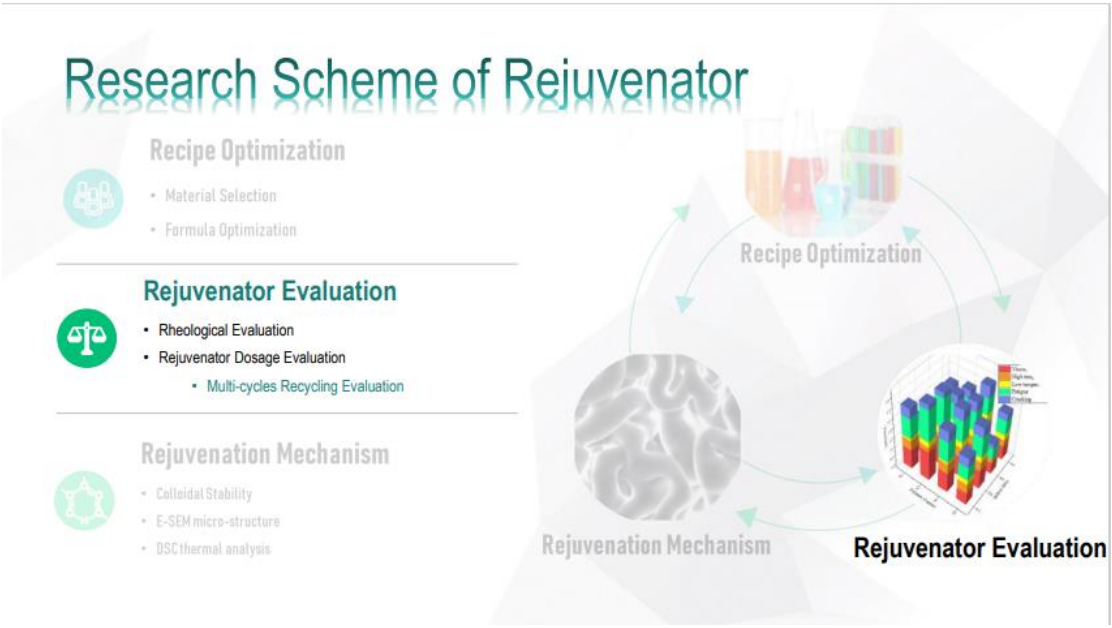
Rejuvenator Dosage Determination



Traditional Methods
(Penetration, Softening point)

Performance Based Methods
(High, Low, Medium performance)

Peng Lin, Xueyan Liu, Panos Apostolidis, Sandra Erkens, Shisong Ren, Shi Xu, Tom Scarpas, and Weidong Huang. "On the Rejuvenator Dosage Optimization for Aged SBS Modified Bitumen." Construction and Building Materials 271 (February 15, 2021): 121913.



3. Rejuvenator Evaluation- Multi-Cycles Recycling

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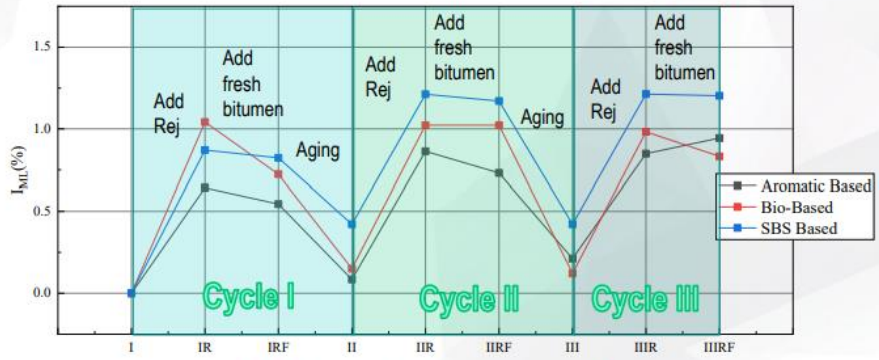
1. Is the rejuvenator still functional?
2. How are the rheological properties influenced?
3. . . . . .

Recycling Cycle I:	Aged Binder(I)	Rejuvenator	Rejuvenated Binder(IR)	Fresh PMB	Recycled Binder(IRF)	
			Aging (RTFOT+80h PAV)			
Recycling Cycle II:	Aged Binder(II)	Rejuvenator	Rejuvenated Binder(IIR)	Fresh PMB	Recycled Binder(IIRF)	
			Aging (RTFOT+80h PAV)			
Recycling Cycle III:	Aged Binder(III)	Rejuvenator	Rejuvenated Binder(IIIR)	Fresh PMB	Recycled Binder(IIIRF)	

3. Rejuvenator Evaluation- Multi-Cycles Recycling



SBS based rejuvenator shows advantage in multi-cycles recycling.

Research Scheme

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Recipe Optimization

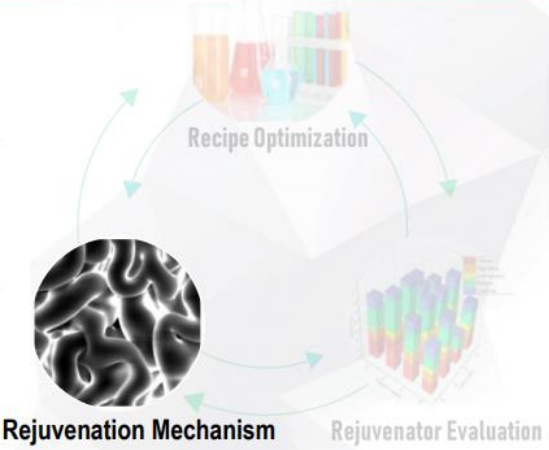
- Material Selection
- Formula Optimization

Rejuvenator Evaluation

- Rheological Evaluation
- Rejuvenator Dosage Evaluation
- Multi-circle Recycling Ability Evaluation

Rejuvenation Mechanism

- Chemical analysis
- E-SEM micro-structure analysis
- DSC thermal analysis



4. Rejuvenation Mechanism

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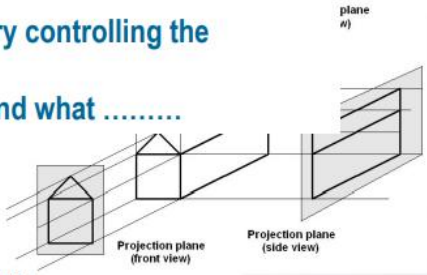
- how is the compatibility of rejuvenator with the aged bitumen?
- how is the chemistry controlling the rheology?
- answer how, why and what .....

FTIR/GPC
Molecular Functional Group

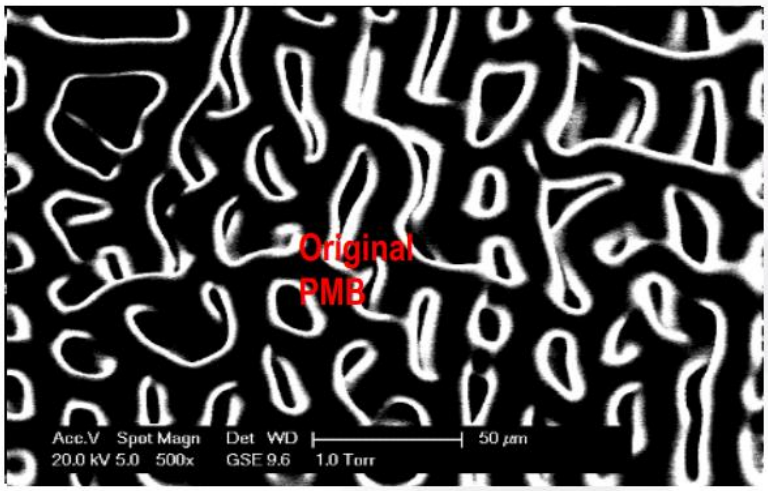


E-SEM
Micro-structure
Compatibility

DSC
Calorimetry
State of Crystallization

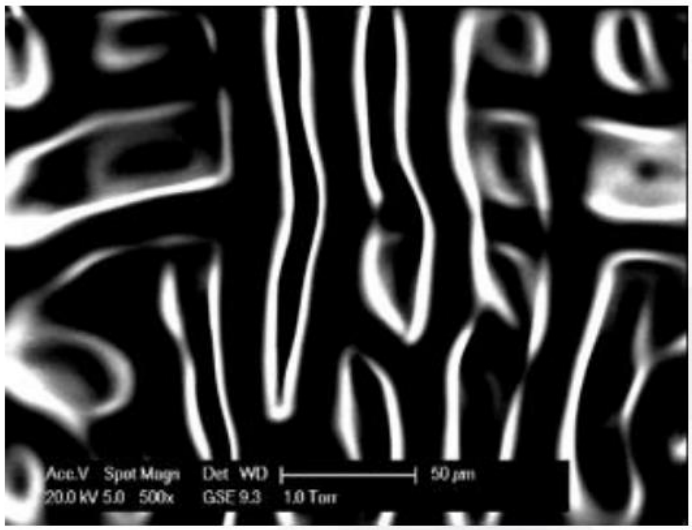
4. Rejuvenation Mechanism

Lin, Peng, X. Liu, P. Apostolidis, S. Erkens, Y. Zhang, and S. Ren. "ESEM Observation and Rheological Analysis of Rejuvenated SBS Modified Bitumen." Materials & Design 204 (June 1, 2021): 109639.



"Worm shape" etching pattern can be observed.

4. Rejuvenation Mechanism



Rejuvenator types influence the morphology of aged PMB

4. Rejuvenation Mechanism

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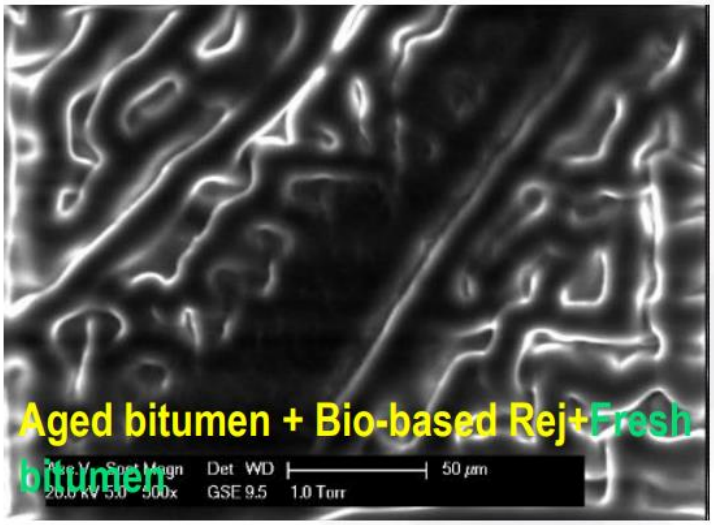
The higher rejuvenator content results in worm structure

4. Rejuvenation Mechanism



4. Rejuvenation Mechanisi

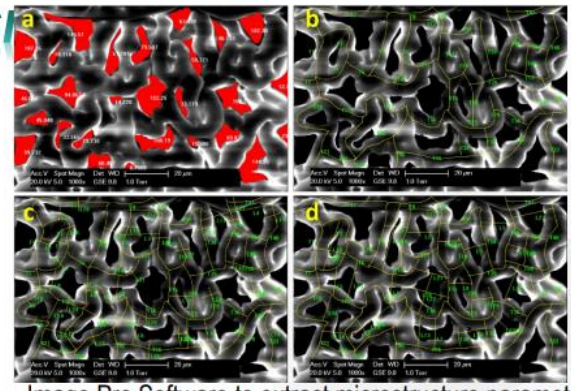


Image Pro Software to extract microstructure parameters:
(a: area coverage; b: length; c: diameter; d: distance…)

Lin, Peng, X. Liu, P. Apostolidis, S. Erkens, Y. Zhang, and S. Ren. "ESEM Observation and Rheological Analysis of Rejuvenated SBS Modified Bitumen." Materials & Design 204 (June 1, 2021): 109639.

Conclusions

- Recipe Optimization
  - Recipe optimization should consider material selection, component ratio determination and functional property balanced at different temperature conditions.
  - SBS-based rejuvenator is one of the most effective rejuvenators for the aged PMB binders.
  - SBS based rejuvenator shows advantages in multi-cycles recycling capability.
  - Bio-based rejuvenator shows advantage in reducing G* at low temperature, but drawbacks in aging resistance and viscoelastic property.
  - Aromatic based rejuvenator shows advantage in viscoelastic property, but drawback
  - in other properties.
  - EBA, TB, TB/SBS rejuvenators show advantage in high-temp property, but drawback in other properties.

Conclusions

- Evaluation methods
  - A series of performance-based experimental methods are selected for evaluation of rejuvenator effectiveness, dosage and multi-cycle recycling capability.
  - Dosage can be determined with performance-based method instead of traditional methods.
  - MSCR and rejuvenation index evaluation are sufficient to determine the rejuvenator dosage.
  - Multi-cycles recycling capability evaluation is important for determination of effectiveness of rejuvenators.

Conclusions

- Rejuvenation Mechanism
  - Fully understanding the rejuvenation mechanism is extremely important for rejuvenator recipe optimization and effective evaluation methods development.
  - E-SEM is a useful tool for rejuvenation mechanism study, as it can detect the morphology structures of the rejuvenated bitumen.
  - Morphology of rejuvenated PMB is influenced not only by the aging degree, rejuvenator dosage/types, but also the addition of the fresh PMB.
  - There is a close link between the chemical composition, rheological property and morphology structure in E-SEM.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Workshop: Changes in binder properties and the role of additives
Thank you !
TUDelft