INSTYTUT BADAWCZY DRÓG I MOSTÓW
ROAD AND BRIDGE RESEARCH INSTITUTE
1955 - 2025

Warsaw, 22 - 23 October 2025

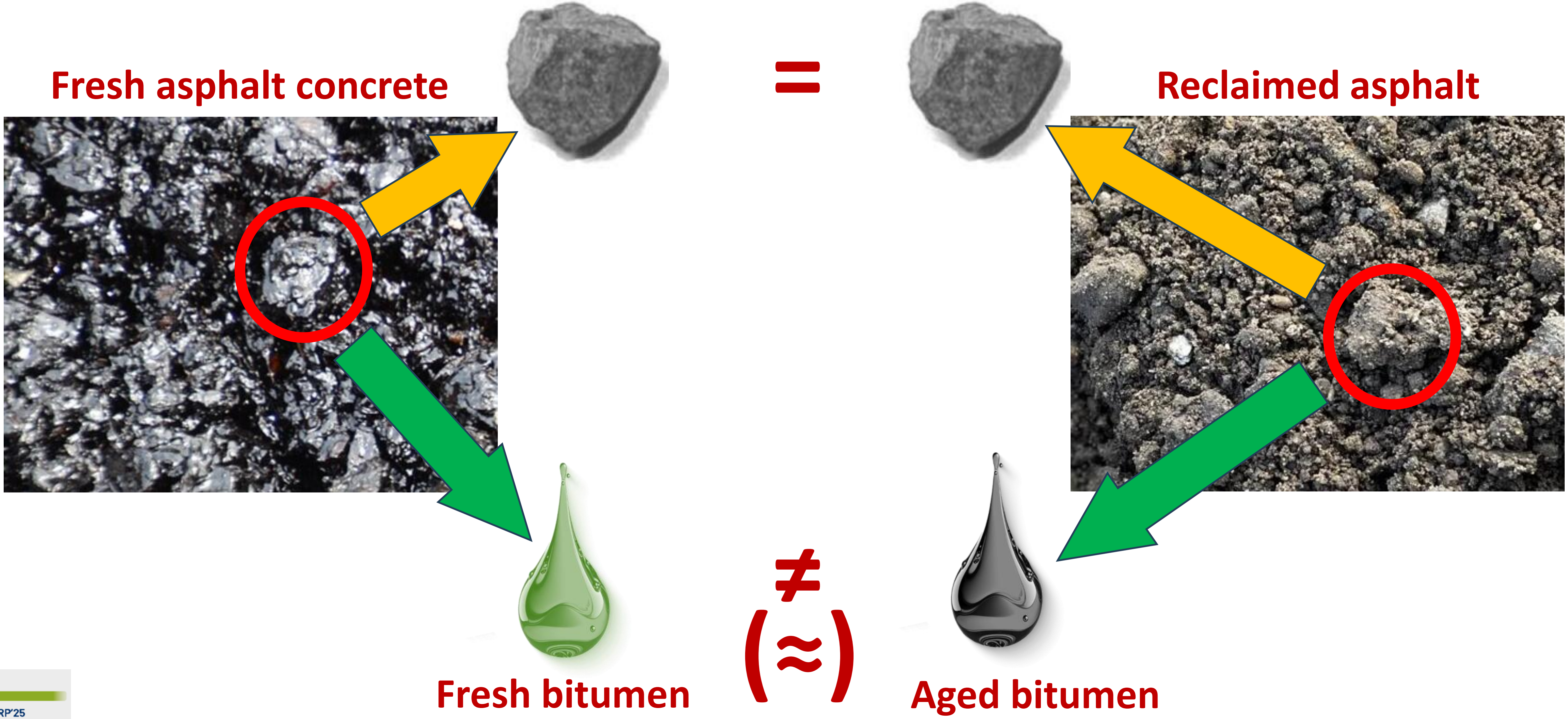
II MIĘDZYNARODOWA KONFERENCJA
Nowoczesne nawierzchnie drogowe – recykling i dekarbonizacja

II INTERNATIONAL CONFERENCE
Modern road pavements - recycling and decarbonization

# Recycling of Reclaimed Asphalt
# Basic Concepts and new perspectives

*Gabriele Tebaldi, PhD, PE, AAPT Fellow, Rilem Fellow*

# Asphalt Recycling



# Asphalt Recycling

## Hot recycling

Aggregates

+

Still available + activable bitumen

**Key Concept**

**Use “old bitumen” and “old aggregates” instead of new ones**

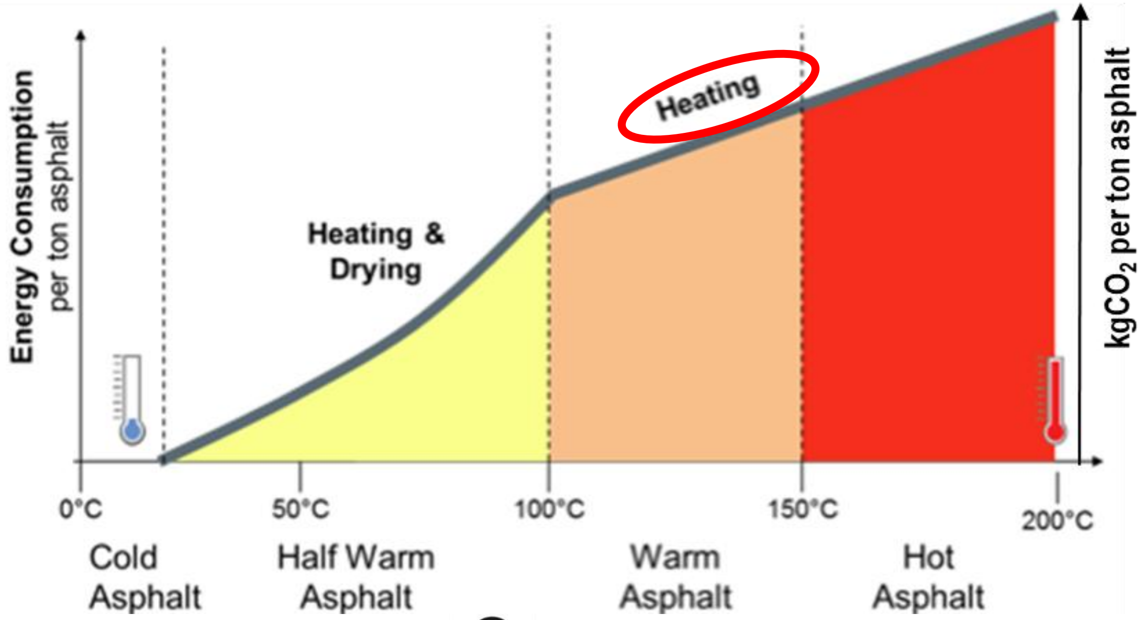
## Cold recycling

“≈ Black rock”

**Key Concept**

**Use RAP almost like aggregates without heating**

# Asphalt Recycling

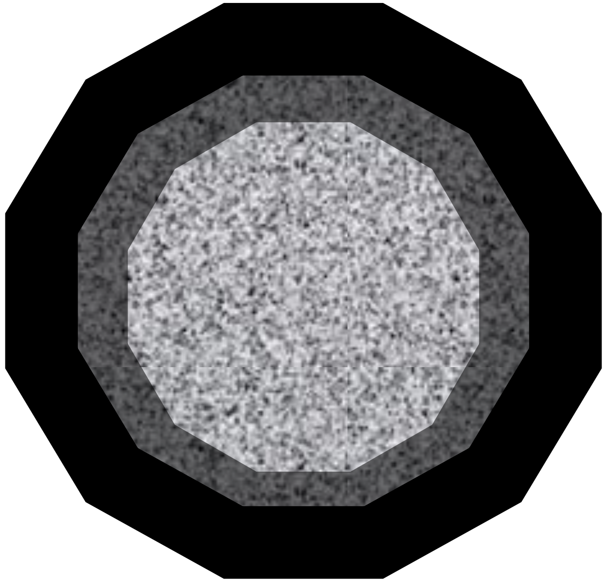



## Hot recycling

Heating the bitumen reduces its viscosity, allowing it to coat the hot aggregates and provide the lubrication necessary for compaction.

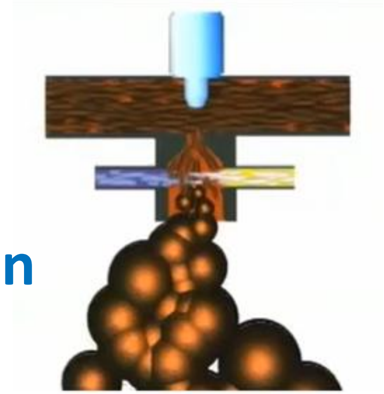
## Cold recycling

In cold recycling techniques, there is no aggregate heating and it's not possible to count on the fluid behavior of the bitumen; therefore, a carrier for the bitumen and a lubricant are needed.



# Cold Asphalt Recycling

+ Carrier



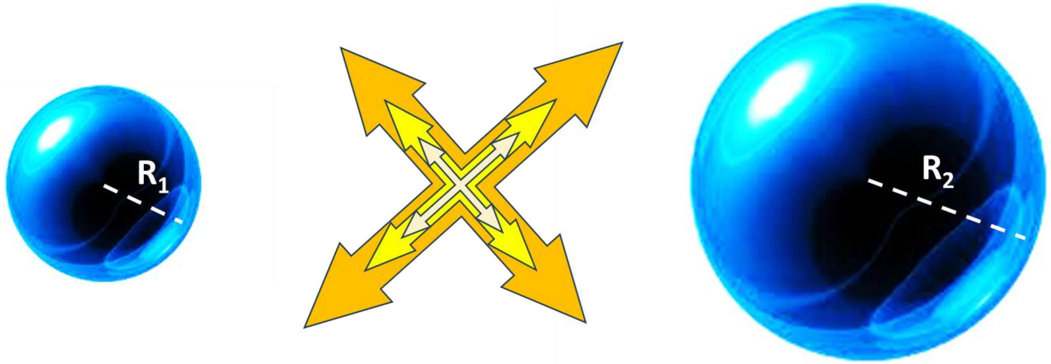

**Foam asphalt**
**The carrier of the bitumen are dust and active filler**

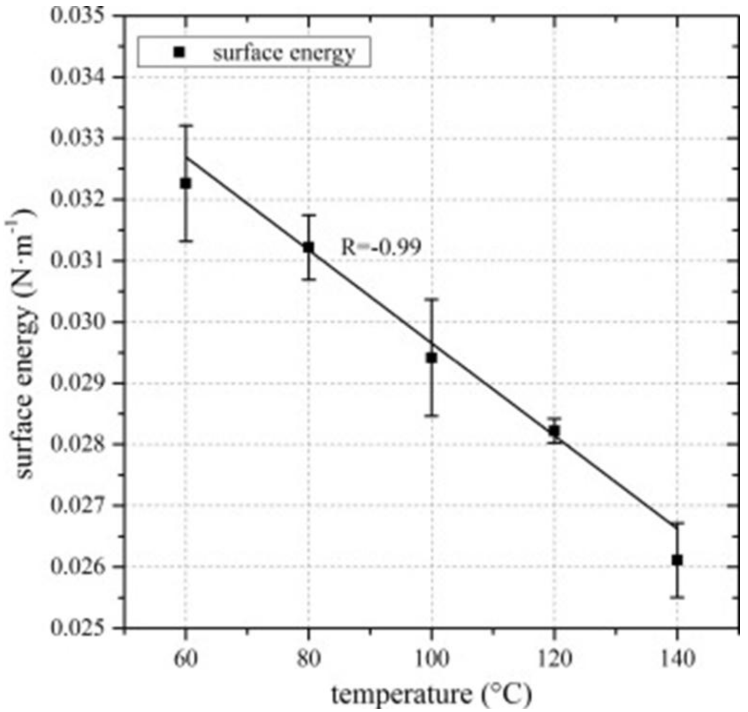
**Bituminous emulsion**
**the carrier of the bitumen is the water**

# Foam bitumen

Surface energy, a fundamental intrinsic property of materials, is defined as the amount of work done to increase a unit surface area of a substance, or the potential energy per unit area of molecules on the substance's surface over molecules inside

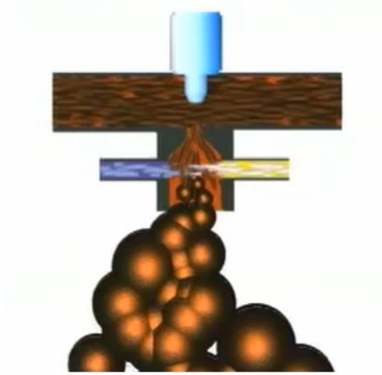
Bitumen surface energy decreases with increasing temperature. This is because at higher temperatures, the intermolecular forces within the bitumen weaken, leading to a reduction in the energy required to create or disrupt the surface.

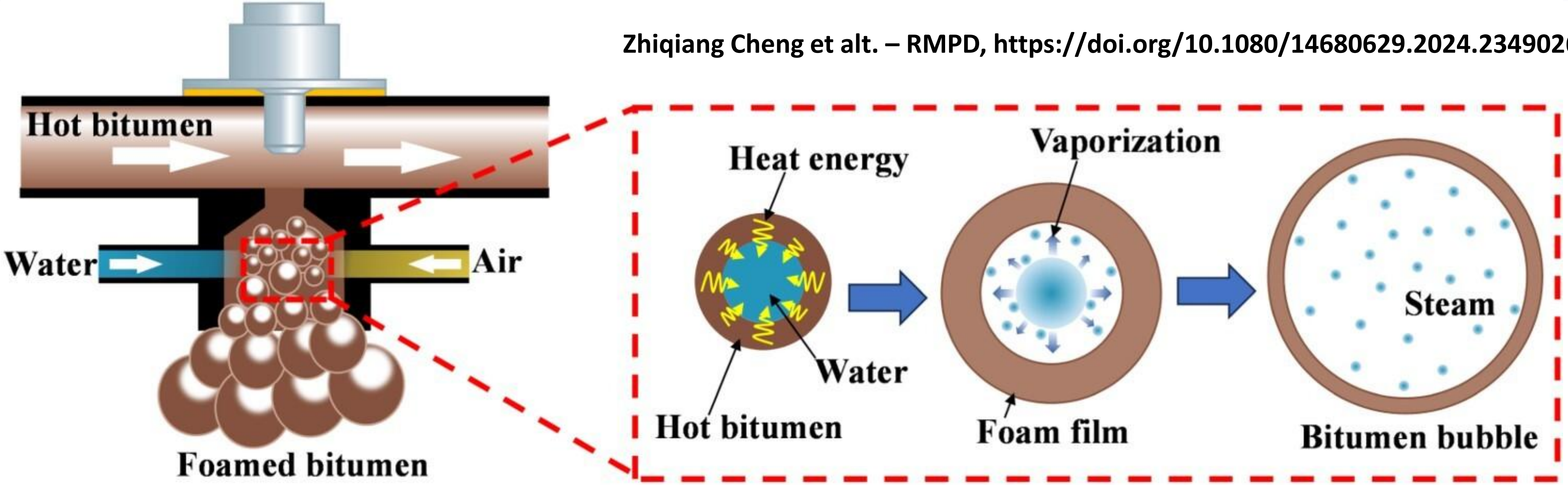


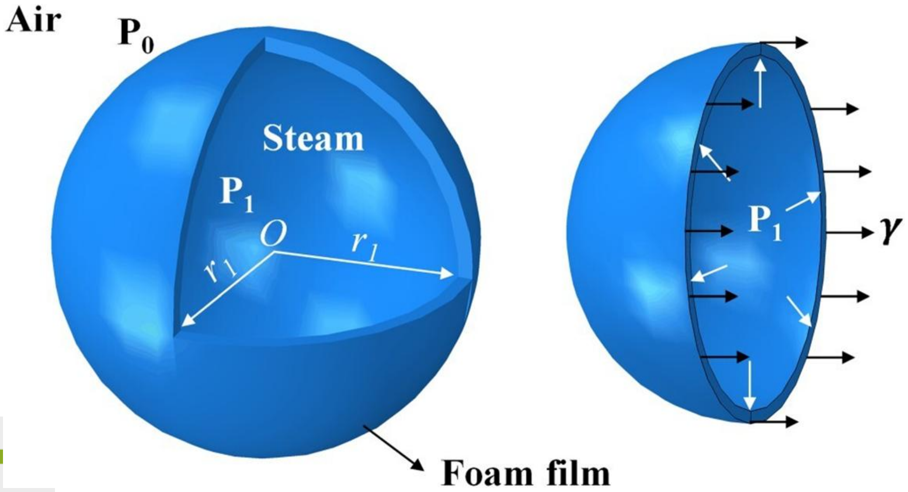

D. Grosseggeret alt. https://doi.org/10.1016/j.applthermaleng.2019.04.034

# Foam Bitumen



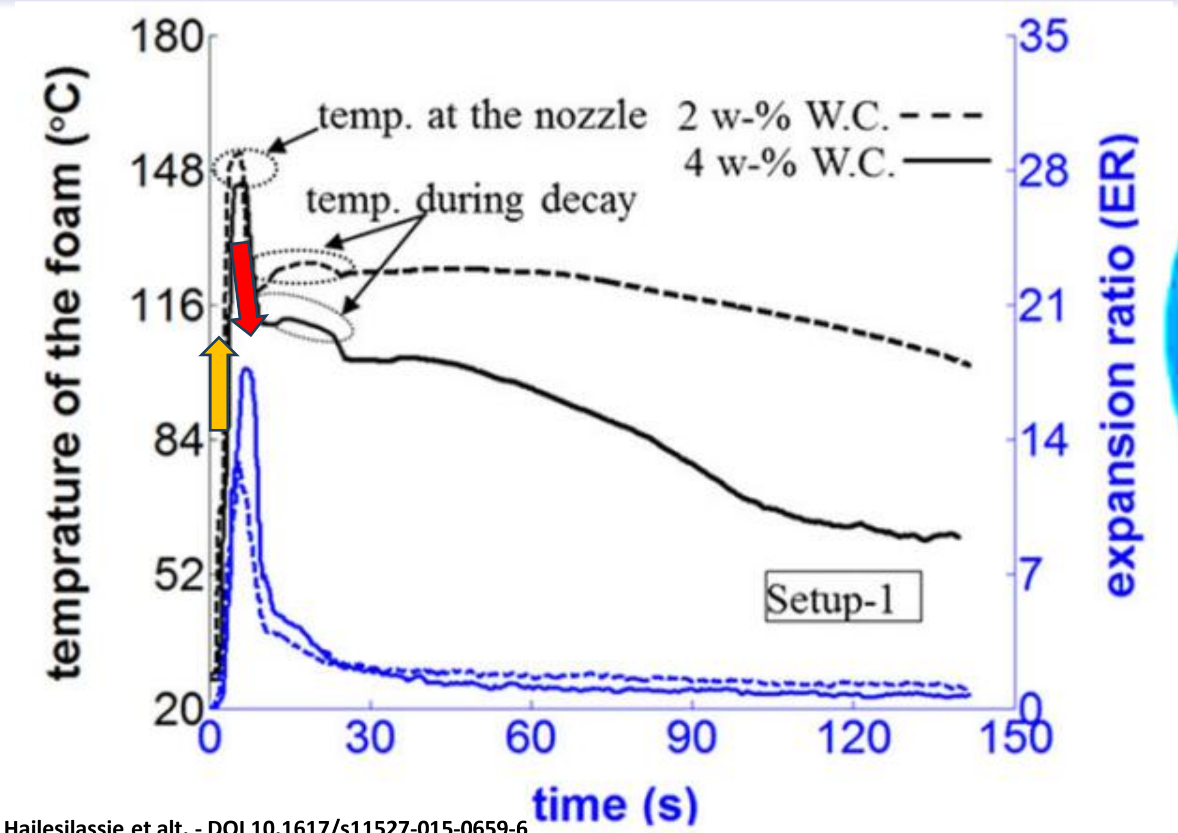



Zhiqiang Cheng et alt. – RMPD, https://doi.org/10.1080/14680629.2024.2349026

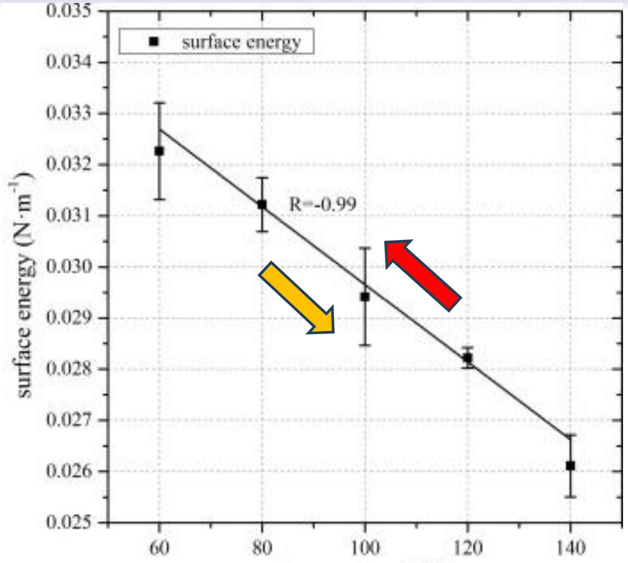


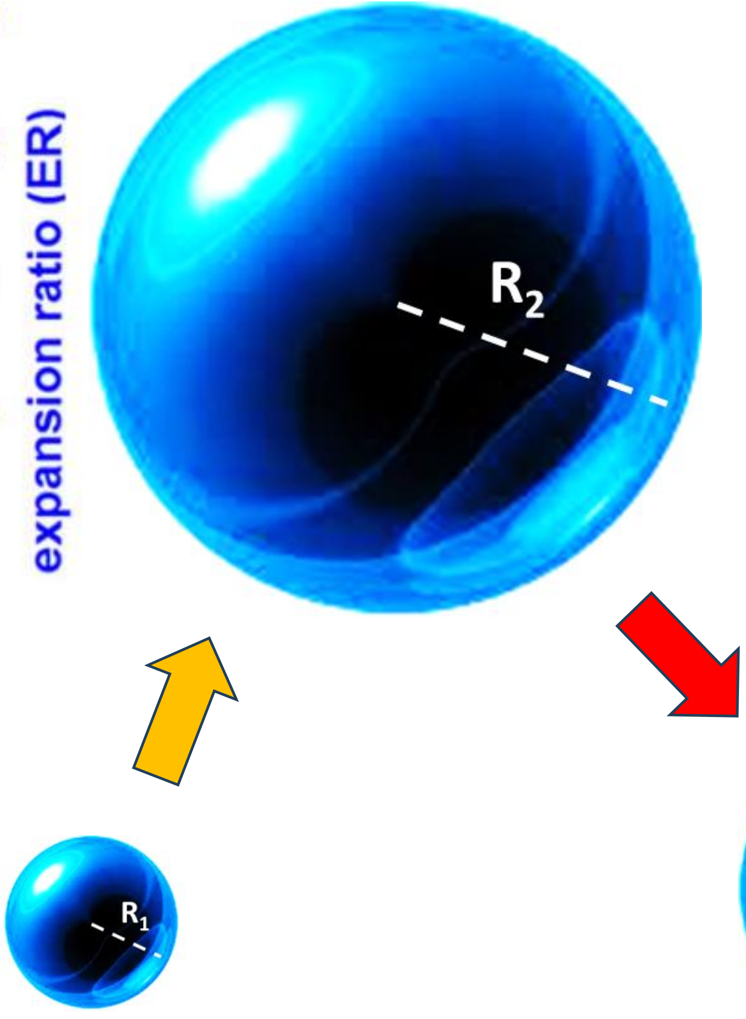

**The evolving steam volume and pressure adhere to the ideal-gas law. Thus, as the bubble expands, its internal pressure reduces until equilibrium between internal and external pressure is achieved.**

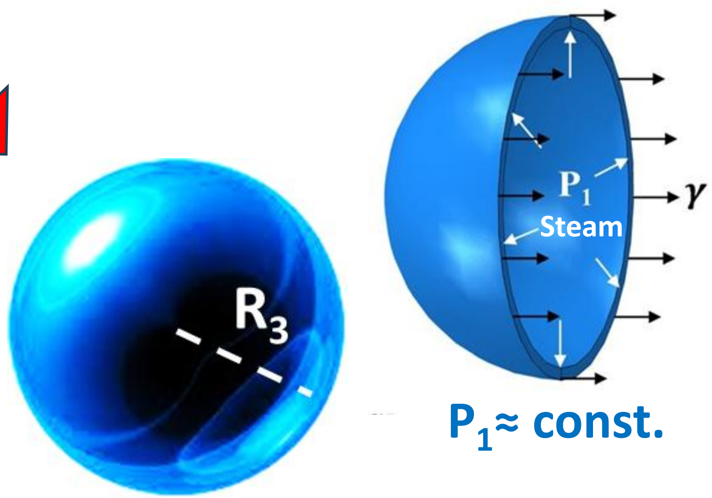
# Foam Bitumen




Hailesilassie et alt. - DOI 10.1617/s11527-015-0659-6



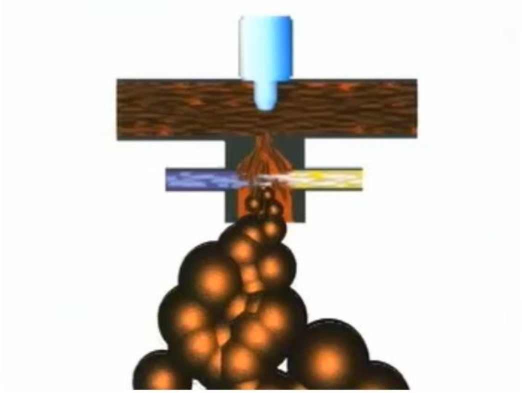



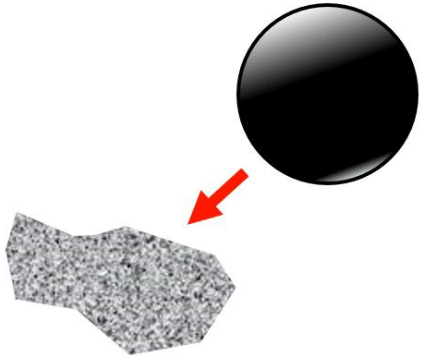

$P_1 \approx$ const.

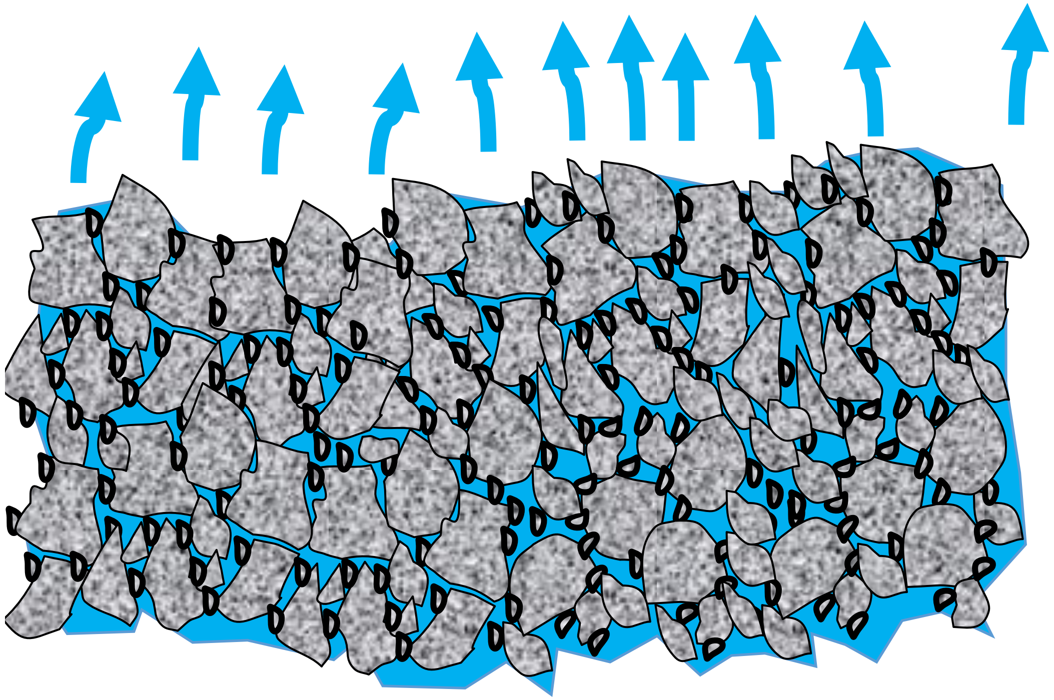
# Foam Bitumen

**The fine particles that catch the bitumen droplets are the elements that partially bind the aggregates among them**



**The blasting and the dust particles are the carriers of bitumen**

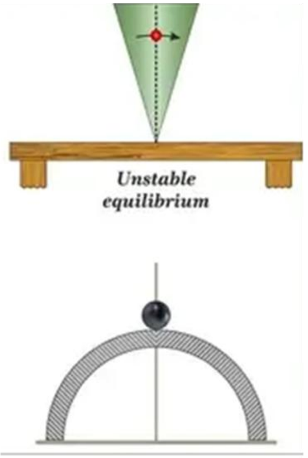




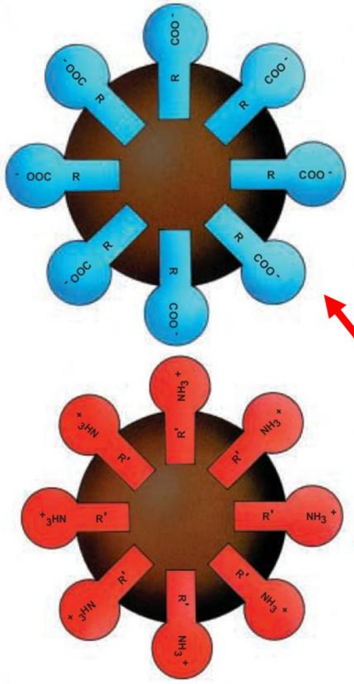
**The total water content (foaming water + additional water) provides the lubricant effect before leaving during the curing phase**

# Bituminous Emulsion

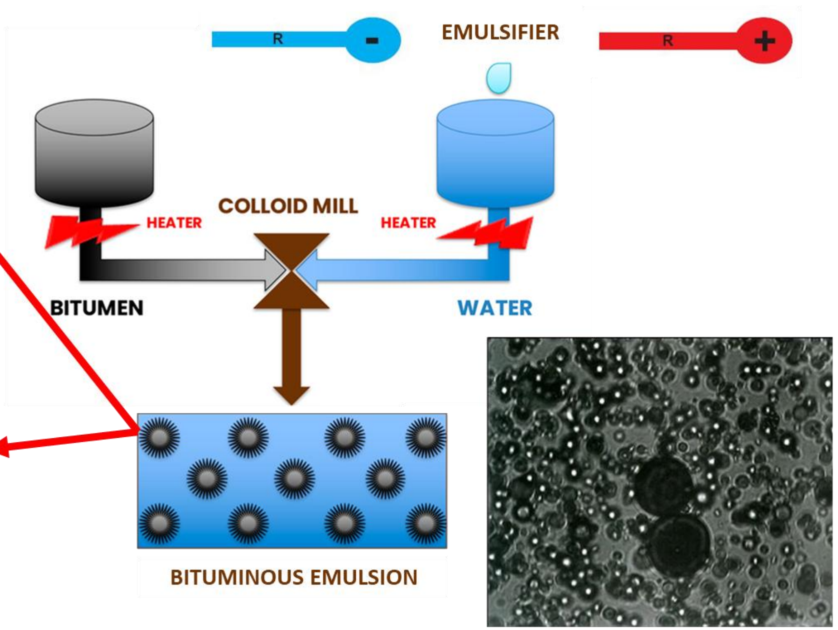
**Emulsion: a fine dispersion of minute droplets of one liquid in another in which it is not soluble or miscible**

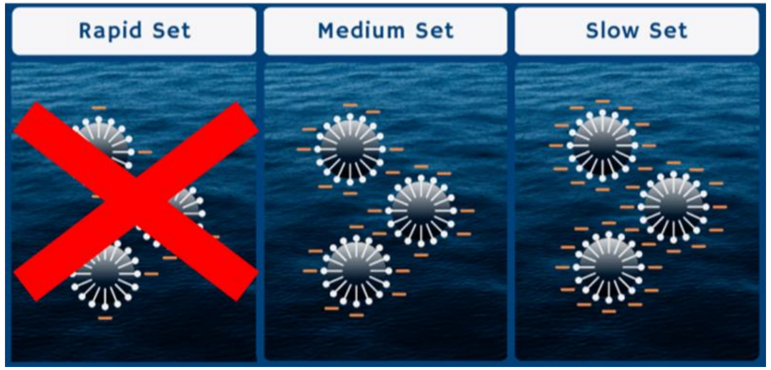



Anionic Emulsion

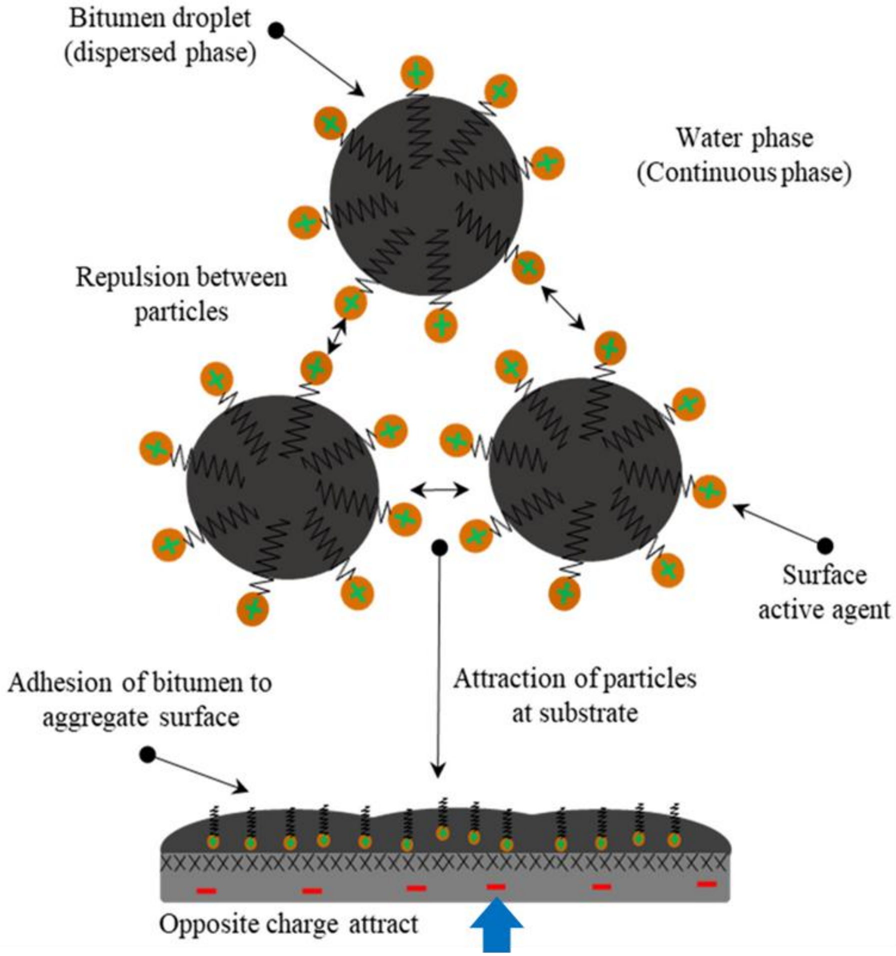



Cationic Emulsion



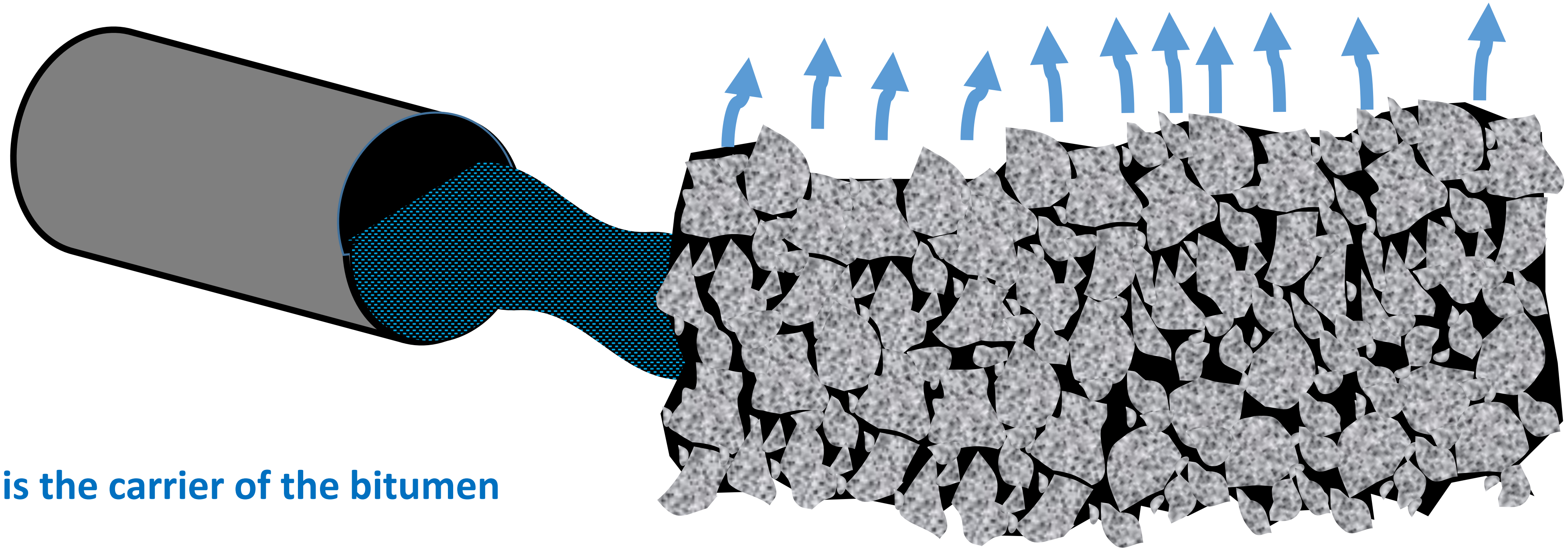

## Emulsion breaking process




*The choice of the emulsifier is function of the aggregates' characteristics*

# Bituminous Emulsion

**The total amount of fluid (emulsion + additional water) provides the lubricant effect before leaving during the curing phase**



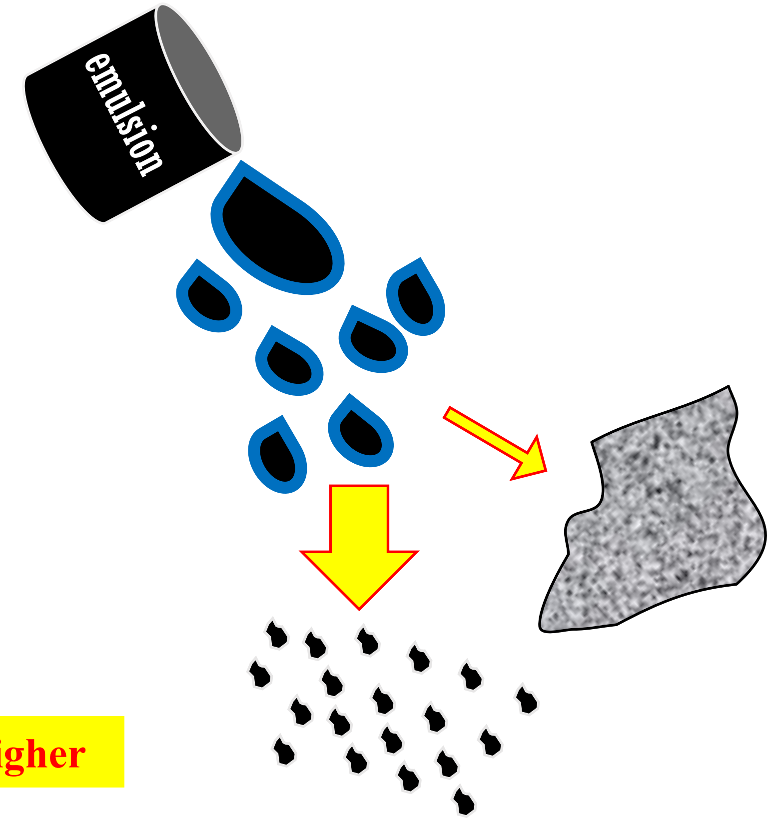
The water is the carrier of the bitumen

# Bituminous Emulsion

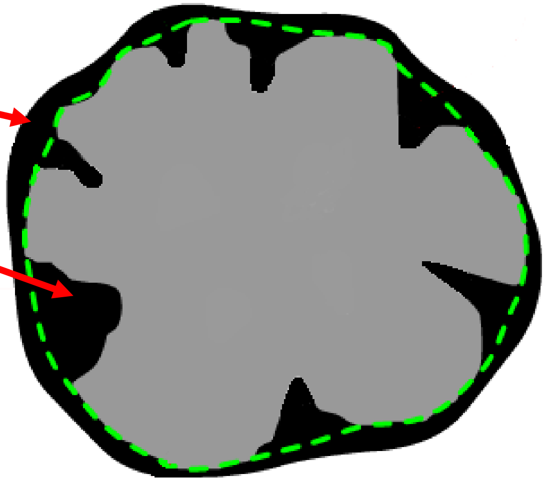
**Because the surface area of the fines aggregates it is much bigger than the surface area of coarse aggregates, the emulsion will be concentrated on the fines fraction.**

| Particle size (mm) | Surface area factor ($m^2/kg$) |
|---|---|
| 19 | 0.13 |
| 13.2 | 0.18 |
| 9.5 | 0.24 |
| 6.7 | 0.31 |
| 4.75 | 0.43 |
| 2.36 | 0.82 |
| 1.18 | 1.64 |
| 0.6 | 2.87 |
| 0.3 | 6.14 |
| 0.15 | 12.24 |
| 0.075 | 32.77 |

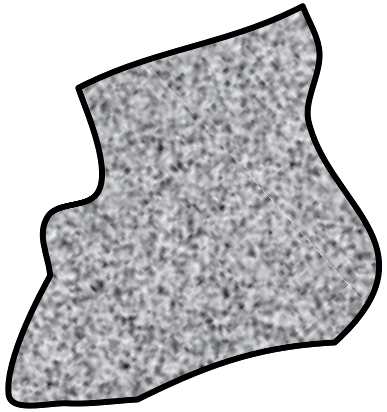
**252 times higher**



# Bituminous Emulsion



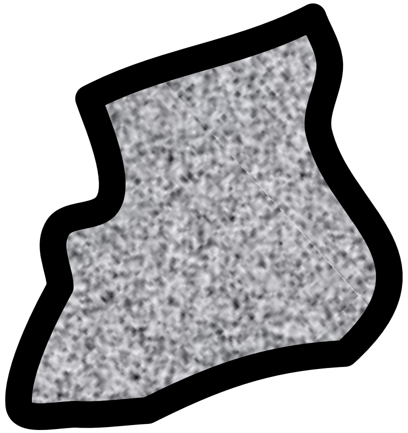

**Non-continuously bounded material**



**Bituminous emulsion stabilized material**

**A bituminous emulsion stabilized materials has the aggregates fully covered by the emulsions, but the film made by the emulsion (in total around 2-3% of the weight of aggregates) it is not enough thick to make a fully bounded material**

**Continuously-bounded material**



**Hot asphalt mixture**

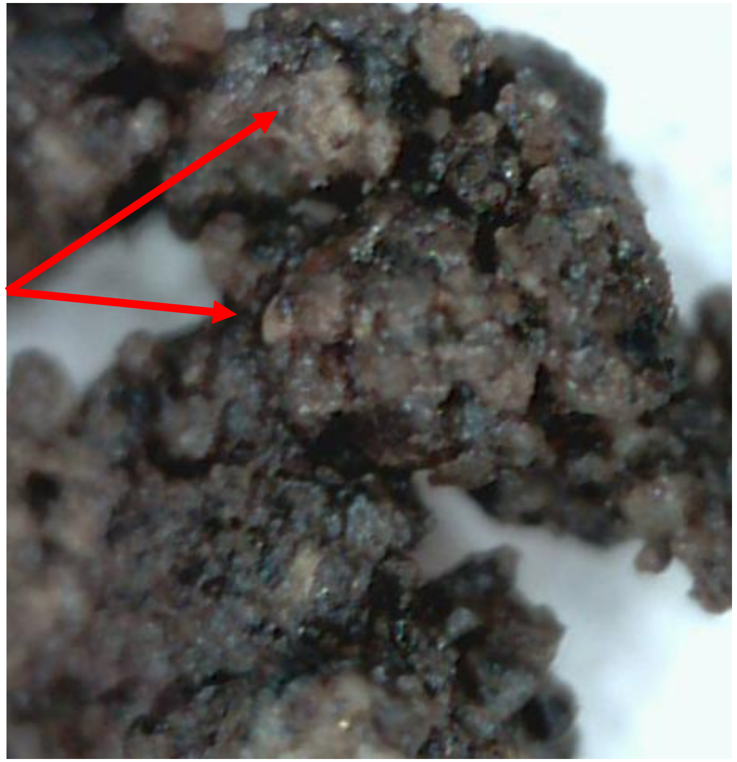
# Bituminous Stabilized Materials (BSM)

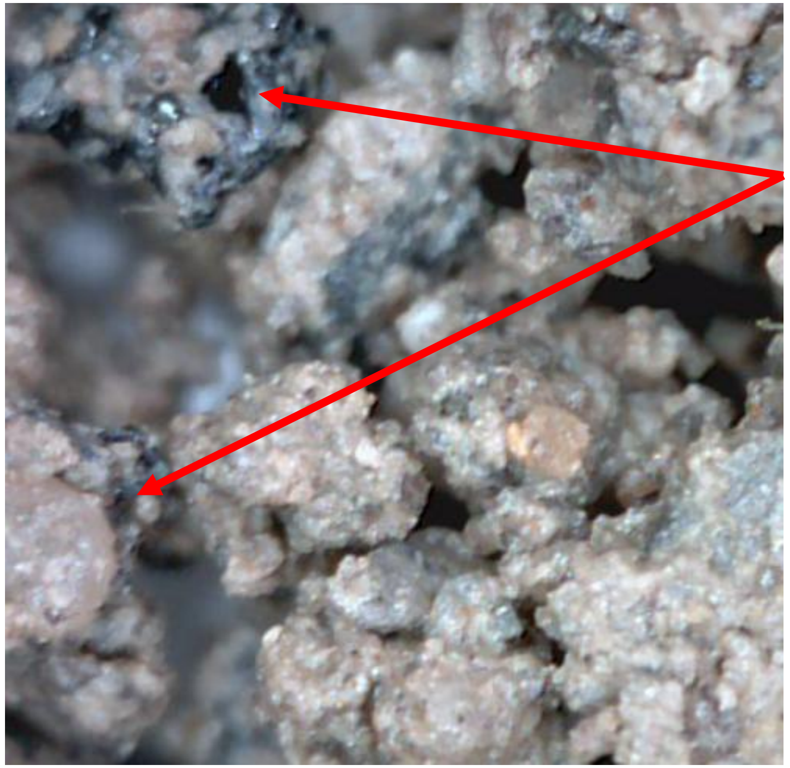
## BSMs are partially bounded materials

**The bitumen carried by fine aggregates (mainly by filler) it makes an adhesive mastic disperse inside the mixture**

### Emulsion

Partially coated aggregates
or non uniformly coated aggregates

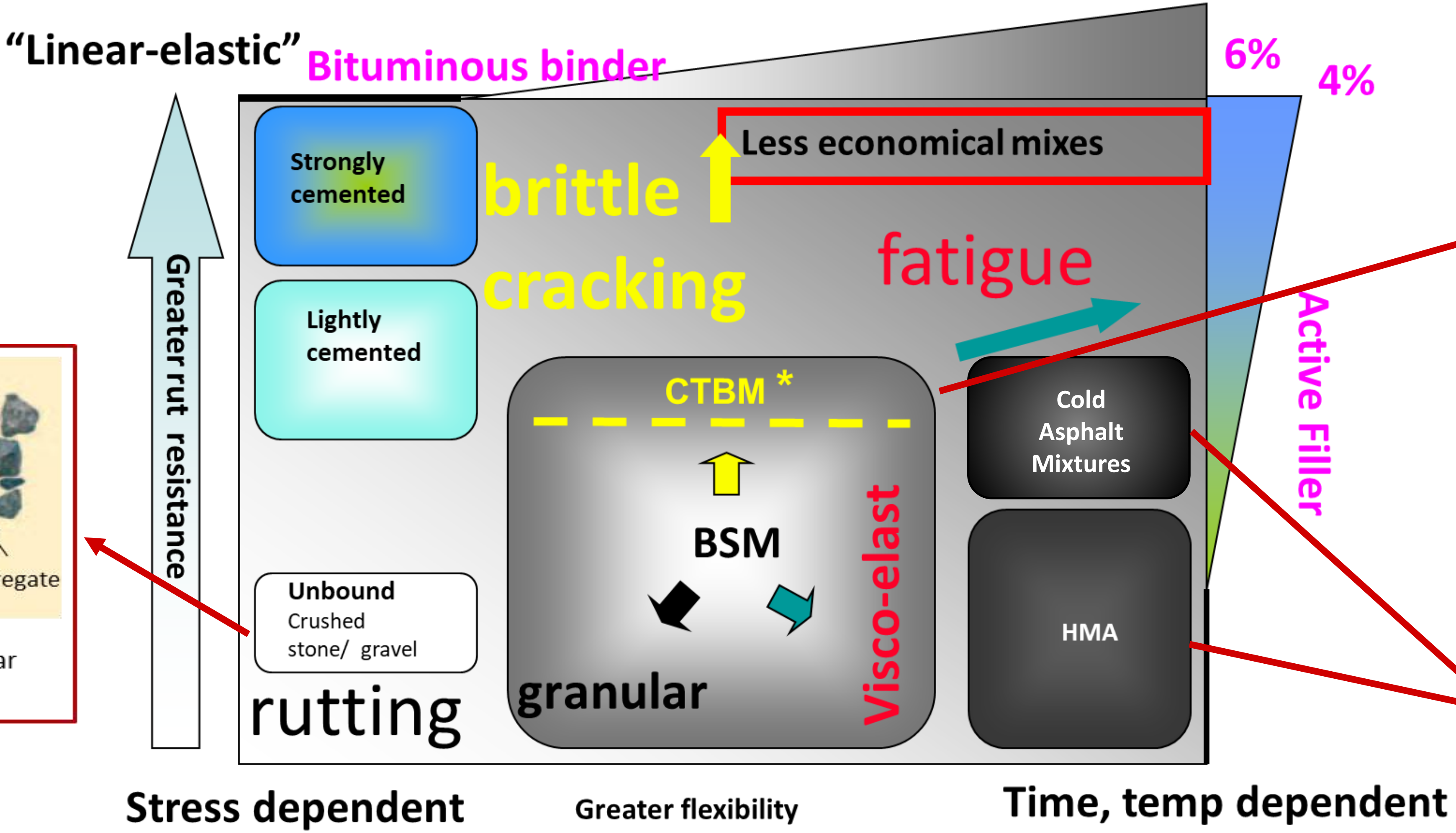




### Foam

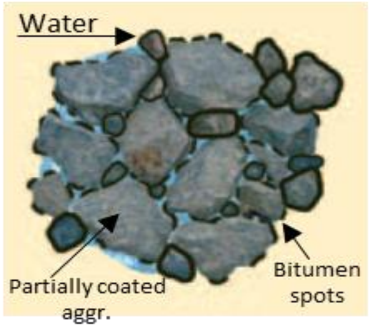
Bitumen spots bitumen absorbed by filler of bitumen drops attached on the aggregates' surface

# Bituminous Stabilized Materials (BSM)

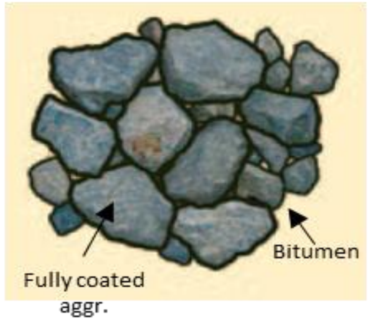




Unbound granular material




Non-continously bound material



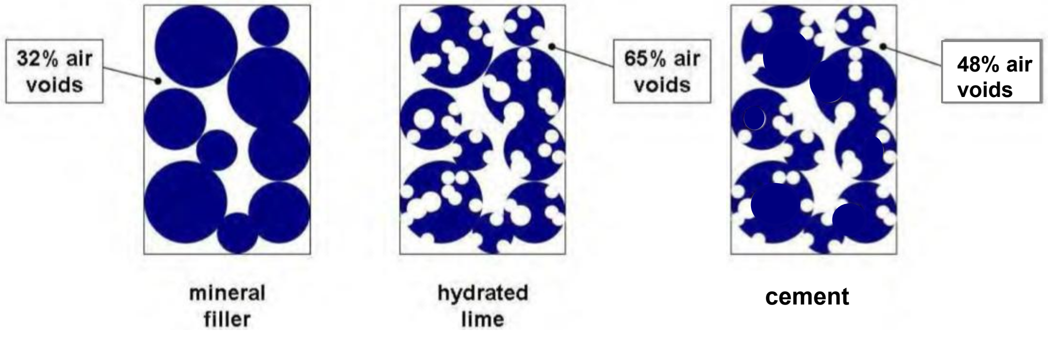

Fully bound material

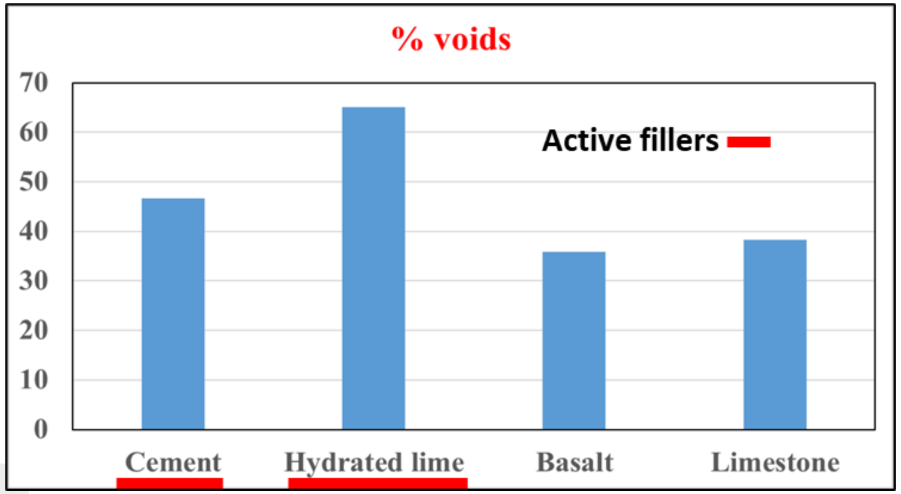
Courtesy of Kim Jenkins

* Cement Treated Bituminous Materials

# BSM & active fillers

**Active filler it is a filler (mineral element part of the aggregates passing at sieve 0.075/0.062) that is chemically active. The most common active fillers are lime, cement and fly ash.**




The purpose of incorporating active filler in BSM is to:

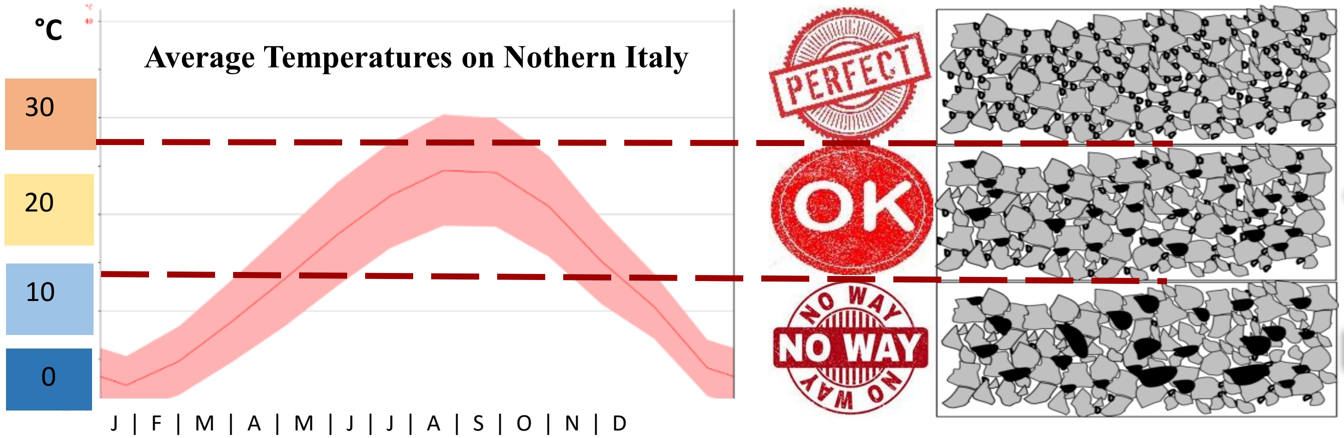
- Improve dispersion of the bitumen in the mix
- Accelerate curing of compacted mix
- Control emulsion's breaking time

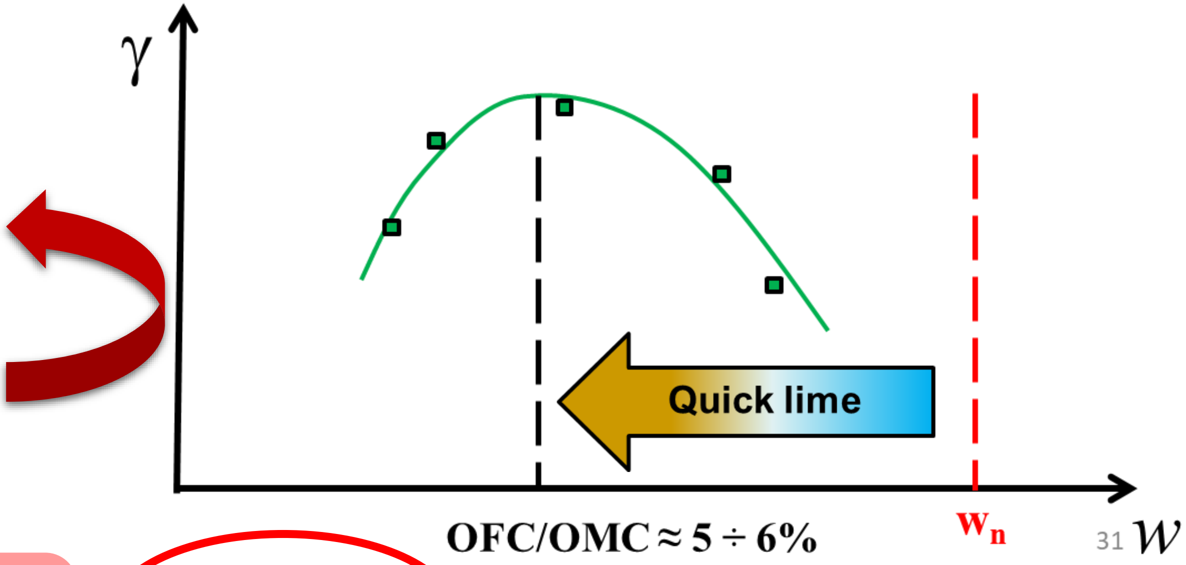
} **hydration**

- Increase stiffness & strength of mix → **setting & hardening**
- Improve adhesion of the bitumen to the aggregate
  → **mainly lime with acid aggregates: it makes basic salts that are able to avoid the "acid-acid contact" between bitumen and aggregate surface**

# Active fillers: collateral physical effects

## Heating






$$CaO + H_2O \rightarrow Ca(OH)_2 + 15.5\ kCal$$

Pre-active filler — Active filler

**High electrochemical potential & high-speed reaction**

**Pre-active filler**: a material that became active filler for a chemical or physical immediate change during the mixing phase


*Use of calcium oxide as active filler for bituminous stabilised materials*
Beatriz Chagas Silva Gouveia, Francesco Preti, Romeo, Kim Jenkins, Gabriele Tebaldi
RMPD https://doi.org/10.1080/14680629.2021.1881591

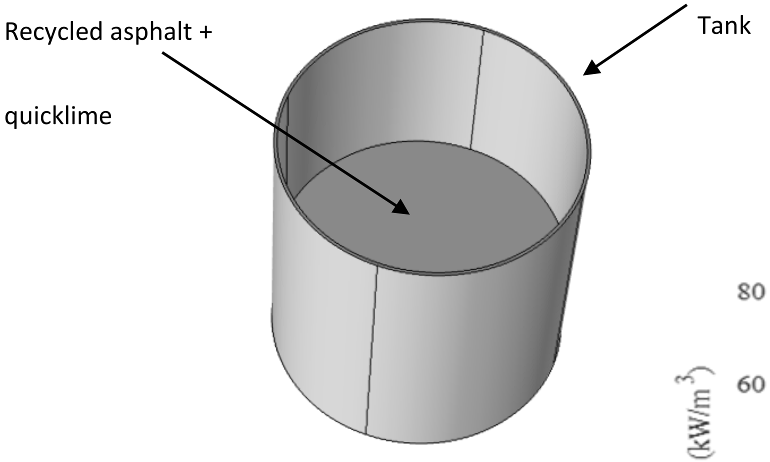

MRP'25

# Active fillers: collateral physical effects

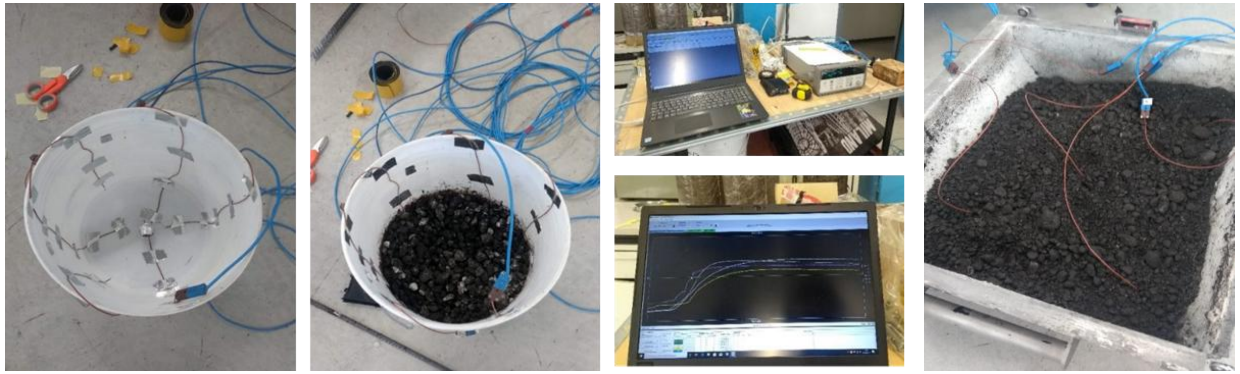
## Heating

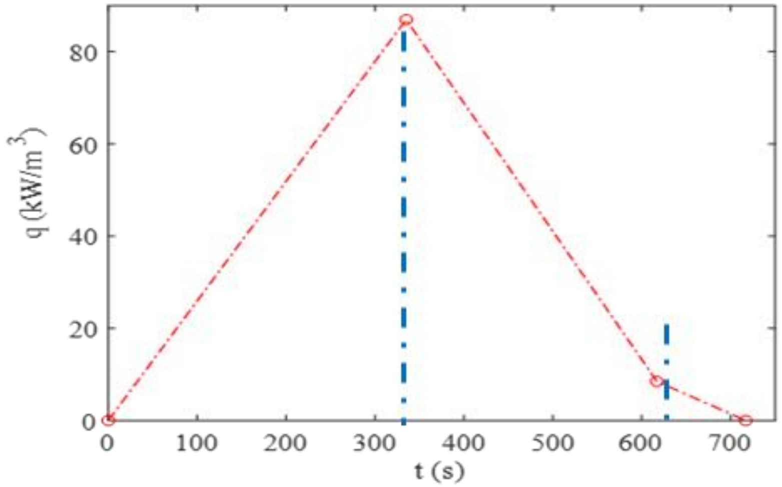
### Emulsion + Quicklime

### Effects of temperature

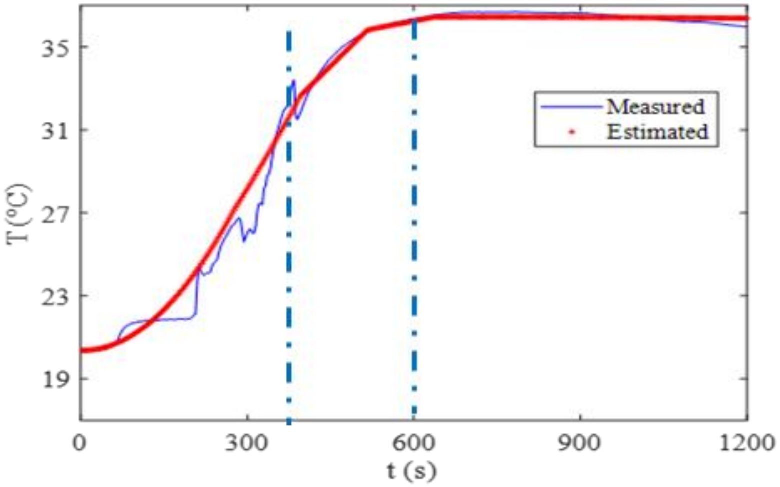



3-D numerical finite element model of the whole test body (tank and volume of material) was implemented within the Comsol Multiphysics® environment






**Function of heat releasing**




**Estimated vs. measured T distribution**

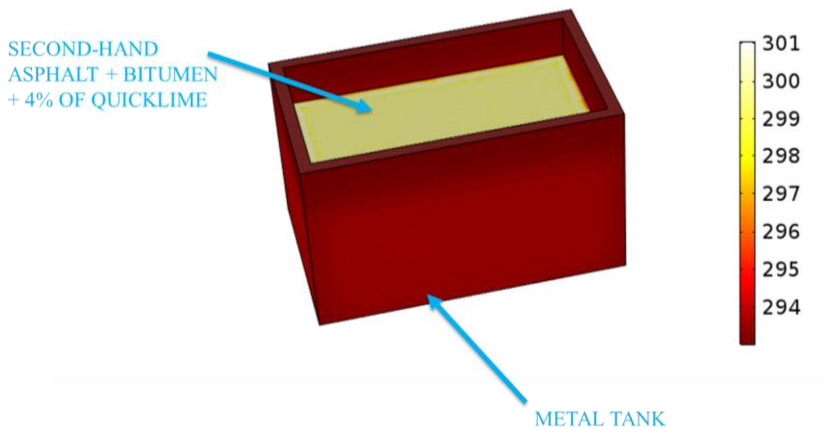
# Active fillers: collateral physical effects

## Heating

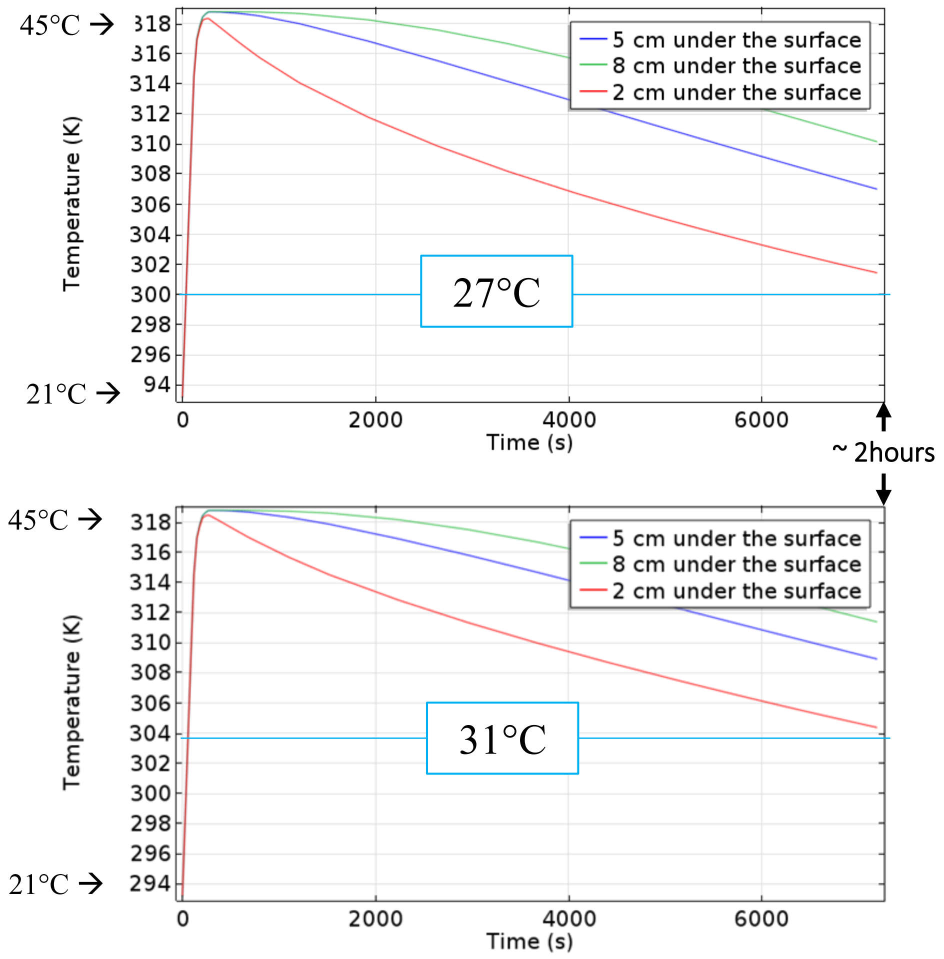
**Emulsion + Quicklime**

**Effects of temperature**

**FEM MODEL** [tetrahedral elements]




**Improving the insulation of the truck**
**→ + 4°C avg. temperature**



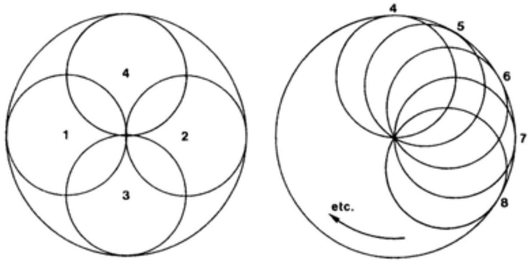
# Compaction of BSM

## Compaction Energy Estimation

**Assumptions:**

- **A literature-based approximation was adopted to compare compaction methods on an equivalent energy basis**
- **RAP behaves as a granular material upon compaction**

**Modified Proctor test (ASTM D1557)**

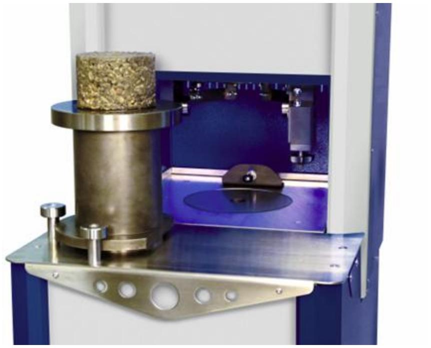


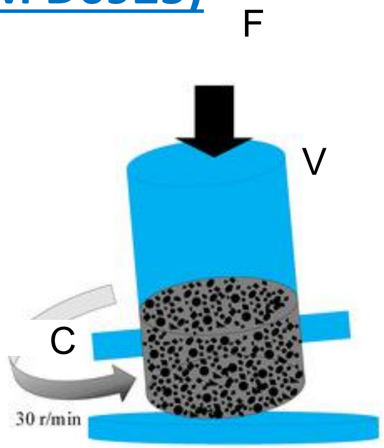

| Compaction Method | Energy Application | Parameters Considered | Estimated Energy (kJ/m³) |
|---|---|---|---|
| Modified Proctor | Impact Loading | Hammer weight ($W_{mh}$), number of blows ($b$), drop height ($h$), number of layers ($l$), volume of the mold ($V$) | $E_p = \dfrac{W_{mh} \cdot b \cdot h \cdot l}{1000 \cdot V}$ |

# Compaction of BSM

## Compaction Energy Estimation

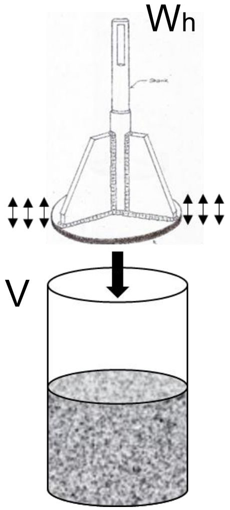
- Gyratory compactor (ASTM D6925)






| Compaction Method | Energy Application | Parameters Considered | Estimated Energy (kJ/m³) |
|---|---|---|---|
| Gyratory compactor | Axial pressure + Rotational shearing | Pressure ($F$), height difference during one gyration ($h$), average torque ($C$), volume of the mold ($V$) | $E_g = \frac{F \cdot h + C \cdot (2 \cdot \pi)}{1000 \cdot V}$ |

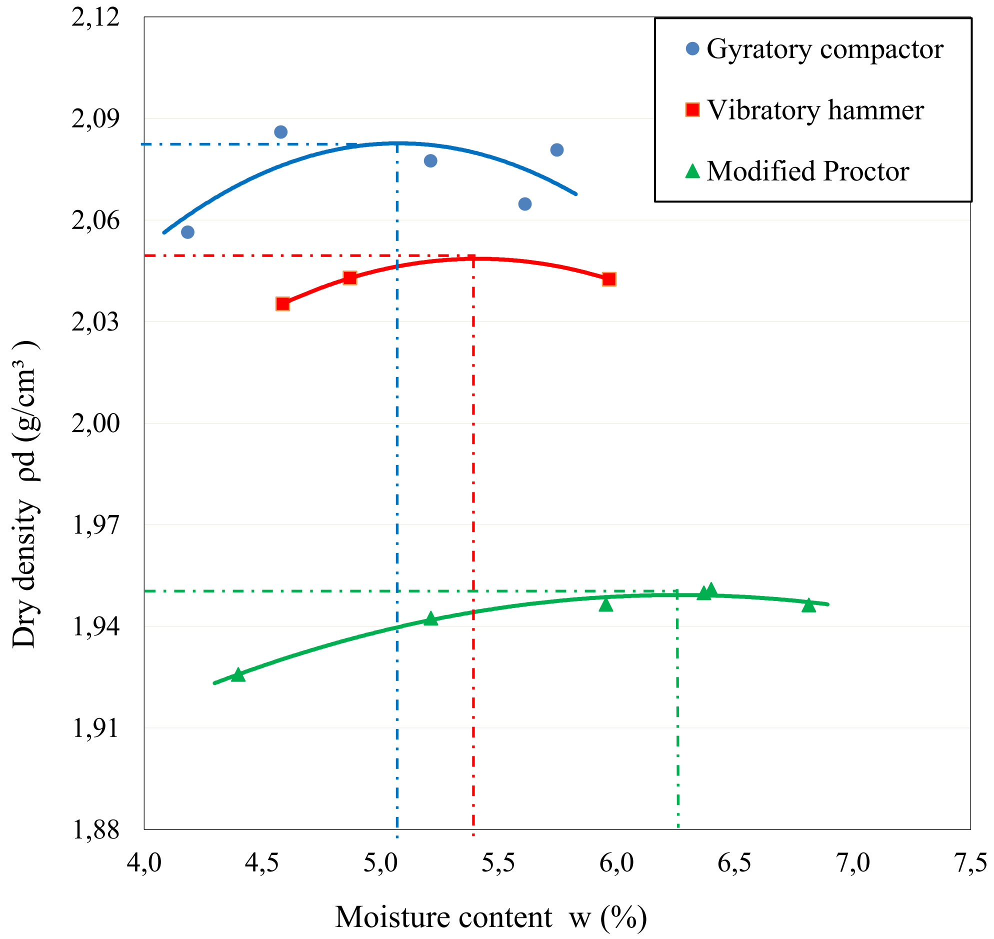
- Vibratory hammer




| Compaction Method | Energy Application | Parameters Considered | Estimated Energy (kJ/m³) |
|---|---|---|---|
| Vibratory hammer | Axial pressure + Vibration | Hammer weight ($W_h$), frequency ($f$), amplitude ($amp$), compaction time ($t$), number of layers ($l$), volume of the mold ($V$) | $E_v = \frac{W_h \cdot f \cdot amp \cdot t \cdot l}{1000 \cdot V}$ |

# Compaction of BSM

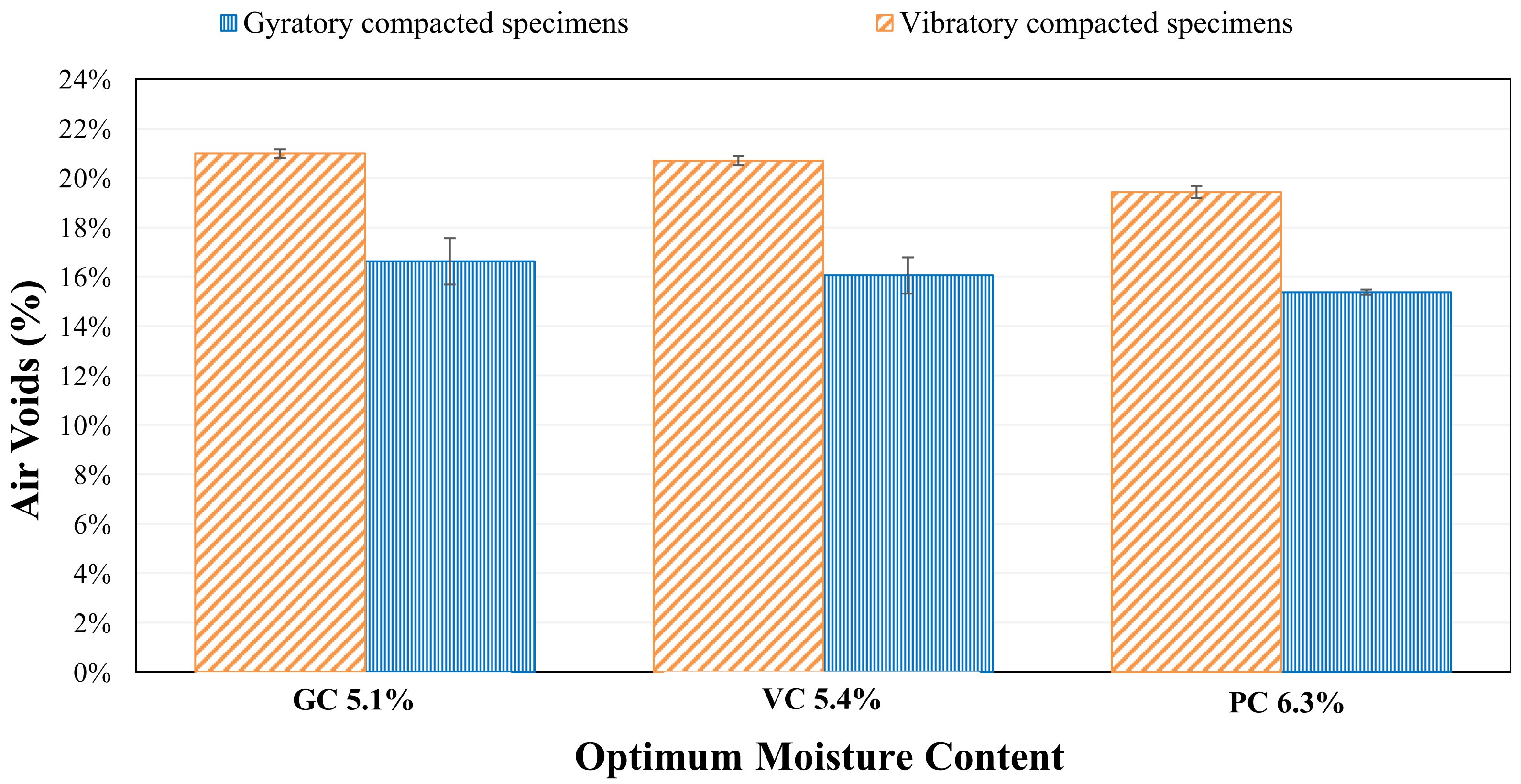
## Different compaction energy application methods provide different density levels




| | Compaction Method | | |
|---|---|---|---|
| **RAP Properties** | **Gyratory** | **Vibratory** | **Mod. Proctor** |
| $\rho_{d,max}$ ($g/cm^3$) | 2.08 | 2.05 | 1.95 |
| $w_{opt}$ (%) | 5.1 | 5.4 | 6.3 |
| ***Estimated compaction energy (kJ/m³)*** | 2289 | 2153 | 1957 |
| ***Label*** | **GC (5.1%)** | **VC (5.4%)** | **PC (6.3%)** |

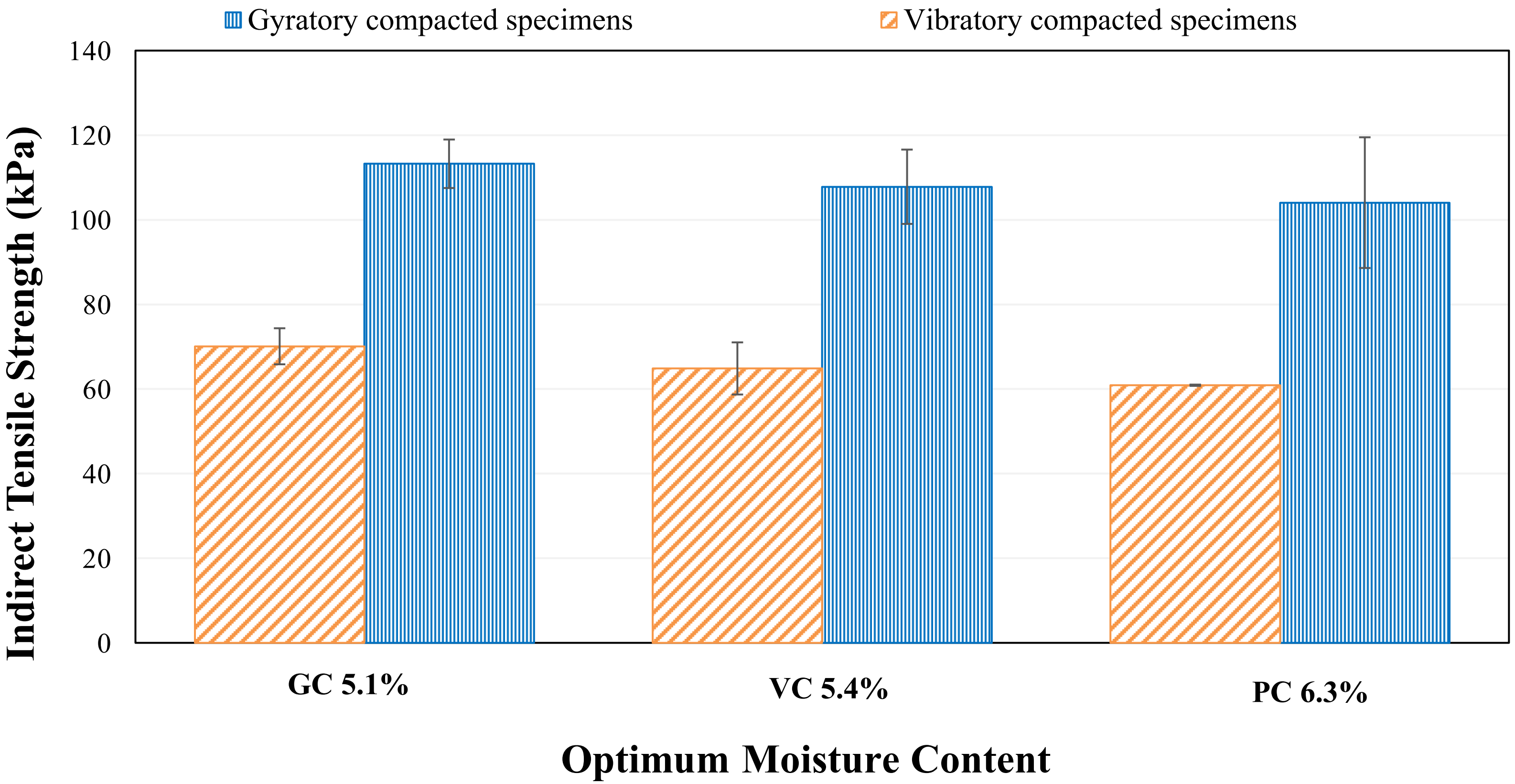
# Compaction of BSM: Residual Air Void Content

- Air voids are always higher when vibratory hammer is used as compaction method
- % air voids decreases as the OMC increases, regardless of the compaction method



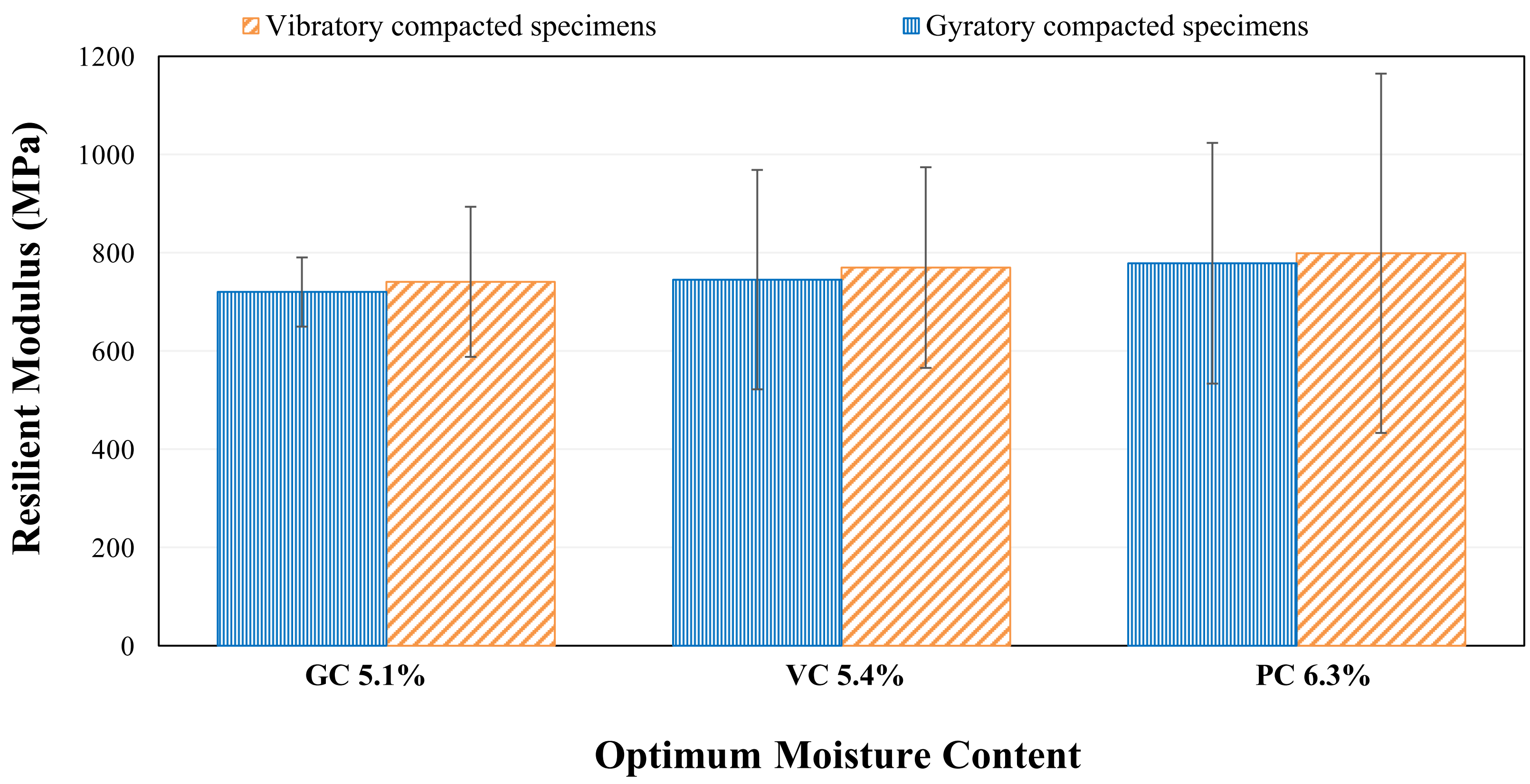
# Compaction of BSM: Indirect Tensile Strength

- **ITS is significantly higher when gyratory compactor is used as compaction method**
- **ITS slight decreases as the OMC increase, regardless of compaction method**
- **Highest ITS observed in the case of the lowest OMC (GC5.1% which has the highest air void content)**



# Resilient Modulus (MR)

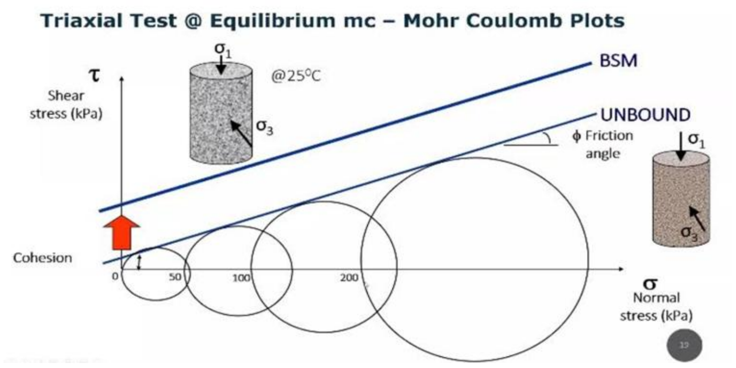
- **Minimal variation as moisture content and compaction method vary**
- **Always higher when vibratory hammer is used as compaction method**
- **Increase as the OMC increases and air void content decreases**

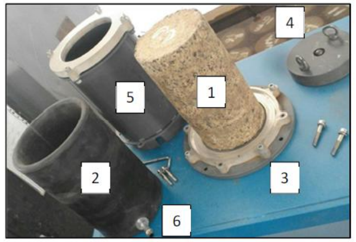


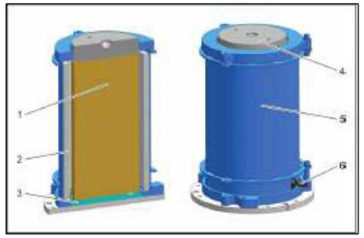
# Compaction of BSM: Triaxial Shear Strength

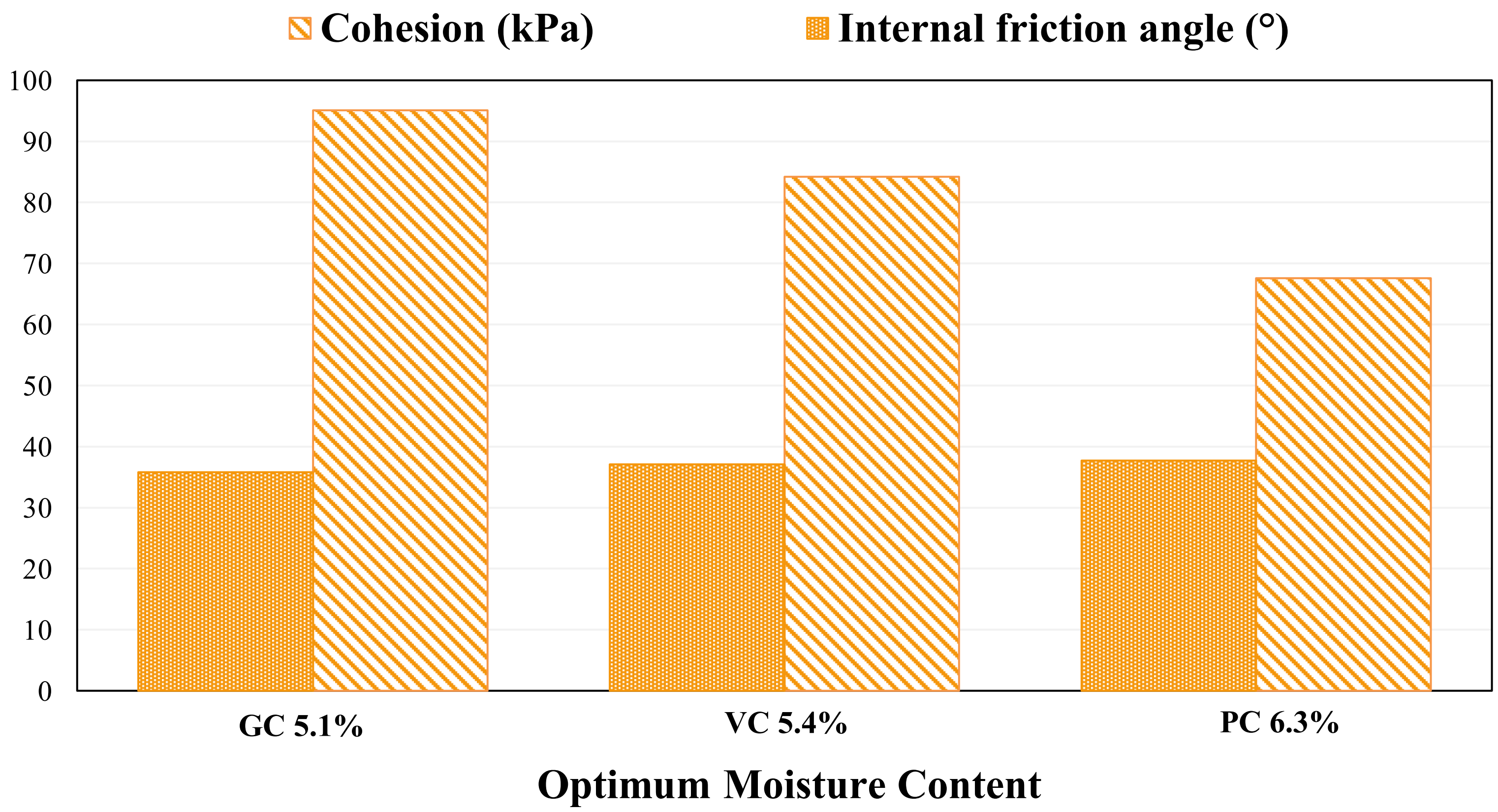
- Cohesion decreases significantly as moisture content increases
- Internal friction angle varies in a narrow range
- GC 5.1% → highest cohesion and lowest internal friction angle

Specimens compacted with vibratory hammer



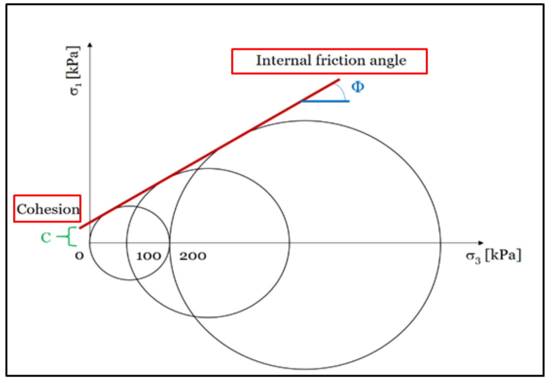
## Design with elasticity and plasticity

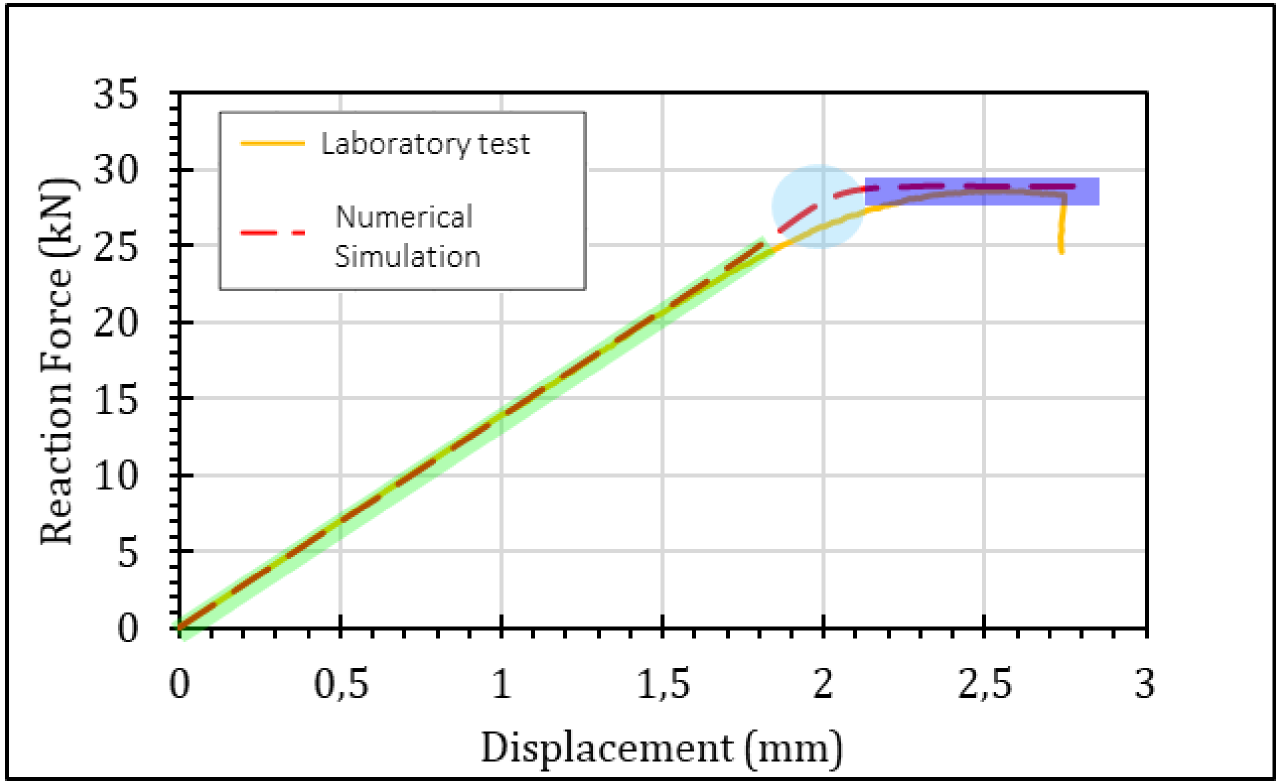
### 3D Elastic-Perfectly Plastic Finite Element Model

Elastic response:
governed by Young's Modulus and Poisson's ratio.

Plastic response:
1. **Criteria** determining when plasticity gets initiated.
2. **Flow rule** dictating how much plasticity happens. (determines the extent of plastic strain for given stress state)

Selected criteria:
Mohr-Coulomb failure envelope



# Design of Pavements with BSM layer

## Design with elasticity and plasticity

| Layer | Thin pavement | Reference (TH 30) | Thick pavement |
|---|---|---|---|
| HMA | 38 mm | 75 mm | 100 mm |
| BSM | 50 mm | 75 mm | 100 mm |
| Granular Base | 100 mm | 250 mm | 300 mm |
| Subgrade | Semi-infinite | Semi-infinite | Semi-infinite |

Temperature: 10, 25 and 40 °C constant throughout HMA and BSM layers (temperature dependent materials)

**Especially for thin pavement structures and high temperatures linear elastic analysis leads to overestimated pavement service life**

| Temperature [°C] | Structure | Model Type | Difference in fatigue life prediction ($N_F$) [%] | Difference in fatigue life prediction ($N_R$) [%] |
|---|---|---|---|---|
| **10** | Thin | Linear elastic | **-64.56** | **-47.62** |
| | | Plasticity-based | | |
| **25** | Thin | Linear elastic | **-75.75** | **-54.14** |
| | | Plasticity-based | | |

# Hot Asphalt Recycling

## Hot recycling

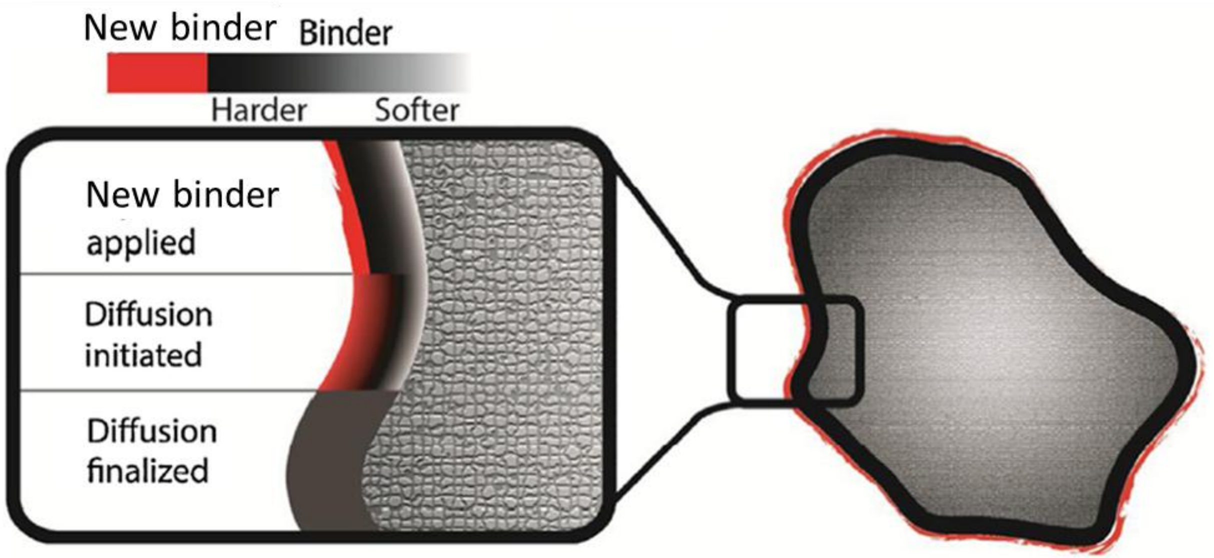
**Aggregates**

**+**

**&**

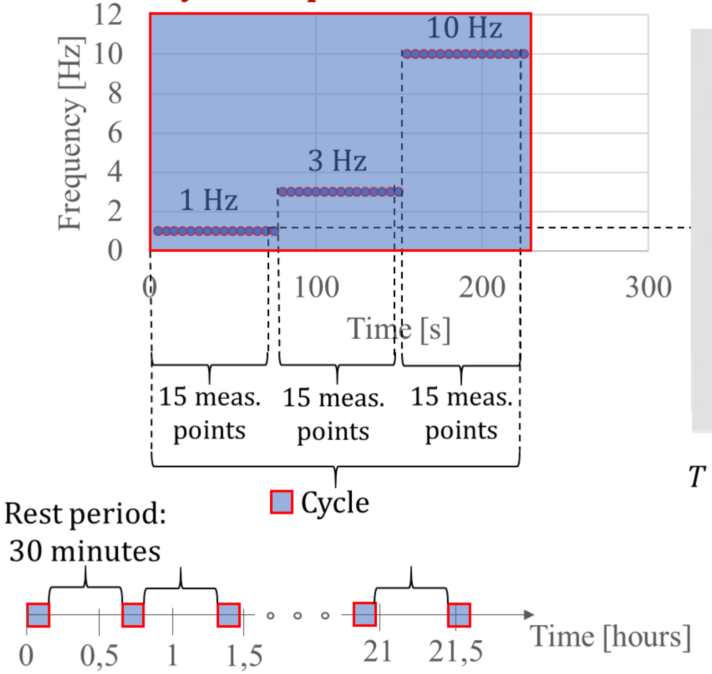
**RA’s bitumen** **fresh bitumen**

# Hot Asphalt Recycling: Diffusion

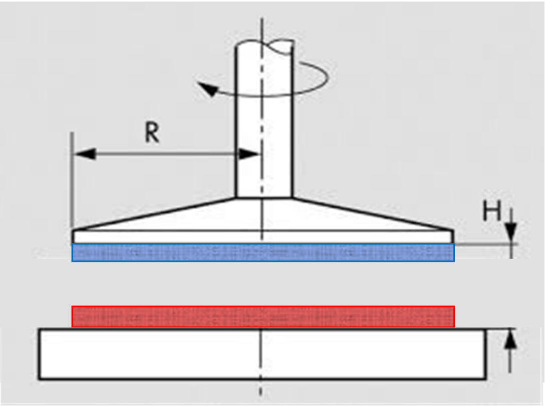



Courtesy of Jan Krol

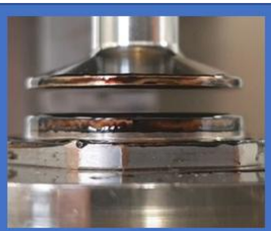
**Double-layer test procedure**




38 cycles → Test duration ≈ between 21 to 22 hours




$T = 50° C$ H $= 0.5mm$ $\gamma = 0.5$ %



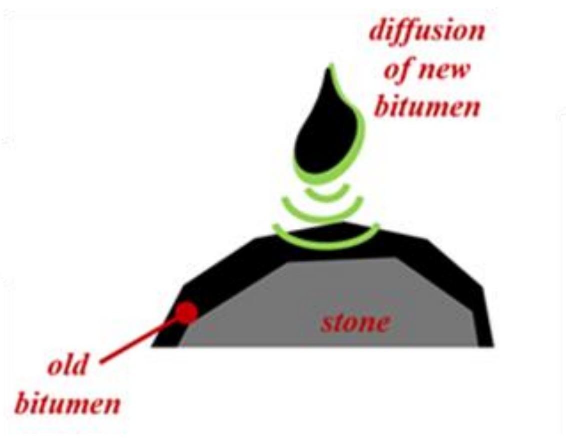
Trimming of the two samples, after the conditioning at 20°C. Sample thickness: 0.5mm

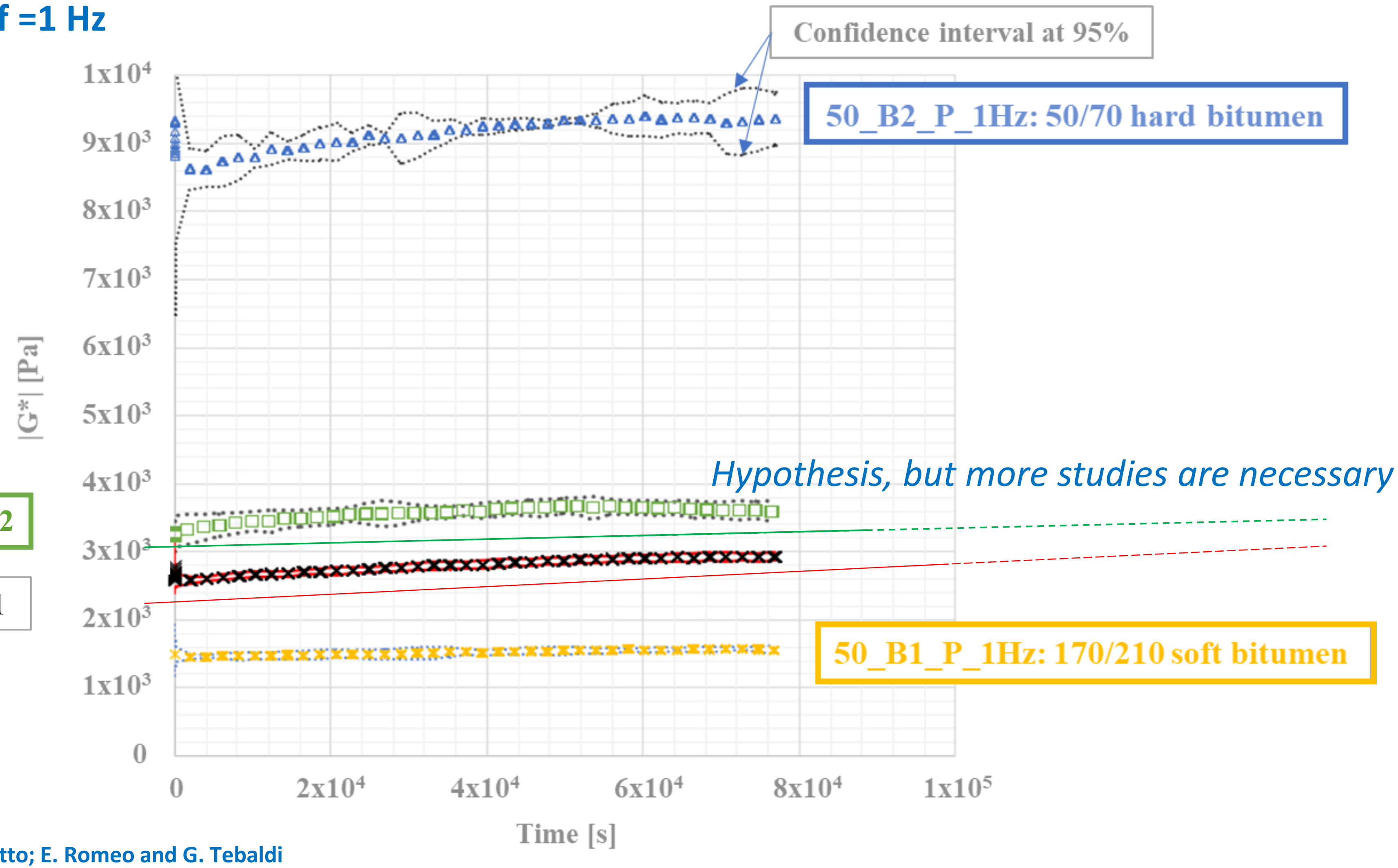
MRP'25

S. Noto; S. Mangiafico; C. Sauzéat; H. Di Benedetto; E. Romeo and G. Tebaldi
Journal of Materials in Civil Engineering; DOI: 10.1061/(ASCE)MT.1943-5533.0004116

# Hot Asphalt Recycling: Diffusion

## Diffusion tests B1/B2 at 50°C – $\gamma$ = 0,5; f =1 Hz

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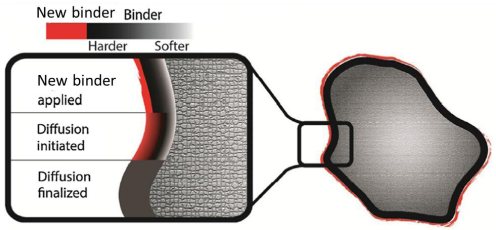
# Hot Asphalt Recycling: Diffusion

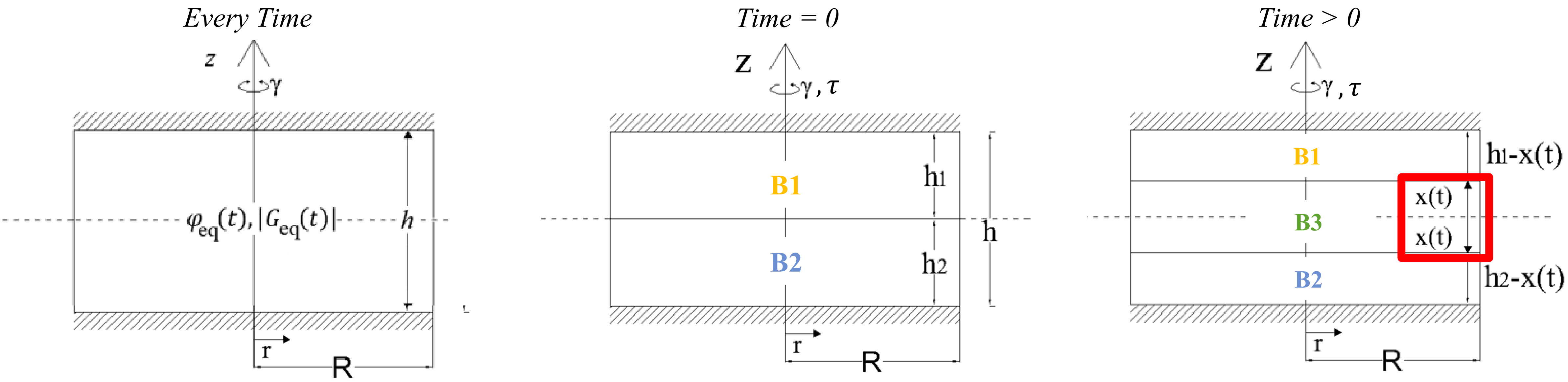
- $G^* = |G^*|e^{i\varphi}$
- x(t) complex number

Bitumen B1
Bitumen B2
Bitumen B3 full-blend B1+B2

Estimate of diffusion thickness

$$\frac{h}{G^*_{eq}(t)} = \frac{h_1 - x(t)}{G^*_1(t)} + \frac{h_2 - x(t)}{G^*_2(t)} + \frac{2x(t)}{G^*_3(t)}$$

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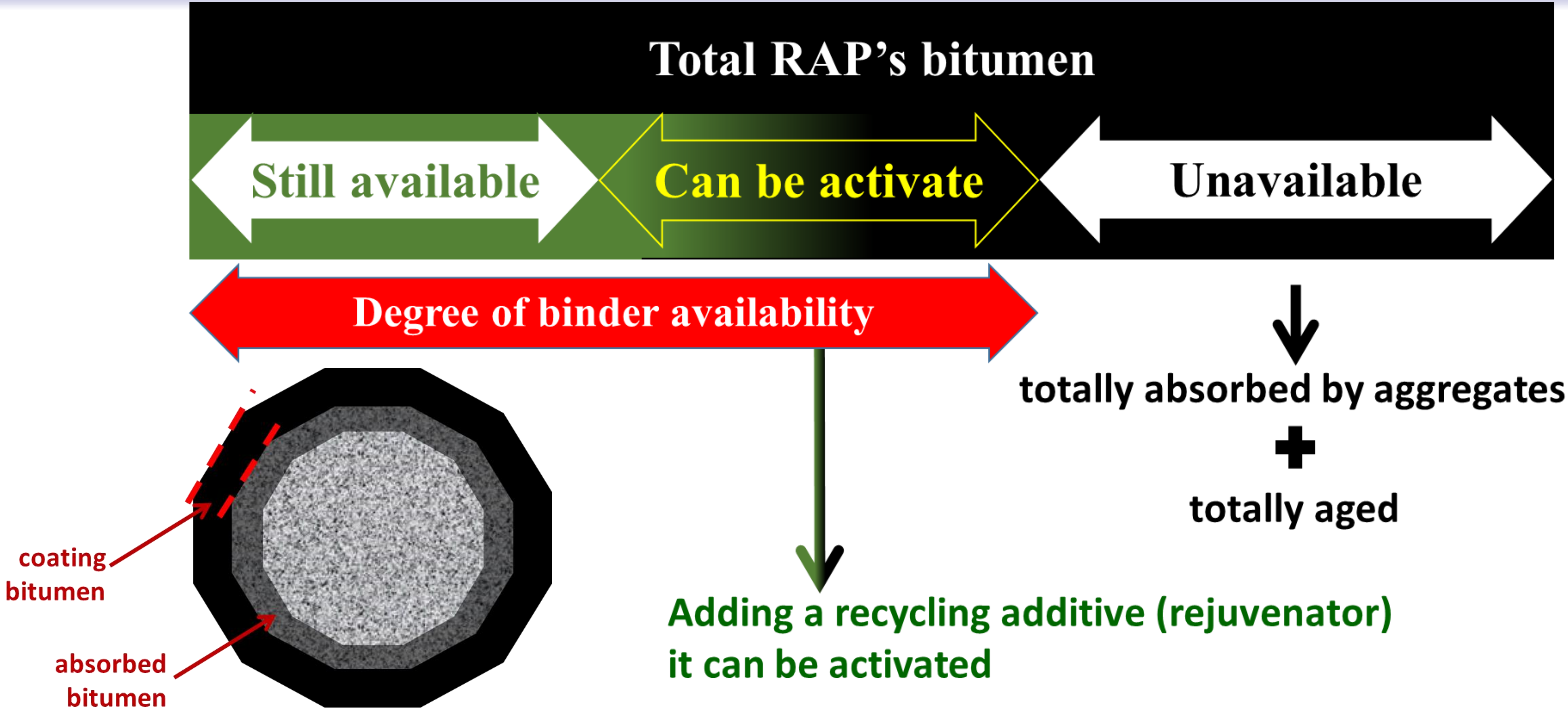
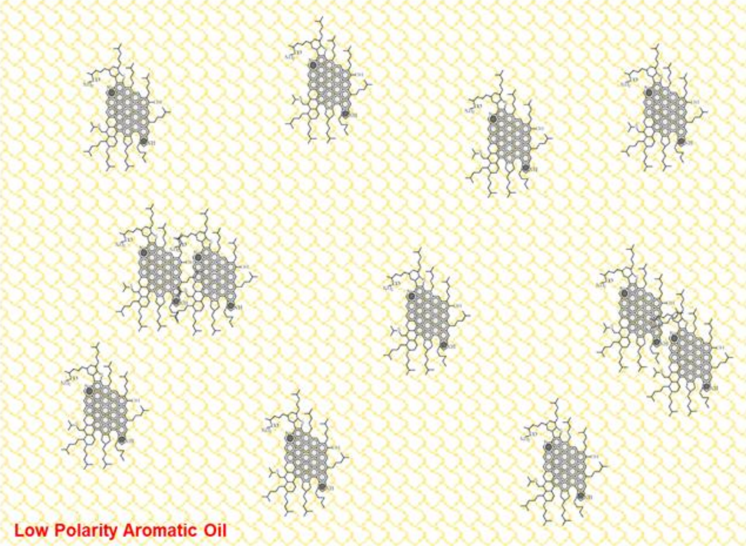
Journal of Materials in Civil Engineering; DOI: 10.1061/(ASCE)MT.1943-5533.0004116

# Hot Asphalt Recycling: Binder Availability

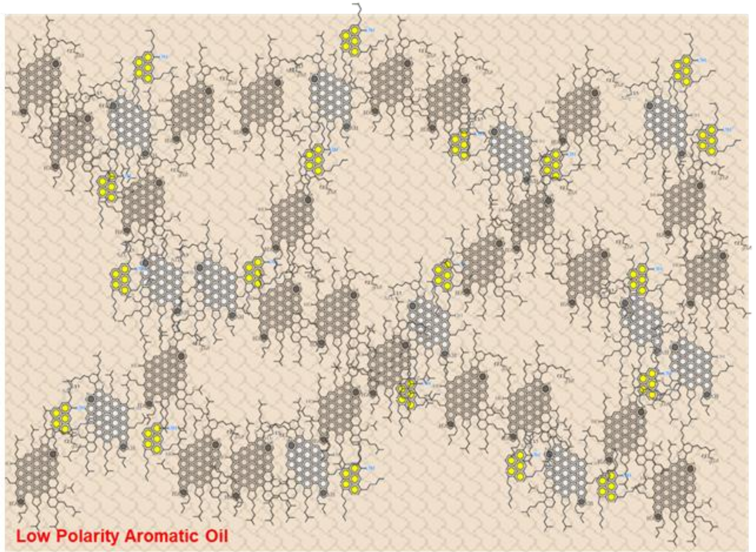


# Hot Asphalt Recycling: R.A. action

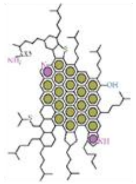
*Unaged Bitumen*



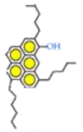

*Aged Bitumen*




**Asphaltene**

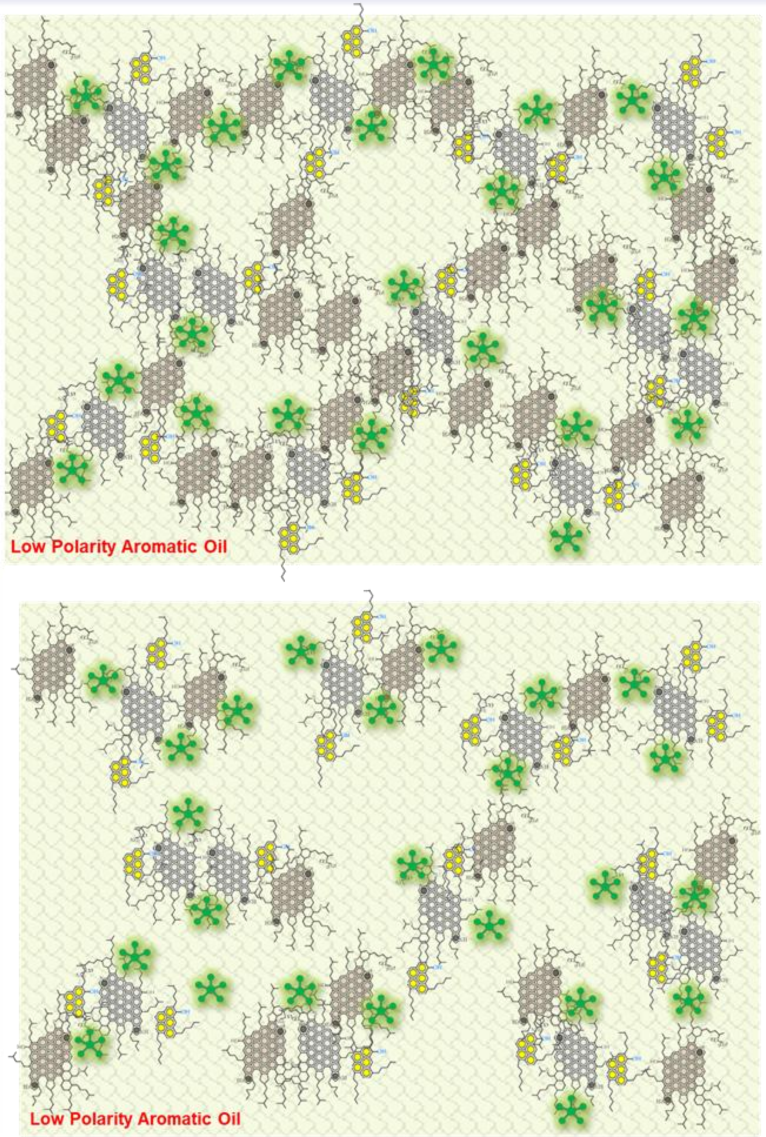


**Resins**



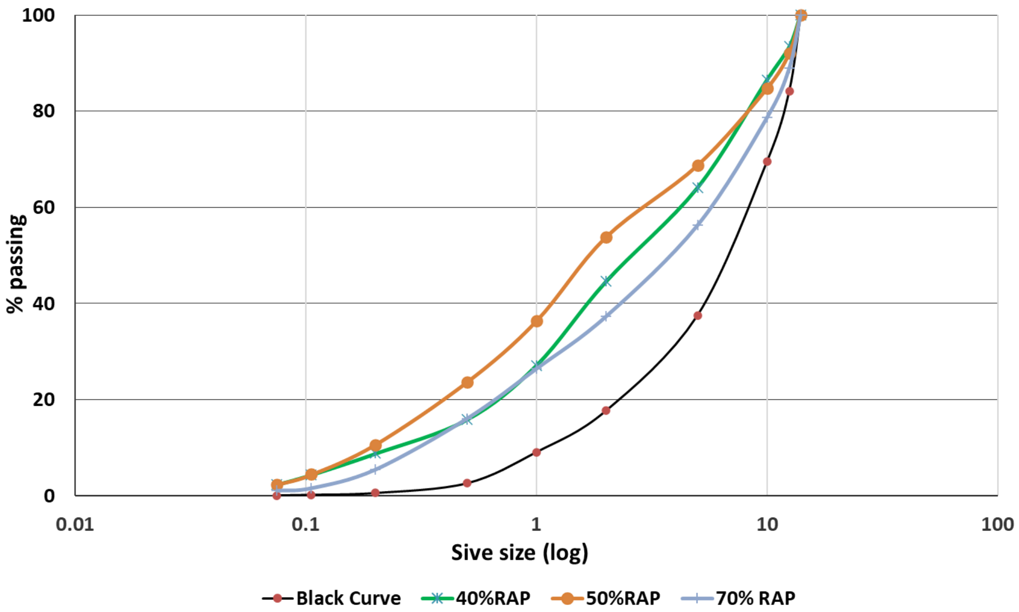
**Rejuvenator**

*Rejuvenation of bitumen*




Courtesy of Dr. Hans Moolenaar

# Hot Asphalt Recycling: High amount of RAP

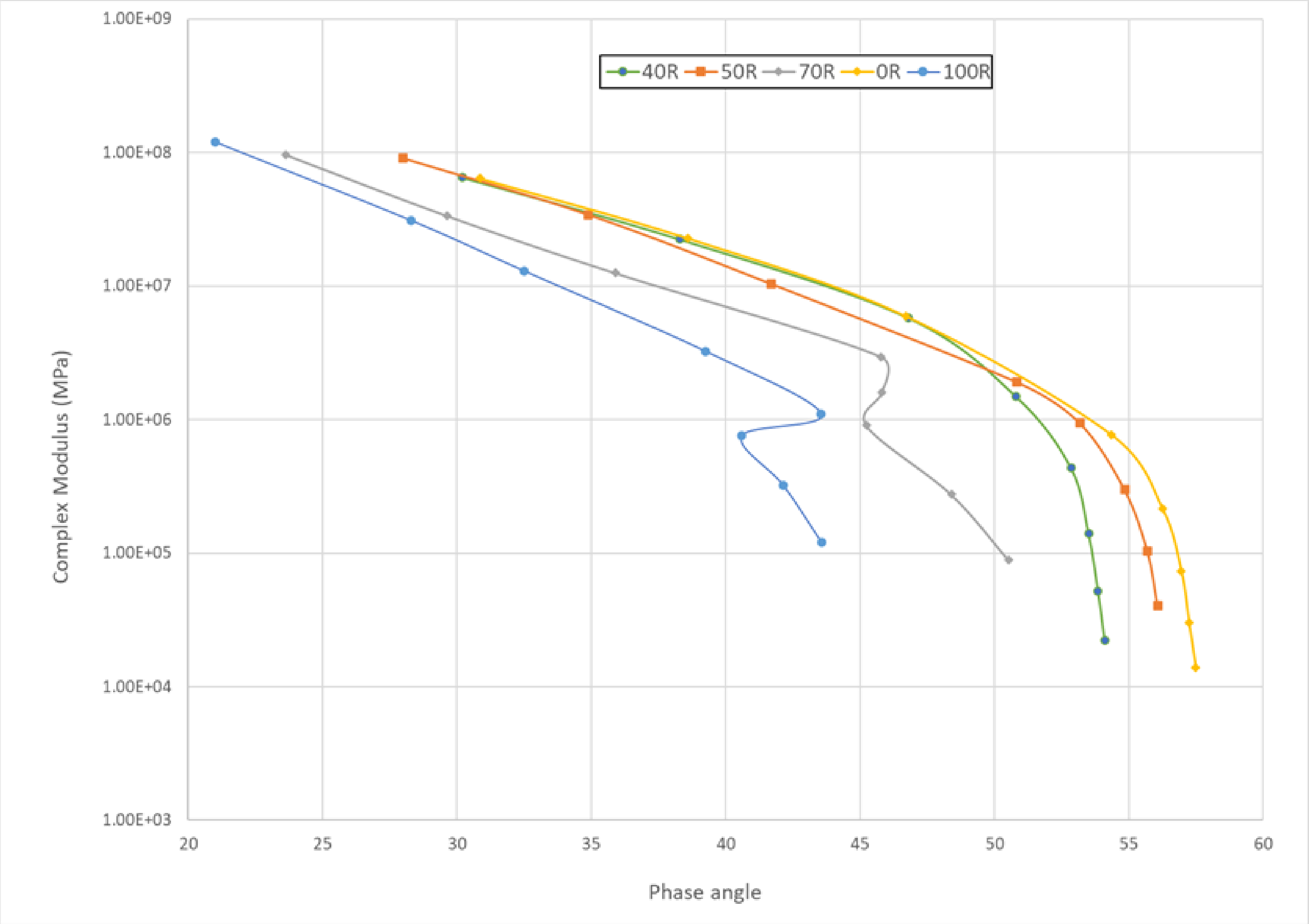



| Label | Virgin aggregates (%) | RAP (%) | Asphalt (%) | Bio-oil (%) |
|---|---|---|---|---|
| 0R | 100 | - | 5.2 | - |
| 20R | 80 | 20 | 5.2 | - |
| 40R | 60 | 40 | 3.3 | 0.11 |
| 70R | 30 | 70 | 1.8 | 0.22 |

**Dosage of R.A. based on viscosity**

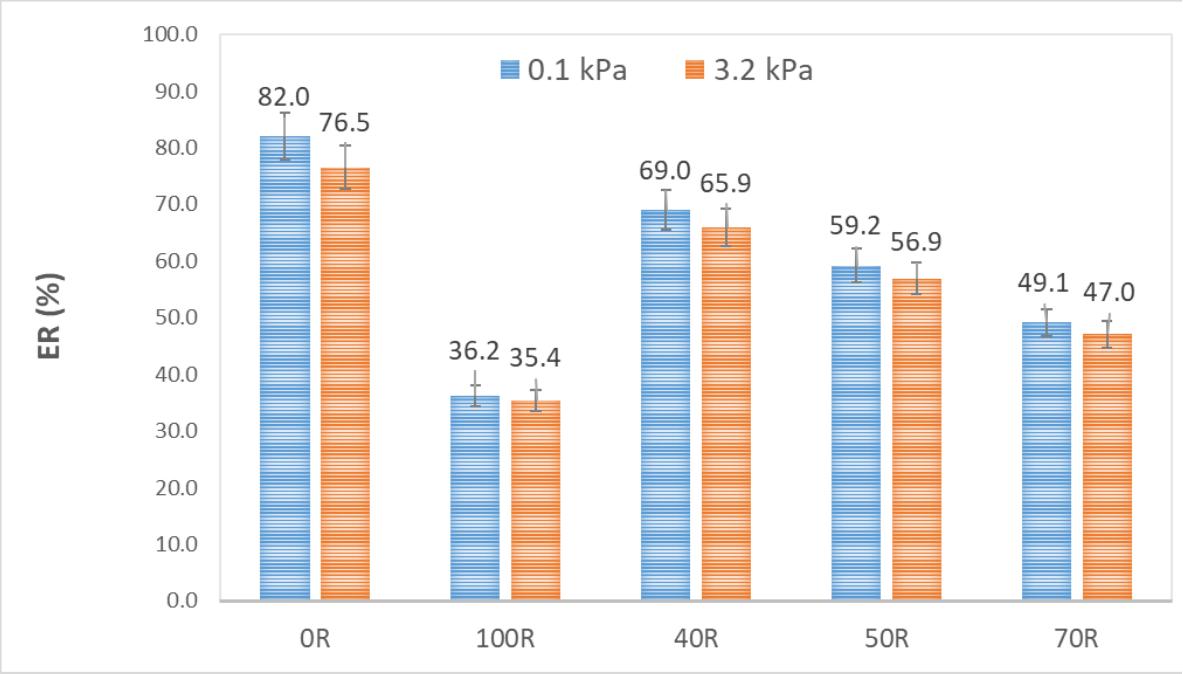
# Hot Asphalt Recycling: High amount of RAP

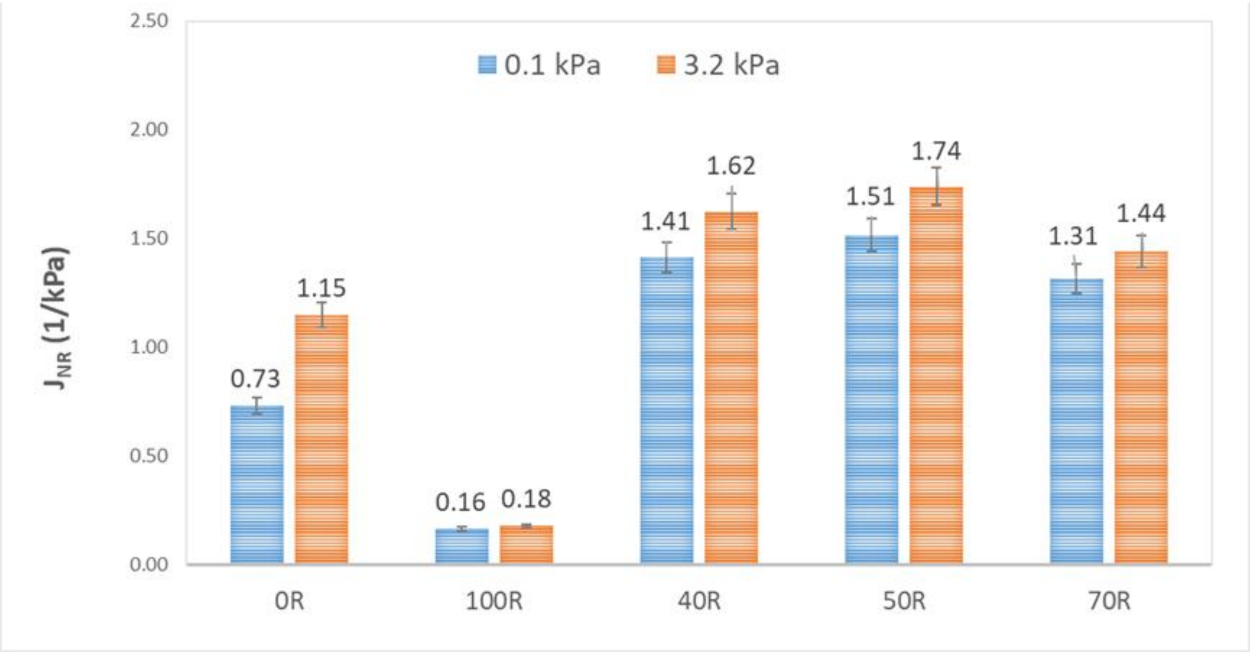
## Full Blending: Black Space @10rad/s



# Hot Asphalt Recycling: High amount of RAP

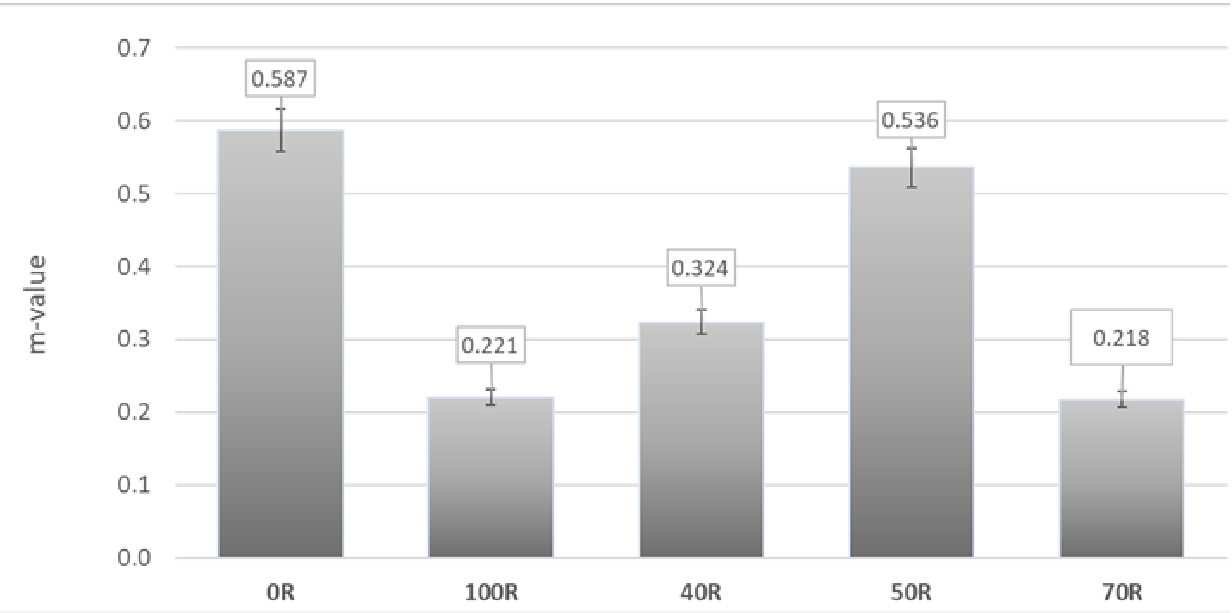
## Full Blending: Elastic Recovery & Non-Recoverable Creep Compliance

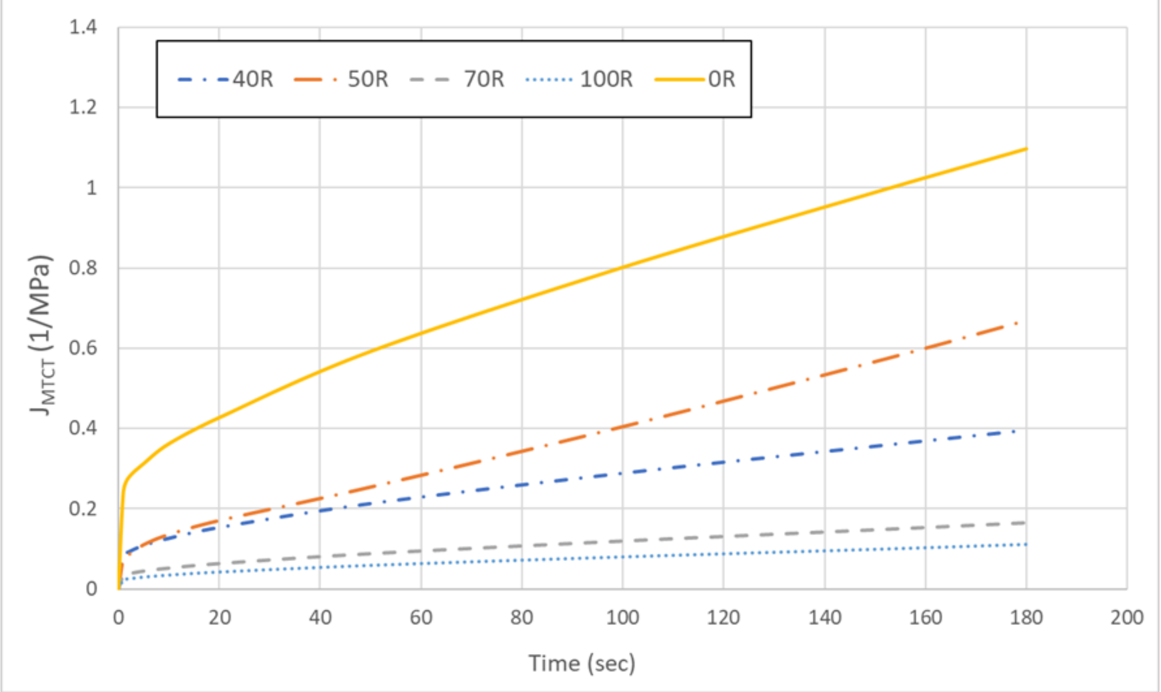


# Hot Asphalt Recycling: High amount of RAP

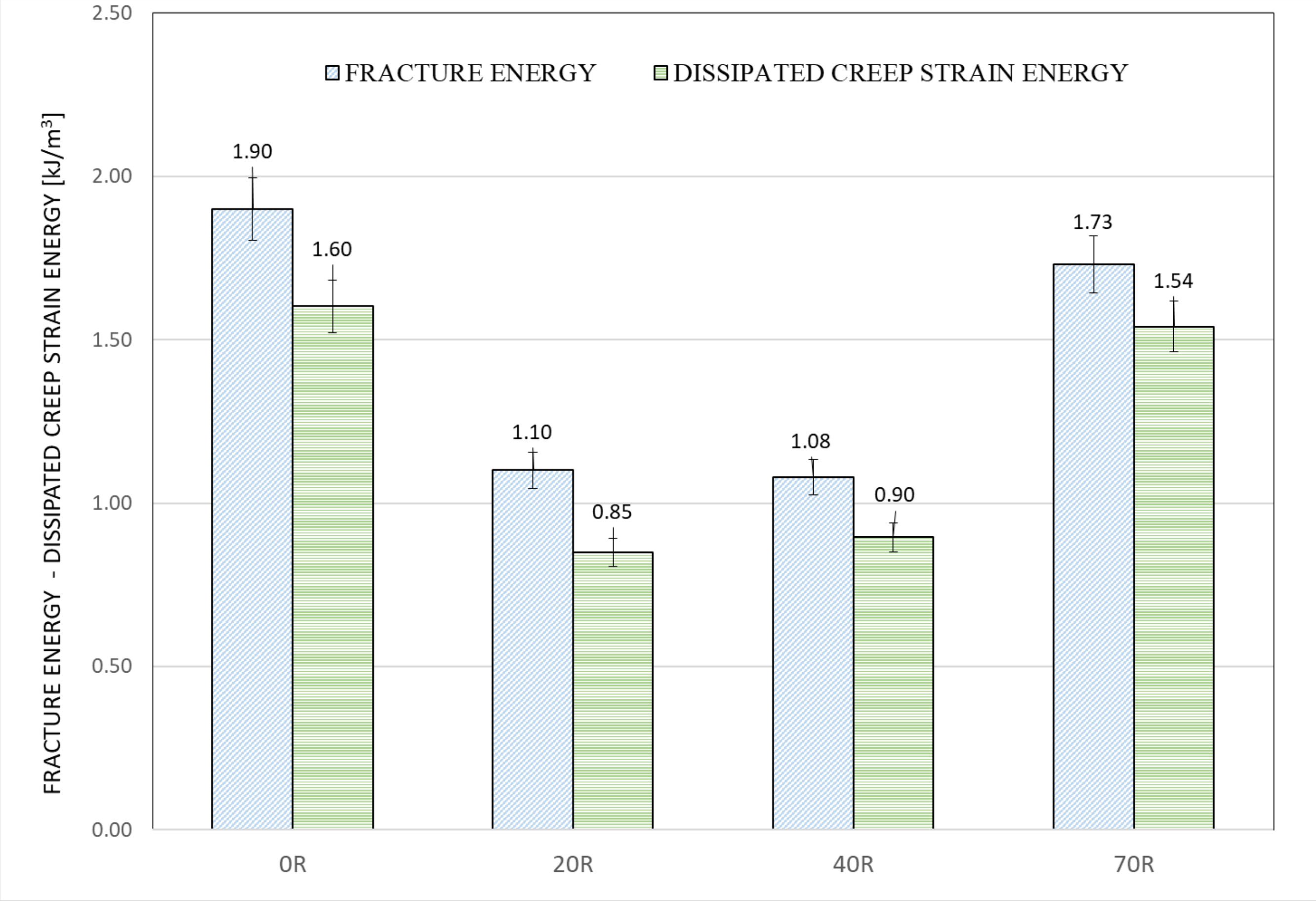
## Mastics' Creep Compliance @10°C



# Hot Asphalt Recycling: High amount of RAP

## SUPERPAVE IDT & HMA Fracture Mechanics analysis

# Hot Asphalt Recycling & Polymer level

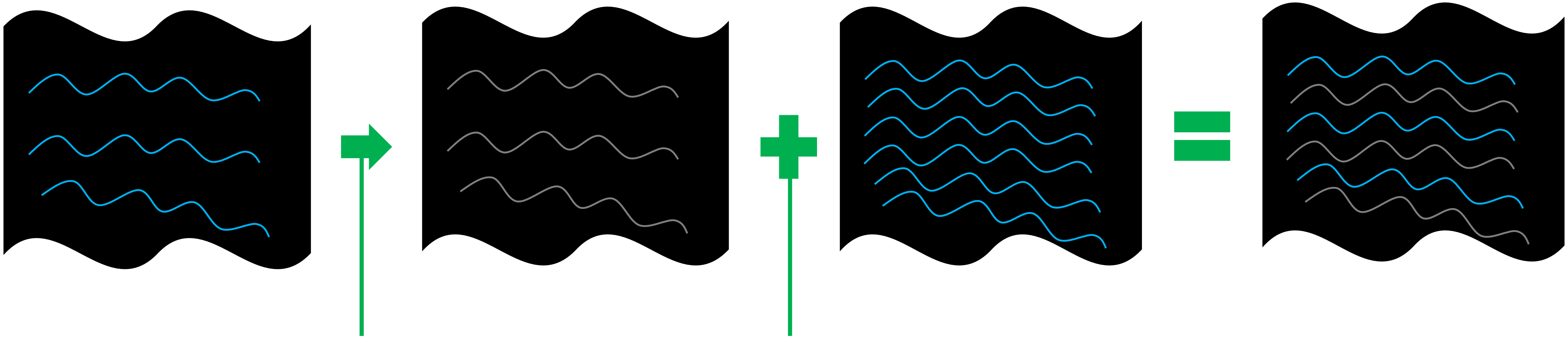
**Diffusion & blending can help to keep the appropriate level of polymers**

“initial”
polymer modified bitumen

aged
polymer modified bitumen
(inefficient polymers)

new
hyper-modified bitumen

the blend new + aged bitumen
has a balanced amount of polymers

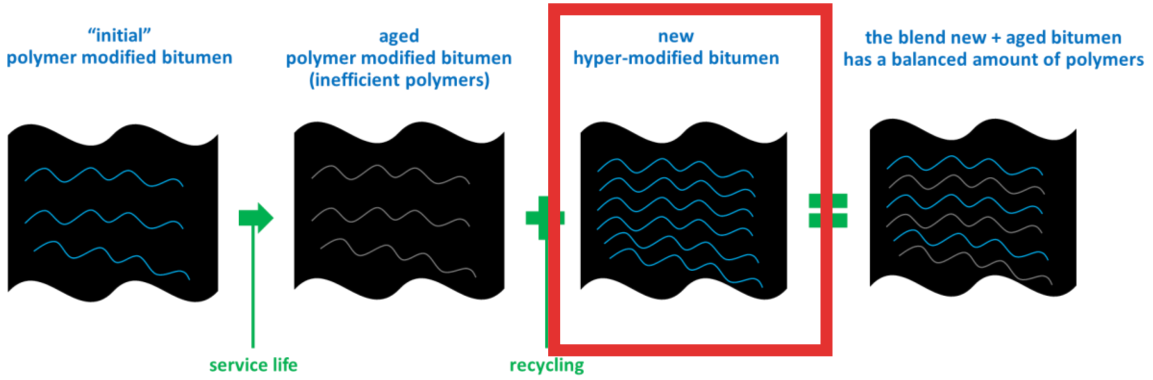


service life

recycling

# Hot Asphalt Recycling & Polymer level

## Hyper-modified bitumen




| | |
|---|---|
| Pen@25°C [UNI EN 1426] | 25÷55 dmm |
| R&B [UNI EN 1427] | >85°C |
| Elastic recovery @25°C [UNI EN 13398] | ≥ 95% |
| Dynamic Viscosity @100°C [UNI EN 13302] | > 80Pa·s |
| Dynamic Viscosity @160°C [UNI EN13302] | > 0,8Pa·s |
| Polymer content (on the bitumen weight) | >7% |
| Evaluation of Storage Stability (tuben test) [UNI EN 13399] | Δ Pen@25°C < 9.0dmm |
| | Δ R&B < 5.0°C |
| Δ Pen@25°C after RTFOT | < 40% |
| Δ R&B after RTFOT | < 5°C |

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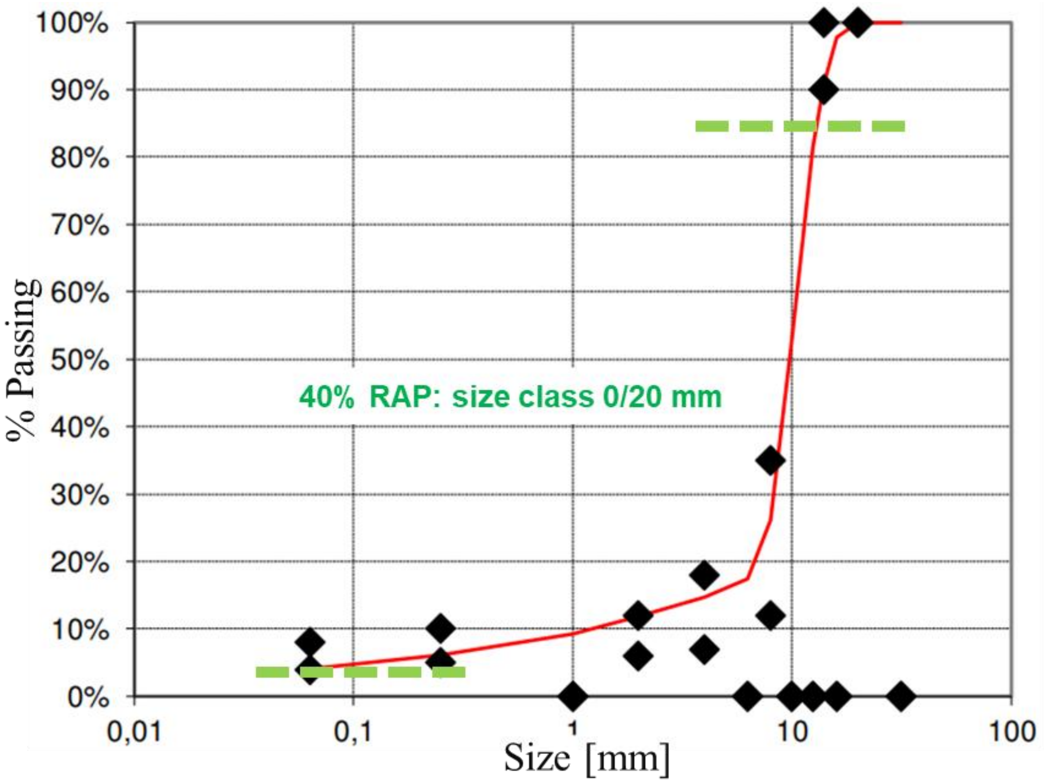
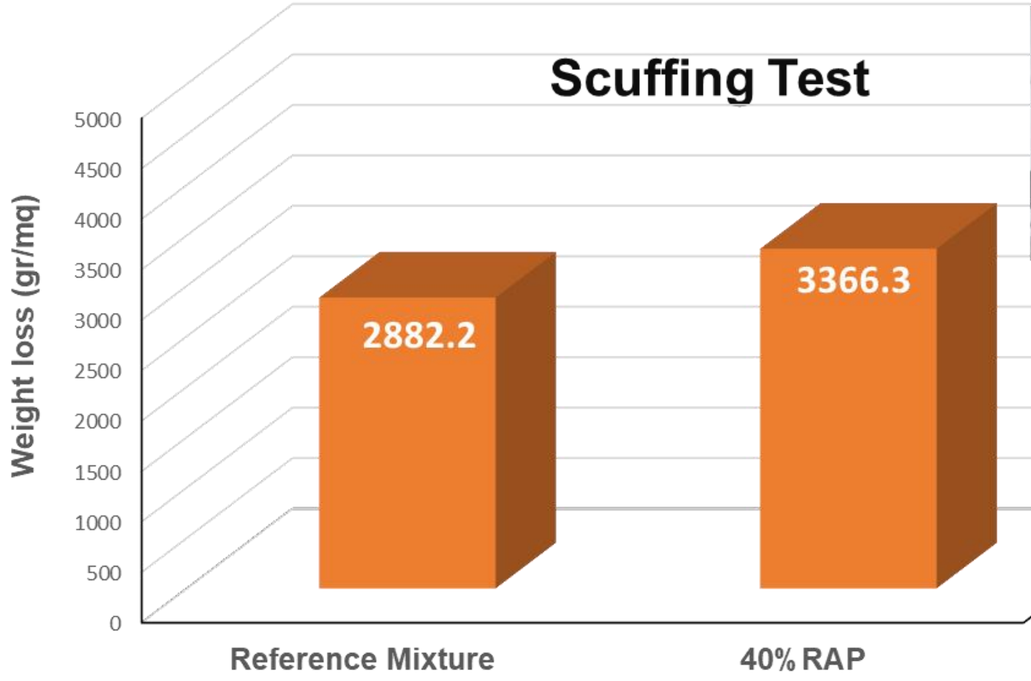
# Hot Asphalt Recycling: R.A. & HyMB

## OGFC: 40% RAP - 60% natural aggregates

The total amount of RAP is due to: asphalt plant characteristics (single drum), agency requirements, Size distribution and aggregates' maximum size of mixtures that generated RAP, “toughness” of RAP particles

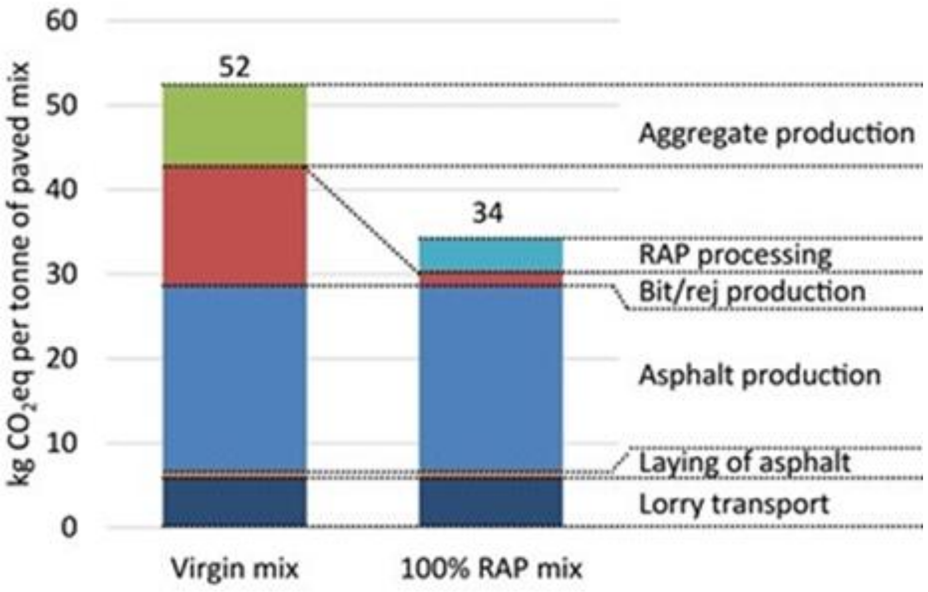


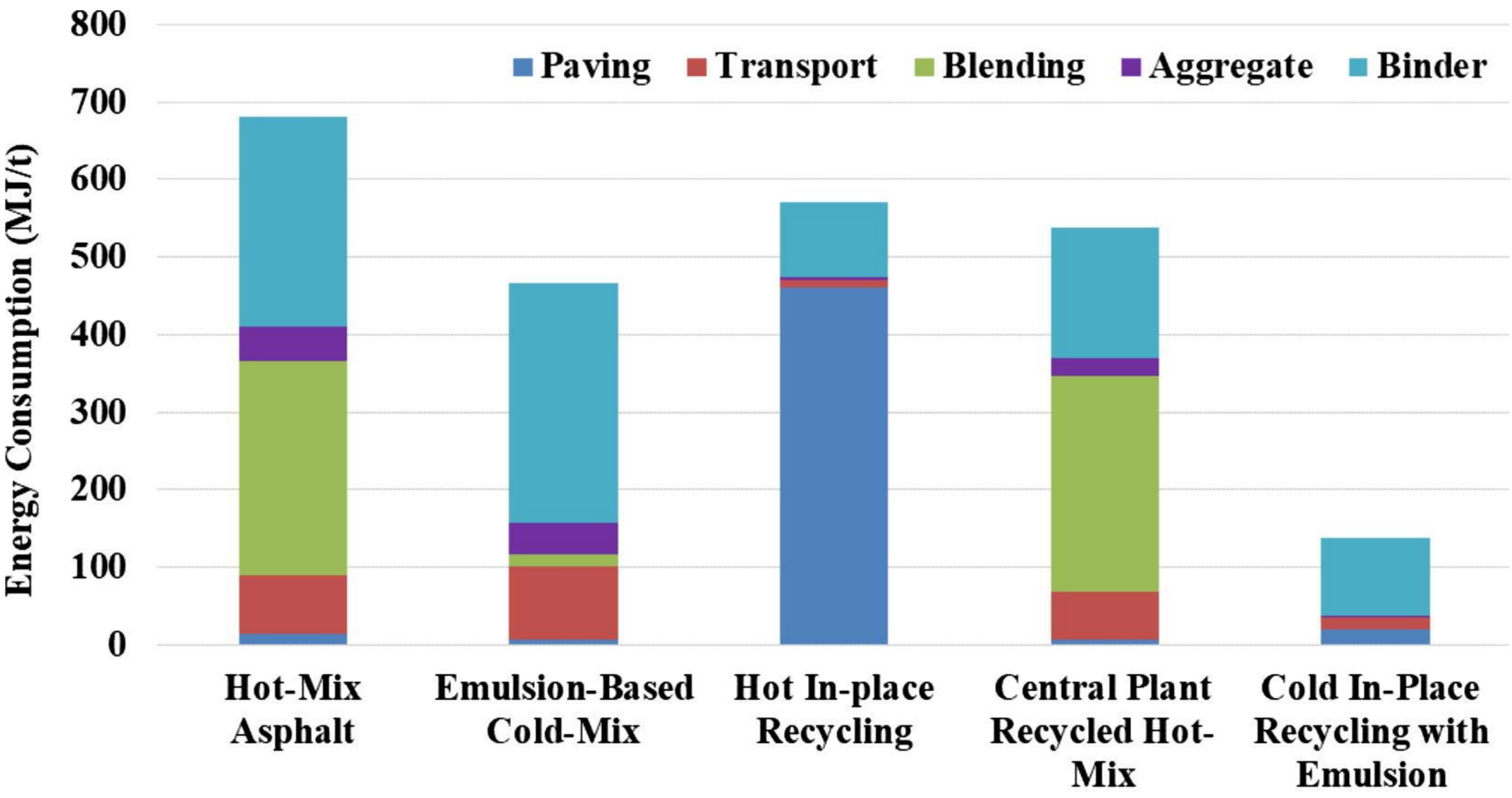




**Dosage of Recycling Agent: 0.13% w/w mixture**

**Total amount of bitumen: 5% (additional bitumen: hyper modified)**

# Recycling & Sustainability




Courtesy of Dr. Martin Zaumanis

Feipeng Xiao et alt. https://doi.org/10.1016/j.conbuildmat.2018.06.006

# Conclusions & Remarks

**COLD RECYLCLING**

- **Optimization of specimen preparation techniques (compaction, curing,..)**
- **“Smart” use  of active fillers**
- **Proper pavement design approach**

**HOT RECYLCLING**

- **Maximization of the amount of RAP**
- **Full understand of blending and diffusion mechanism**
- **Proper approach for Recycling Agents dosage → Rheological approach**

# 2nd RILEM International Symposium on Bituminous Materials

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To be finalized

ISAP International Society for Asphalt Pavements

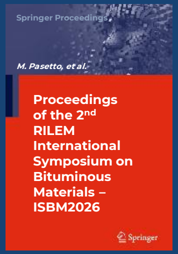
AAPT Association of Asphalt Paving Technologists

NAPA National Asphalt Pavement Association

rilem

# 2nd RILEM International Symposium on Bituminous Materials

## Index publication opportunities

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Volume I and Volume 2

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